Abnormal magnetic-resonance scans of the lumbar spine in asymptomatic subjects. A prospective investigation

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The Three Column Spine and Its Significance in the Classification of Acute Thoracolumbar Spinal Injuries

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From a retrospective study of 412 thoracolumbar injuries, the author introduces the concept of middle column or middle osteoligamentous complex between the traditionally recognized posterior ligamentous complex and the anterior longitudinal ligament. This middle column is formed by the posterior wall of the vertebral body, the posterior longitudinal ligament and posterior annulus fibrosus. The third column appears crucial, as the mode of its failure correlates both with the type of spinal fracture and with its neurological injury. Spinal injuries were subdivided into minor and major. Minor injuries are represented by fractures of transverse processes, facets, pars interarticularis, and spinous process. Major spinal injuries are classified into four different categories: compression fractures, burst fractures, seat-belt-type injuries, and fracture dislocations. These four well-recognized injuries have been studied carefully in clinical terms as well as on roentgenograms and computerized axial tomograms. They were then subdivided into subtypes demonstrating the very wide spectrums of these four entities. The correlation between the three-column system, the classification, the stability, and the therapeutic indications are presented. [Key words: thoracolumbar injury, fracture dislocation, structural spinal columns, classification, roentgenography, and CT stability]

Sir Frank Holdsworth's investigations have had a major impact on the understanding of thoracolumbar injuries. His classification,[7,8] based on the spine subdivided into two columns, has been quite useful in appreciating the complexity of spinal injuries. However, he insisted that rupture of the posterior column was sufficient to create instability of the spine. In contradistinction, several experimental studies[1,4,11,13,14] demonstrate that instability or the ability to subluxate or dislocate appears only after additional rupture of the posterior longitudinal ligament and of the annulus fibrosus. Finally, Holdsworth did not acknowledge flexion distraction injuries in spite of the intriguing report by Chance published in the British literature in 1948. Treatment of spinal fractures remains controversial. The lack of an updated classification of spinal fractures may be instrumental in preventing communication and comparison of different treatments between different centers. A new biomechanical concept and a new classification are proposed.

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MATERIALS AND METHODS

This is a retrospective review of 412 thoracolumbar spinal injuries carried out by the author at the St. Paul-

Ramsey Medical Center, St. Paul, Minnesota, and at the Ottawa Civic Hospital, Ottawa, Canada. The charts, operative notes, roentgenograms, myelograms, C.A.T. scans, and pathology notes were reviewed. The history of mechanism of the injury was correlated with the x-ray appearance, the neurological deficit, the operative findings, and the C.A.T. scans whenever available (120 operative notes were available, 53 patients had a C.A.T. scan done in this series). All cases of metastatic fractures, severe osteoporosis, ankylosing spondylitis, bone tumors, and other metabolic bone disease were eliminated from this study. The average age of the patient population was 32.3 years with a range from 17–75. The average follow-up was 30.1 months. The purpose of this part of the study was not to analyze different methods of treatment and their results in terms of patient function but instead, was to emphasize the pathologic anatomy of the different types of spinal injuries, under a new classification.

NEW BIOMECHANICAL CONCEPT

Complete rupture of the posterior ligamentous complex alone is insufficient to create instability in flexion, extension, rotation, and shear.[1,4,11,13,14] However, when in addition there is also disruption of the posterior longitudinal ligament and posterior annulus fibrosus, one may then obtain instability at least in flexion.[1,4,11,13,14] For this reason, the two-column theory was replaced by a three-column theory (Figure 1). The third column is represented by the structures that have to be torn in addition to the posterior ligamentous complex in order to create acute instability. The third or middle column is formed by the posterior longitudinal ligament, the posterior annulus fibrosus, and the posterior wall of the vertebral body. The posterior column remains essentially the same as that described by Holdsworth. It is formed by the posterior bony complex (posterior arch) alternating with the posterior ligamentous complex (supraspinous ligament, interspinous ligament, capsule, and ligamentum flavum). The anterior column is formed by the anterior longitudinal ligament, the anterior annulus fibrosus, and the anterior part of the vertebral body. The mode of column failure of the major spinal injuries is summarized in Tables 1 and 2. It will be explained in more detail for each type of fracture.

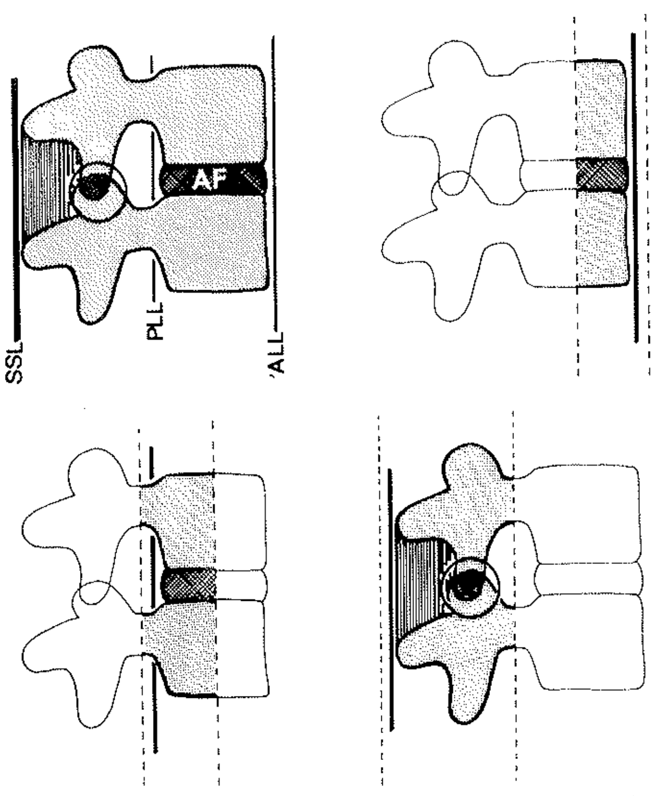

Fig 1. The anterior, middle, and posterior column are illustrated.

CLASSIFICATION OF SPINAL FRACTURES

Spinal fractures were divided into minor injuries and major injuries (Table 3). Minor injuries were represented by: 56 fractures of the transverse process in 28 patients, 3 fractures of the articular process in 3 patients, 4 fractures of the pars interarticularis in 4 patients, and 5 isolated fractures of the spinous process in 5 patients. They were all isolated injuries of part of a column, and none of them led to acute instability. Similar fractures were encountered in conjunction with a major spinal injury either at the same level or at an adjacent level; they were then considered as a part of the major injury complex.

Transverse process fractures resulted, in a majority of cases, from direct blunt trauma to the lumbar area. Other mechanisms included violent lateral flexion to the lumbar spine, and finally, Malgaigne fractures (Figure 2).

Table 1. Basic Modes of Failure of the Three Columns in the Four Major Types of Spinal Injuries*

TYPE OF FRACTURE	COLUMN Anterior	Middle	Posterior
Compression	Compression	None	None or distraction (severe)
Burst	Compression	Compression	None
Seat-belt type	None or compression	Distraction	Distraction
Fracture dislocation	Compression rotation shear	Distraction rotation shear	Distraction rotation shear

* In seat-belt type injuries, the component of compression failure of the anterior column is either absent or minimal and takes place in the anterior part of the vertebral body (collapse of about 10% to 20% of the anterior height).

Table 2. The D

TYPES

Compressi

-Anterior
-Lateral

Burst

-Type A
-Type B
-Type C
-Type D
-Type E

Seat-belt

Fracture d

-Flexion rota
-Shear

-Flexion Dis

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Major spi

Table 3.

Minor spi

Articular pr
Transverse
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Compressi
Burst frac
Fracture d
Seat-belt

Table 2. The Different Mechanisms of the Four Major Types of Injuries are Demonstrated

TYPES	MECHANISMS
Compression	**Flexion**
-Anterior	-Anterior flexion
-Lateral	-Lateral flexion
Burst	**Axial load**
-Type A	-Axial load
-Type B	-Axial load + flexion
-Type C	-Axial load + flexion
-Type D	-Axial load + rotation
-Type E	-Axial load + lateral flexion
Seat-belt type	**Flexion distraction**
Fracture dislocation	
-Flexion rotation	**Flexion rotation**
-Shear	**Shear**
	-AP shear
	-PA shear
-Flexion Distraction	**Flexion distraction**

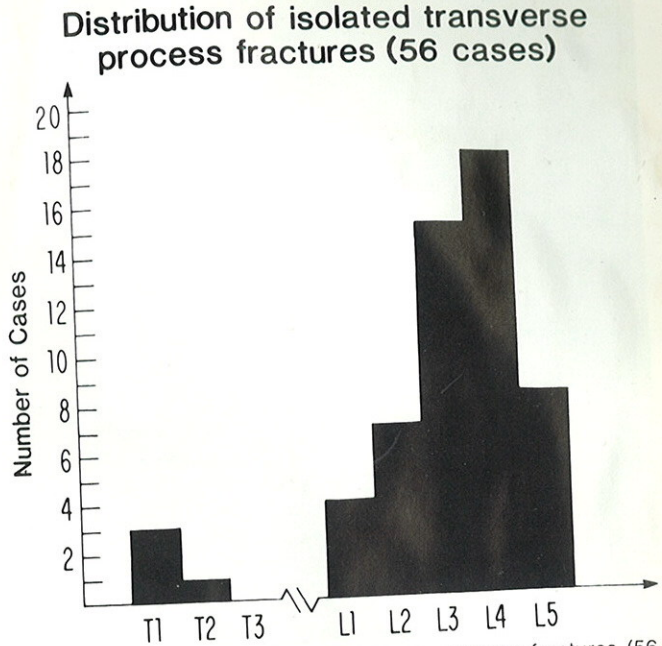

Fig 2. Distribution of isolated transverse process fractures (56 cases).

Fractures of the articular process resulted, in the three cases, from direct trauma to the back (1 case) and from falls from heights onto the back (2 cases).

Pars-interarticularis fractures were seen in young individuals involved in sports: one volleyball player, two ice skaters, and one football player. They were diagnosed as acute fractures on the basis of the initial roentgenograms. In these four cases, healing after body cast immobilization confirmed their acute nature.

Major spinal injuries were classified into four different categories: 197 compression fractures in 136 patients, 59 burst fractures in 58 patients, 19 seat-belt-type injuries in 19 patients, and 67 fracture dislocations in 67 patients. Each of these four different categories was then subdivided into types and subtypes in an attempt to demonstrate their wide spectrum (Tables 1 and 2).

Table 3. Distribution of 412 Spinal Injuries by Diagnosis

Minor spinal injuries		
Articular process fracture	3	(0.7%)
Transverse process fracture	56	(13.59%)
Spinous process fracture	7	(1.69%)
Pars interarticularis fracture	4	(0.97%)
Major spinal injuries		
Compression fractures	197	(47.81%)
Burst fractures	59	(14.32%)
Fracture dislocations	67	(16.26%)
Seat-belt type spinal injuries	19	(4.61%)

1. Compression Fractures (197 cases)

Biomechanics. The compression fracture is a failure under compression of the anterior column. The middle column is totally intact and acts as a hinge. In severe cases, there may be a partial tension failure of the posterior column. The fact that the middle column is intact is of major importance, since it is pathognomonic to this fracture and, therefore, absent from the three other categories of fractures.

Subtypes. The two subtypes of compression fractures are: anterior (Figures 3A and B) and lateral (Figures 4A and B). Their mechanism is for the former, anterior flexion, and for the latter, lateral flexion. Out of 197 fractures reviewed, only 148 were recorded specifically as to their subtypes of anterior or lateral compression, due to the lack of emphasis on that difference in the first protocol. These 49 cases not included in the subtype histogram were otherwise studied in terms of their mechanisms, their clinical, and radiological characteristics. They will, therefore, be presented with the 148 others as they do not decrease the significance of the latter, and still bring in additional information. The most frequent type of compression

Fig 3A. Anterior compression fracture with disruption of the inferior end plate (Type C compression fracture). Note the normal height of the posterior part of the vertebral body.

fracture involves failure of the upper end-plate of the vertebra in its anterior portion. However, there are isolated failures of the inferior end-plate, sometimes failure of both end-plates. For this reason, compression fractures are further subdivided (Table 4 and Figure 5).

Radiographic Characteristics of the Compression Fracture. On the lateral film, the height of the anterior vertebral body is decreased. The posterior height of the body remains unchanged. The posterior cortex of the vertebral body is also intact. There is no subluxation of the vertebral bodies either above or below.

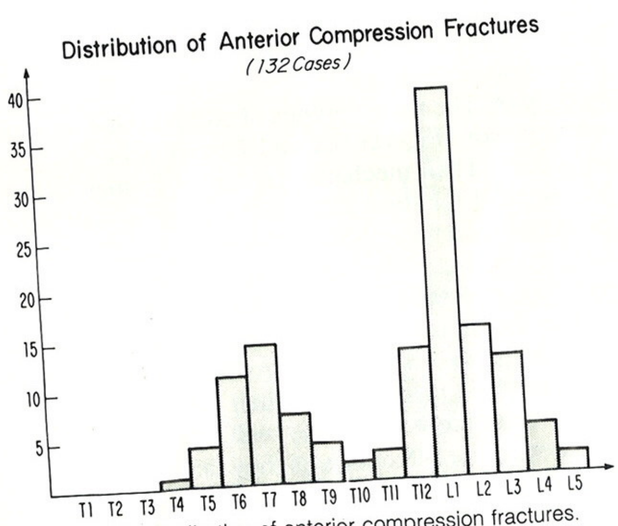

Fig 3B. Distribution of anterior compression fractures.

Fig 4A. Lateral compression fracture.

The interspinous distance of the motion segment involved in the end-plate failure is increased in the very proportions that are expected from the angulation at that level. The AP film shows the buckling of the lat-

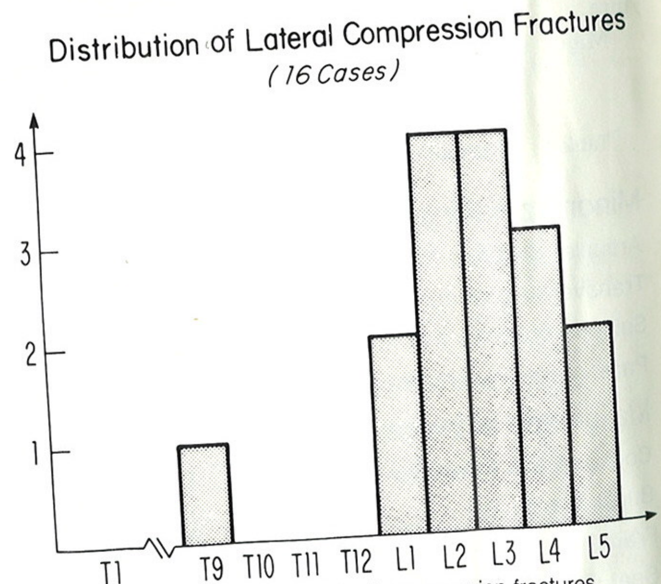

Fig 4B. Distribution of lateral compression fractures.

Table 4. Distribution of Compression Fractures by Type

Type A	32	(16.2%)
Type B	123	(62.4%)
Type C	12	(6.09%)
Type D	30	(15.2%)

eral vertebral cortex next to the end-plate that has failed. The AP film may also demonstrate the lateral wedging, proof of the lateral flexion component.

Characteristics on C.A.T. Scan. Computerized axial tomography confirmed in 10 cases, that the vertebral ring (posterior wall, pedicles, and lamina) was totally intact[5,6] (Figure 6). The neural canal had not been transgressed by the injury. This correlated well with the absence of neurological findings. The rupture of the anterior end-plate and its comminution were well demonstrated.

2. Burst Fractures (59 cases)

Biomechanics. The burst fracture results from failure of the vertebral body under axial load. This results in failure of the anterior and middle columns both under compression (Figure 7).

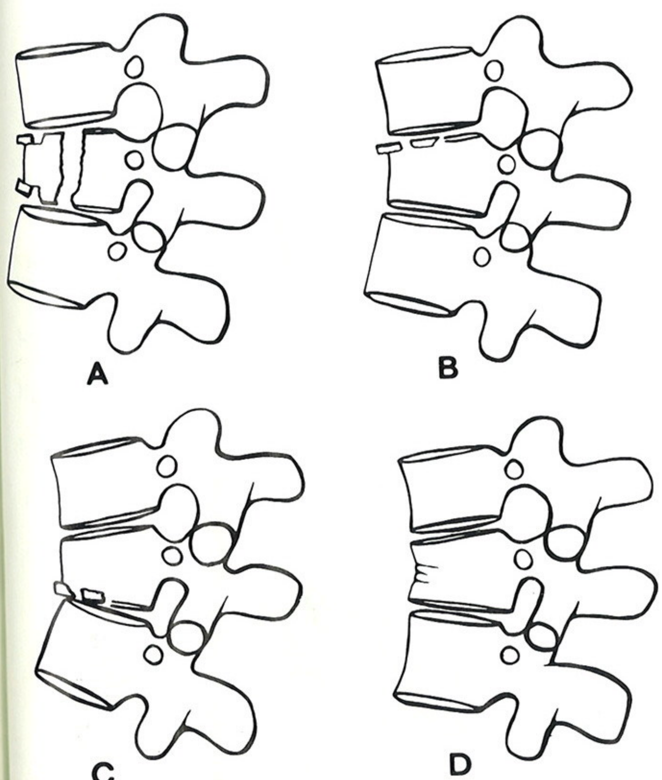

Fig 5. Classification of compression fractures.

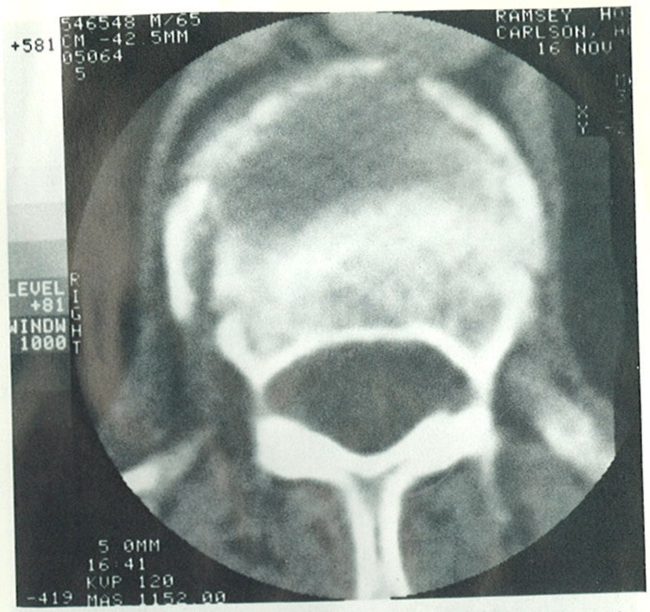

Fig 6. Computerized axial tomogram of compression fracture. Note anterior end-plate fracture and totally intact posterior wall of the vertebral body.

Radiographic Characteristics of the Burst Fracture. The failure of the middle column is delineated on the lateral film by (Figure 8A): fracture of the posterior wall cortex; loss of posterior height of the vertebral body; tilting and retropulsion of a fragment of bone into the canal from either or both end plates; and the characteristic increase of the interpediculate distance, the vertical laminar fracture and the splaying of the posterior joints (Figure 8B). The two last signs are both another expression of the increase of the interpediculate distance leading to the splay of the entire posterior arch of the vertebra involved. The vertical laminar fracture is best described as a greenstick fracture of the anterior cortex of the lamina. At surgery from a posterior approach, the posterior cortex of the lamina is usually intact. Only a careful decortication will demonstrate the fracture of the anterior cortex.

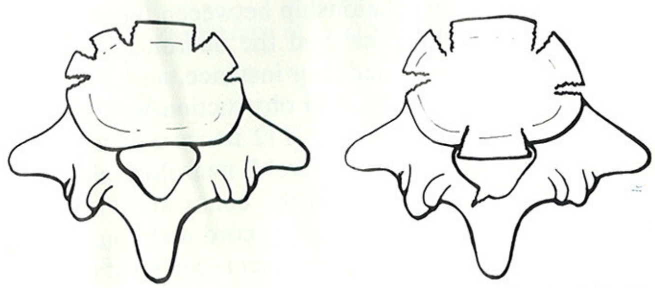

Fig 7. The basic difference between the compression and the burst fracture resides in the middle column. It is intact in the former and fractured in the latter. Note the fracture of the posterior wall as well as the fracture of necessity of the lamina (related to the increased interpediculate distance.)

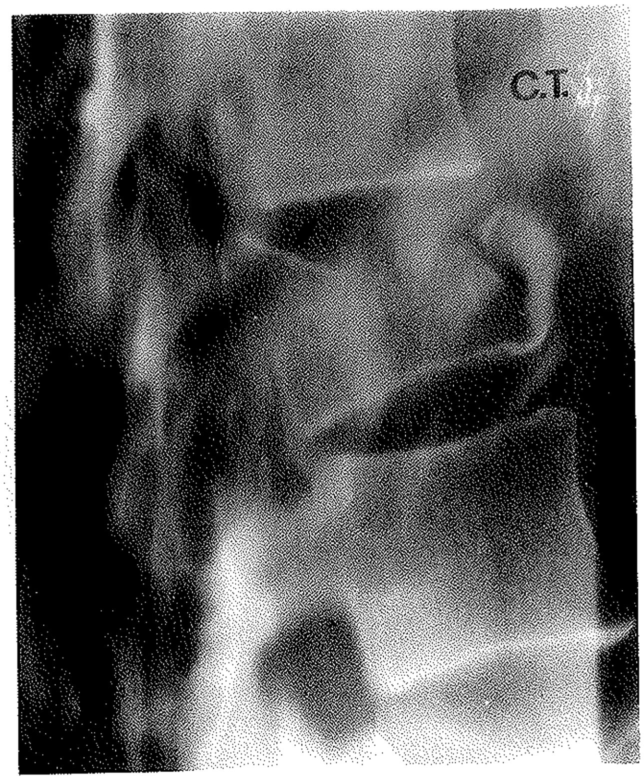

Fig 8A. Lateral tomogram of a burst fracture (Type B). Note severe disruption of superior end-plate, loss of height of posterior vertebral body, and fracture of posterior wall of body. The arrow shows the large fragment retropulsed into the canal.

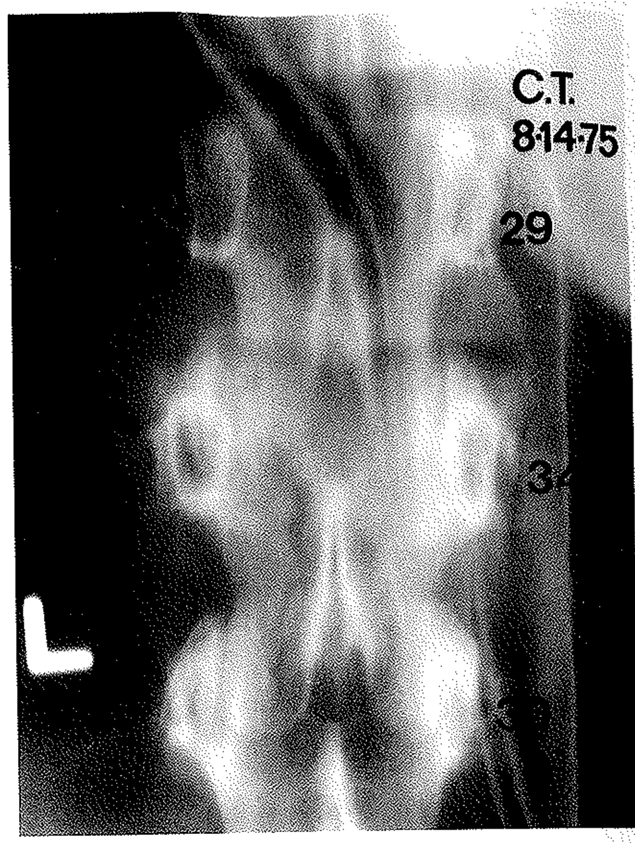

Fig 8B. Anteroposterior tomogram of a burst fracture. Note the increased interpediculate distance (34 mm) and the vertical laminar fracture.

Characteristics of Burst Fractures on C.A.T. Scan.

What clearly differentiated the burst fracture from the compression fracture is the integrity of the vertebral ring in the latter. On the contrary, in the former, it is fractured both anteriorly and posteriorly[5,6] (Figure 9). In 29 cases, the C.A.T. scan demonstrated the most important characteristic of burst fractures: the break of the posterior wall of the vertebral body with marked retropulsion of bone into the canal and obstruction, in the average case, of about 50% of the cross section of the canal at that level. The increase of the interpediculate distance, fracture of the lamina and splay of the facets were also visualized.

A simple direct relationship betweeen the degree of obstruction of the canal and the neurological deficit could not be established. For instance, an L3 fracture presented with a 60% canal obstruction without neurological deficit, whereas a T12 fracture with a 25% obstruction sustained a Frankel B neurological deficit. The space available around the conus at T11–T12 is less than at L3–L4. The spinal cord and conus medullaris are very sensitive to impact received at the time of explosion of the vertebral body and the size of the fragment in these instances may not be a primary factor in neural damage. Impact loading rate of the bone fragment against the conus may be more significant. On the other hand, the cauda equina is less sensitive to impact but more so to continued compression. The cases were therefore divided into two groups; the conus group (T11, T12, L1) and the cauda equina

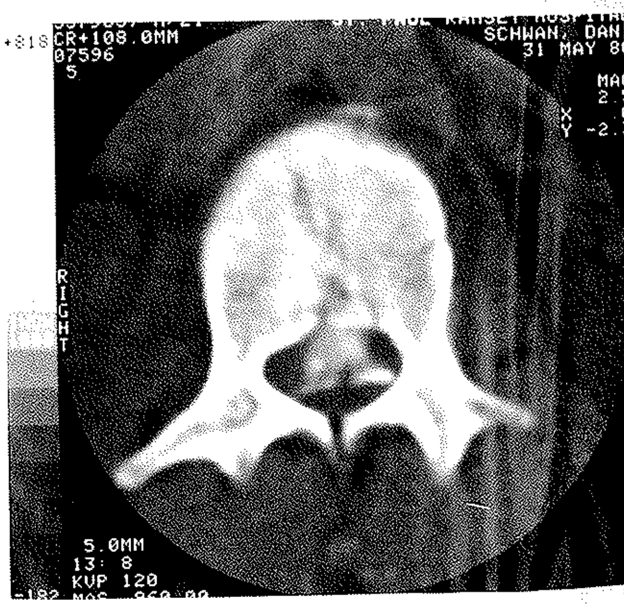

Fig 9. Computerized axial tomogram of a burst fracture. Note the large fragment of bone retropulsed from the posterior wall.

group (L2, L3, L4, L5). Obstructions greater than 75% of the canal cross section were accompanied by neurological damage (Frankel B for the conus group and Frankel C for the cauda equina group). An obstruction of 25–50% rarely presented with neurological damage in the second group, whereas it was more frequent in the first group.

Depending upon the mode of failure and the site at which the fracture occurs, different types of burst fractures will appear (Tables 1, 2, 5, and 6; Figures 10 and 11). For instance the burst fracture, as described by Holdsworth (comminution of the entire vertebra without any kyphotic component) is encountered mainly in the low lumbar region, L3, L4, or L5. In contradistinction, in the upper lumbar spine or the thoracolumbar junction, burst fractures involve disruption of the upper end-plate with a slight kyphotic component. This appears to be due to the natural tendency for the axial load to lead to flexion in the thoracolumbar junction, whereas the same axial load would tend to increase extension in the low lumbar region. For this reason, the author described five different types of burst fractures (Table 5, Figure 11).

Type A: Fracture of both end plates (Figure 11A). As previously mentioned, it is seen in the low lumbar region. It does not lead to kyphosis. Its mechanism is pure axial load. The importance of recognizing it resides in the fact that decompression needs to be done at two levels (between the involved vertebra and both adjacent vertebrae).

Type B: Fracture of the superior end-plate (Figure 11B). This is the most frequent burst fracture. It is seen at the thoracolumbar junction. The C.A.T. scan demonstrates well the burst of the upper end-plate and frequently shows a sagittal split of the lower end-plate.

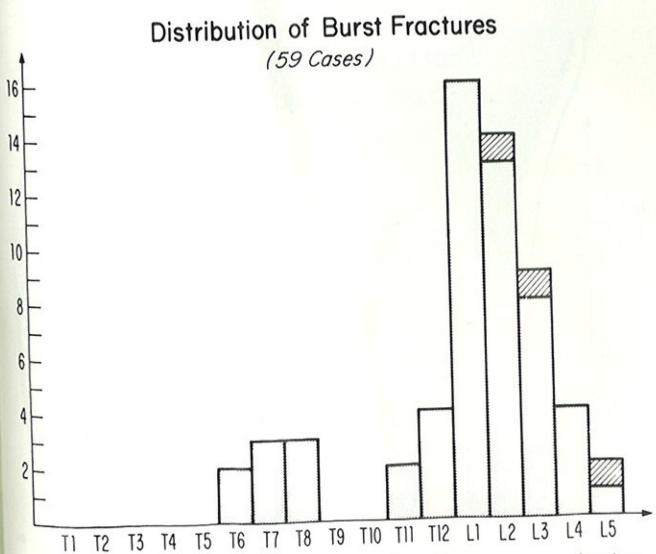

Fig 10. Distribution of burst fractures. Most fractures are lumbar. The hatched area on column L2, L3, and L5 represent three cases of lateral burst fractures.

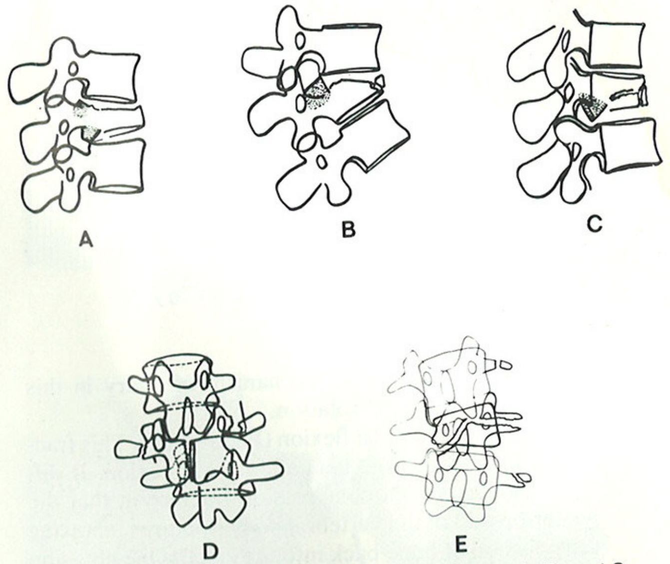

Fig 11A–E. Classification of burst fractures: Types A, B, and C are mainly diagnosed on lateral roentgenogram, their anteroposterior roentgenograms reveal the basic pathognomonic features seen on Figure 8. Types D and E are diagnosed on anteroposterior roentgenograms. The lateral film of a Type D looks like a Type A, whereas the lateral film of a Type E may look like Type A, B, or C.

The mechanism of injury is axial load and flexion. When indicated, decompression will be done at the upper level, between the burst vertebra and the vertebra above.

Type C: Fracture of the inferior end-plate. This fracture is rare and, therefore, no particular site pattern could be located. The mechanism of injury appears to be also axial load and flexion.

Type D: Burst rotation (Figure 11D). This is typically a midlumbar fracture which could be misdiagnosed for a fracture dislocation due to the rotational malalignment of the spine. However, it presents all the pathognomonics of the burst fracture, including comminution of the vertebral body, increase of the interpediculate distance, vertical fracture of the lamina, bone retropulsed into the canal, loss of posterior height, and a large central defect on myelogram as well

Table 5. Distribution of Burst Fractures by Type

Type A	14	(23.7%)
Type B	29	(49.2%)
Type C	4	(6.8%)
Type D	9	(15.2%)
Type E	3	(5.1%)

Table 6. Frankel Classification at Admission of Burst Fractures

A	1	(1.7%)
B	6	(10.1%)
C	14	(23.7%)
D	7	(11.8%)
E	31	(52.6%)

as on C.A.T. scan. The mechanism of injury in this case is axial load and rotation.

Type E: Burst lateral flexion (Figure 11E). This fracture results from axial load and lateral flexion. It differs from the lateral compression fracture in that the posterior wall of the vertebral body fractures, allowing retropulsion of bone back into the canal. One notes on C.A.T. scan that the extruded fragment is usually lateralized to the side towards which lateral flexion took place. The importance of differentiating the lateral burst from the lateral compression fracture resides in the potential neurological deficit either present or to be anticipated in the former and absent in the latter.

3. Seat-Belt-Type Injuries (19 cases) Table 7

Semantics. This title may sound unjustified and for this reason the author would like to explain the reasons of his choice. Three other terms could also be applied to this type of injury as a title. The use of "seat-belt injuries" would be inaccurate since many of these do not result from the wearing of a seat belt. The use of "Chance fracture"[3] describes only one of the subtypes of this injury. Finally, the use of "flexion distraction injuries" would introduce a mechanistic title amongst a descriptive classification, and also ignore the difference between "posterior opening" without dislocation from the "posterior opening" with dislocation (compare Figures 13B and 21).

Biomechanics. This injury represents failure of both the posterior and middle columns under tension forces generated by flexion and sometimes by superadded distraction. The anterior part of the anterior column may partially fail under compression without losing its role as a hinge (this will differentiate it from the flexion distraction type of fracture-dislocation, where the hinge is also disrupted).

Radiographic Characteristics of the Seat-Belt-Type Fractures. There is a frequent marked increase of interspinous distance, with horizontal split of the transverse processes, horizontal split of the pedicles, and pars interarticularis fractures. Typical, too, are increased height of the posterior vertebral body, fracture of the posterior wall of the vertebral body, and posterior opening of the disc space (probable rupture of the annulus fibrosus and posterior longitudinal ligament).

Characteristics of Seat-Belt-Type Injuries on C.A.T. Scan. Computerized axial tomography does not provide much information in this type of injury, but it may demonstrate the fracture lines in the vertebral body and also the rupture of the very anterior end plate.

Table 7. Distribution of Seat-Belt-Type Injuries

Type A (one level bone injury)	9	(47.3%)
Type B (one level ligamentous injury)	2	(10.5%)
Type C (two level through bone middle column)	5	(26.3%)
Type D (two level through ligamentous middle column)	3	(15.8%)

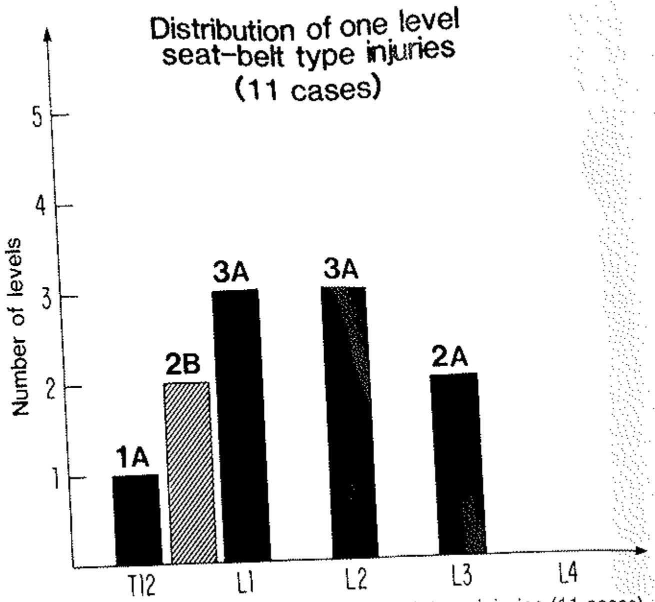

Fig 12A. Distribution of one level seat-belt-type injuries (11 cases). The dark columns represent Chance fractures, whereas the hatched area represents two cases of purely ligamentous one-level injuries.

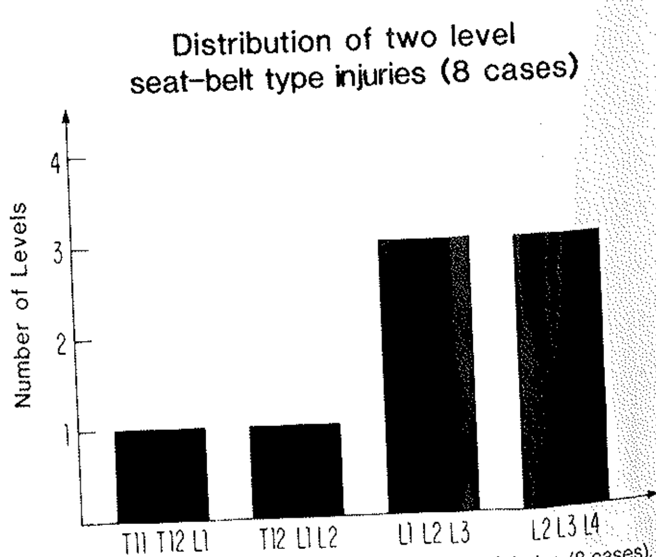

Fig 12B. Distribution of two-level, seat-belt-type injuries (8 cases). One-level, seat-belt-type through bone (Chance fracture).

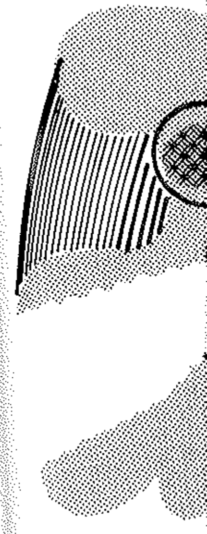

Fig 13A. One level

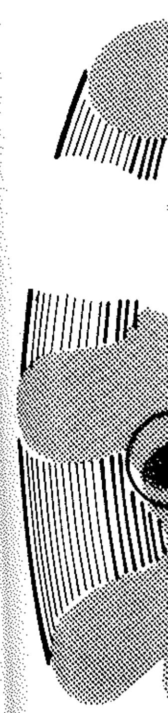

Fig 13C. Two-
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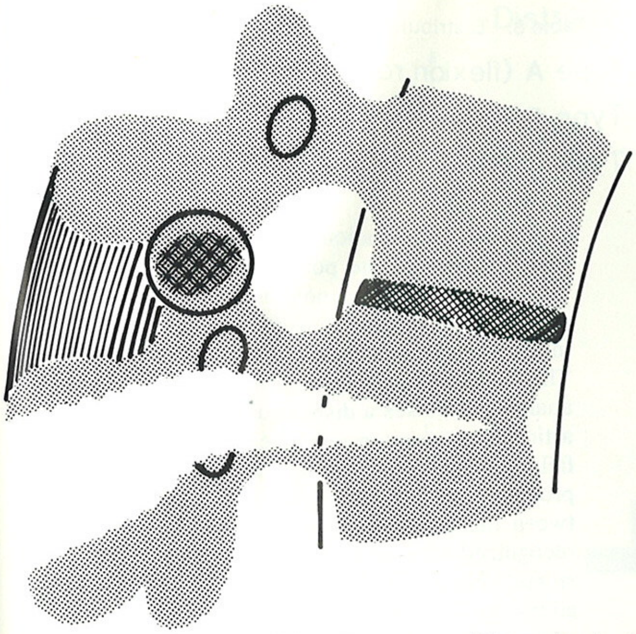

Fig 13A. One level, seat-belt-type through bone (Chance fracture).

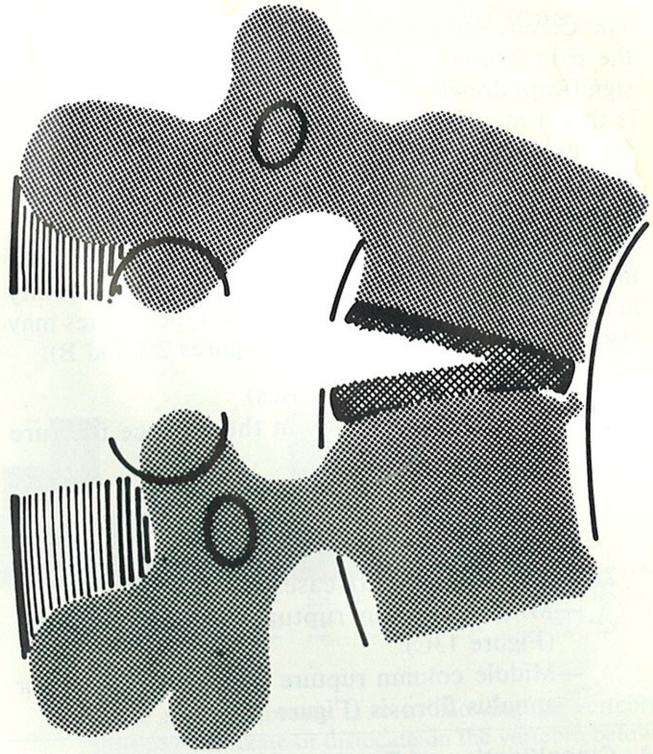

Fig 13B. One-level, seat-belt-type injury through the ligaments.

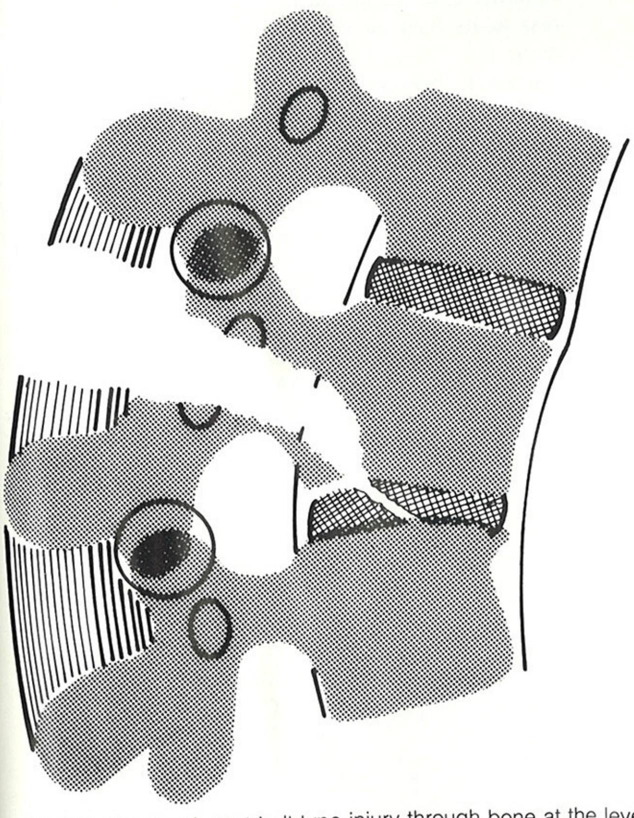

Fig 13C. Two-level, seat-belt-type injury through bone at the level of the middle column.

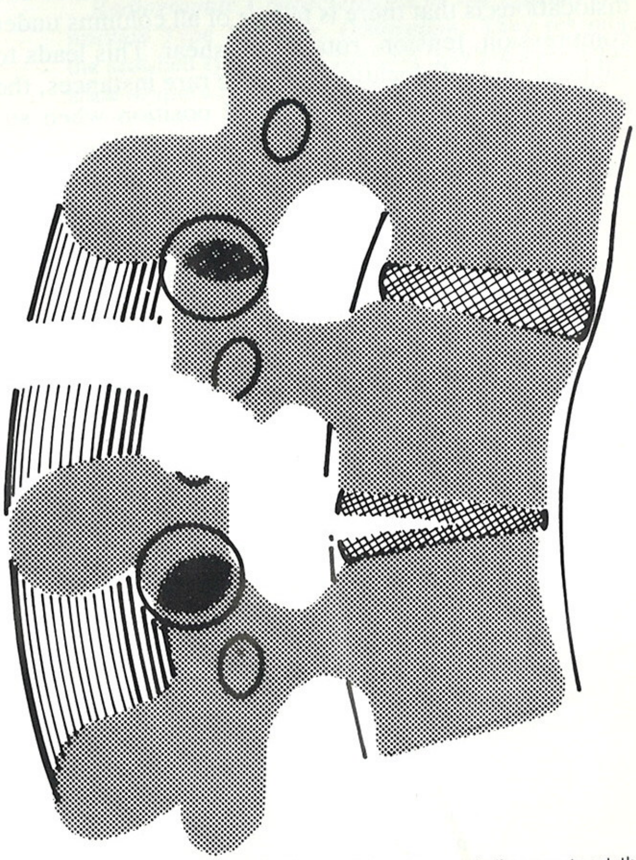

Fig 13D. Two-level, seat-belt type injury through ligaments at the level of the middle column.

The C.A.T. scan may also assist in the recognition of the pars interarticularis fracture. However, the most significant drawback of a C.A.T. scan in these injuries is that it may totally miss the fracture, since the cuts are most often parallel to the injury itself. For this reason we recommend lateral tomograms before C.A.T. scan in these injuries.

Subtypes of Seat-Belt-Type Injuries. In the same fashion as one frequently observes a C2–C3 instability in the hangman's fractures, seat-belt type injuries may also involve one or two levels (Figures 2A and B):

1. One-level lesions (11 cases)
   —Bone disruption as in the Chance fracture (Figure 13A)
   —Ligamentous disruption (Figure 13B)—tearing apart all the ligaments from the supraspinous down to the middle of the disc.
2. Two-level lesions (8 cases)
   —Middle column rupture through the bone (Figure 13C)
   —Middle column rupture through the posterior annulus fibrosis (Figure 13D).

4. Classification of Fracture Dislocations (67 cases)

Biomechanics. The main characteristic of fracture dislocations is that there is failure of all columns under compression, tension, rotation or shear. This leads to subluxation or dislocation. In some rare instances, the patient may present in a reduced position when supine. A high index of suspicion will allow one to recognize the subtle signs demonstrating the unstable nature of the injury (no obvious dislocation but multiple rib fractures, multiple transverse process fractures, unilateral articular process fractures, horizontal laminar fractures, spinous process fractures).

Types and Subtypes of Fracture Dislocations (Table 8)

Type A—Flexion rotation (Figures 14–17)
Type B—Shear (Figures 18–20)
Type C—Flexion distraction

Type A: Flexion Rotation. In this particular injury, the posterior and middle columns are totally ruptured under tension and rotation forces. The anterior column has failed under a combination of compression and rotation forces, leading to some anterior wedging of the vertebral body and to a partial tear of the anterolateral periosteum and stripping of the remaining anterior longitudinal ligament off the vertebral body below. The pathologic anatomy of the posterior and middle columns was recognized and described in the operative reports of the posterior surgery. The anterior column features were observed in one anterior fusion with instrumentation as well as in two pathologic specimens.

Radiographic Characteristics. The lateral film usually shows subluxation or dislocation. There is good conservation of the posterior wall of the vertebral body, which gives it a normal height when dislocation goes through the disc (Figures 16A and 16B). Increase in the interspinous distance is seen on the lateral film. The AP film often appears innocuous although careful analysis discloses a displaced fracture of the superior articular process on one side, proof of the rotational failure of the posterior column. Multiple transverse process and rib fractures are associated. Rotation between the segment above and the segment below is recognized from the orientation of the pedicles and spinous processes. Flexion rotation injury may either go through the disc (it is then accompanied by variable amounts of wedging of the lower vertebral body) or it may go right through the vertebral body itself leading to the traditional "slice"[7,8] type of fracture (Figures 15A, B, and C).

Characteristics of the Flexion Rotation Subtype on C.A.T. Scan (11 cases). Offset of the vertebra above on the vertebra below is noted with rotation between the two. There is restriction of canal cross-section related to that offset (Figure 17), and jumped facets are demonstrable. Frequent fracture of one articular process at its base or at the base of the pedicle is also seen.

Type B: Shear Type of Fracture Dislocation. All three columns are disrupted, including the anterior longitudinal ligament. This shear force is applied most frequently in the posteroanterior direction but also sometimes in the anteroposterior direction. Six out of seven patients presented with a very clear picture of the circumstances of their injury. Four of them were lumberjacks who were hit across the midback by falling trees. The fifth patient was trying to pull his car out of a ditch with the help of two other friends. He was sitting in the driver's seat with half his body through the open door checking whether or not his rear wheels were spinning. The car suddenly backed up on him and his trunk was severely bent between his open door and a small tree against which the car had come to rest. The anterior part of his upper trunk

Table 8. Distribution of Fracture Dislocations by Type

Type A (flexion rotation)	56	(13.59%)
Type B (shear)	7	(1.69%)
Type C (flexion distraction)	4	(0.97%)

Table 9. Frankel Classification at Admission of Flexion-Rotation Fracture Dislocations

A	22	(39.2%)
B	10	(17.8%)
C	5	(8.9%)
D	5	(8.9%)
E	14	(25.0%)

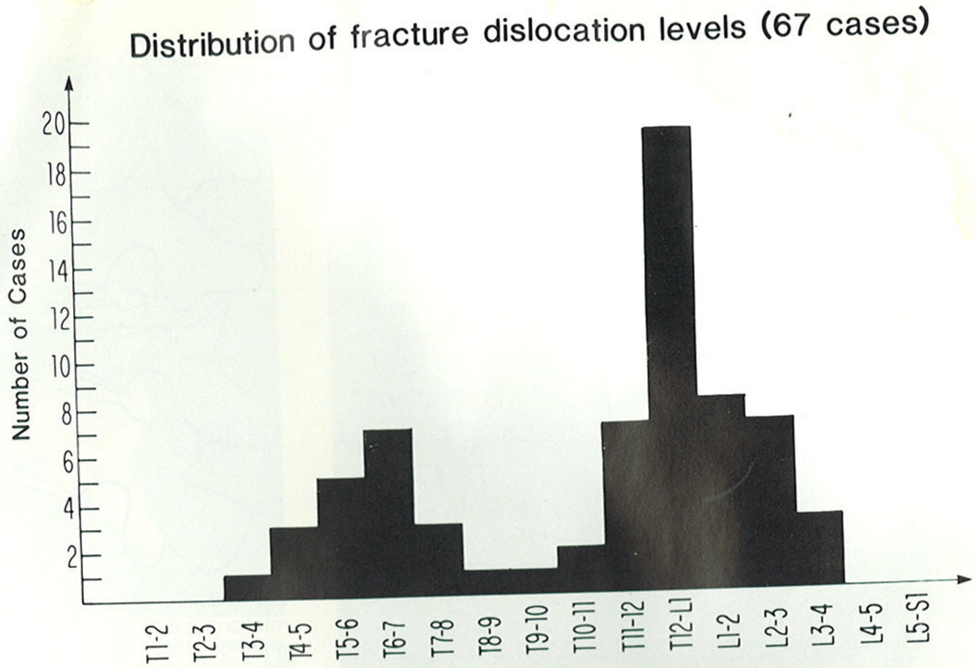

Fig 14. Distribution of fracture dislocation levels (67 cases).

was pushed backwards by the door as the middle part was pushed forwards by the tree. The sixth patient was involved in a snowmobile accident in which he was thrown off his machine landing back first against a tree.

1. In the PA shear subtype (Figure 18), the segment above shears off forward on the segment below. This takes place in the extended position so that the vertebral bodies are intact without any loss of anterior or posterior height. On the contrary, the posterior arch of the dislocated vertebral segment is fractured usually at several levels due to its difficulties in clearing the posterior arch of the level below at the time of dislocation. As a result of this, the posterior approach will often disclose: a free floating lamina, fractures of several spinous processes in the upper segment, fracture of the superior facet of the lower vertebra (different from the superior articular process fracture seen in flexion rotation injuries), and complete rupture of the anterior longitudinal ligament as demonstrated by accidental overdistraction obtained with Harrington distraction instrumentation.
2. Characteristics of the AP shear (Figure 19): In this particular subtype, the segment above shears off on the segment below in a posterior direction. The posterior arch of the segment above has nothing to clear in its posterior displacement. There is, therefore, no free floating lamina. There may be a fracture of the spinous process. On C.A.T. scan, the anterior aspect of the vertebral body of the upper segment may be locked on the superior facet of the vertebra (Figure 20).

Type C: Fracture Dislocation of the Flexion Distraction Type. This injury resembles the seat-belt-type of injury, including both the posterior and middle column ruptures under tension; in addition to this, the entire annulus fibrosus is torn, allowing the vertebra above to subluxate or dislocate on the vertebra below. This is accompanied by stripping of the anterior longitudinal ligament of the lower vertebra without disruption of its continuity (Figure 21).

Radiographic Characteristics of the Flexion Distraction Type Fracture. Dislocation: They resemble the seat-belt type, but in addition they present subluxation or more rarely, dislocation of the vertebra above on the vertebra below.

Characteristics on C.A.T. Scan: One may note the absence of signs of rotation between the two vertebrae involved in the injury. In addition, one may notice the offset of the two vertebral bodies with reduction of canal cross-section as well as the absence of superior articular process fracture as would be expected in the flexion rotation injuries.

CORRELATION OF THE CLASSIFICATION WITH NEUROLOGICAL DEFICITS

There appeared to be a close link between mechanism of injury, type of fracture, and neurological deficit.

Isolated transverse process fractures were associated with neurological deficits in two areas: T1 and T2 (two cases of brachial plexus injuries) L4 and L5 (five cases of Malgaigne pelvic fractures with lumbosacral plexus injuries).

Isolated spinous process fractures in the dorsolumbar region are often due to direct trauma. Three of the seven patients presented with temporary conus contusions, which recuperated neural function within a week. Two of the three cases were diagnosed on lateral tomograms demonstrating the difficulty in making the diagnosis on plain roentgenograms unless

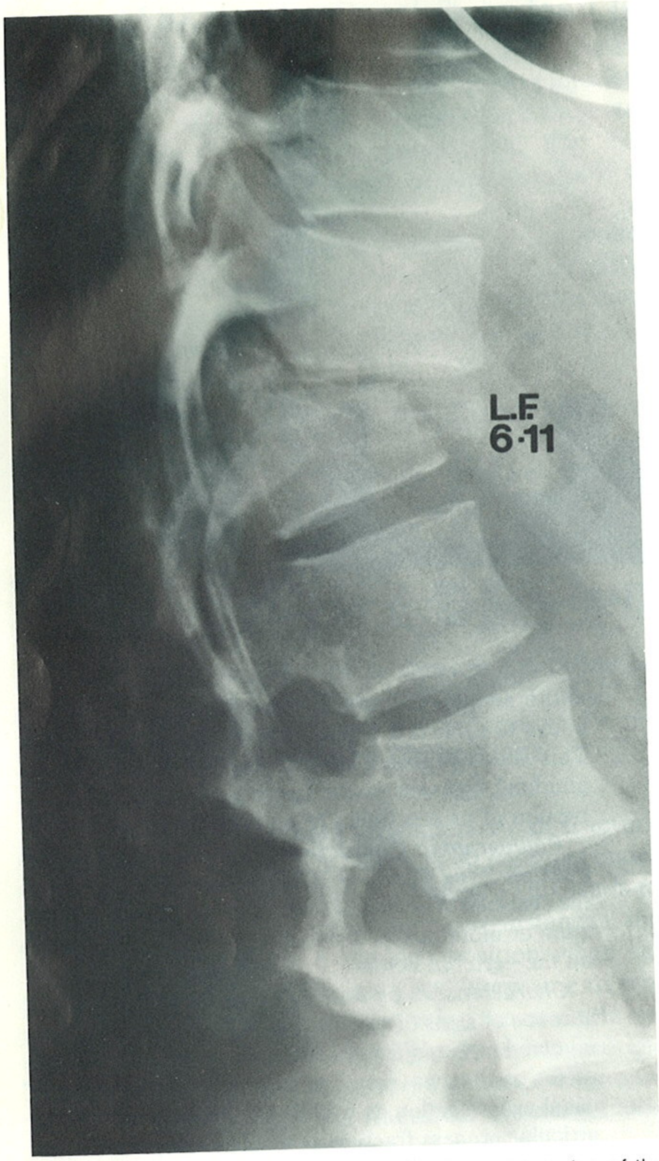

Fig 15A. Lateral roentgenogram of a fracture-dislocation of the flexion rotation type through bone (slice fracture).

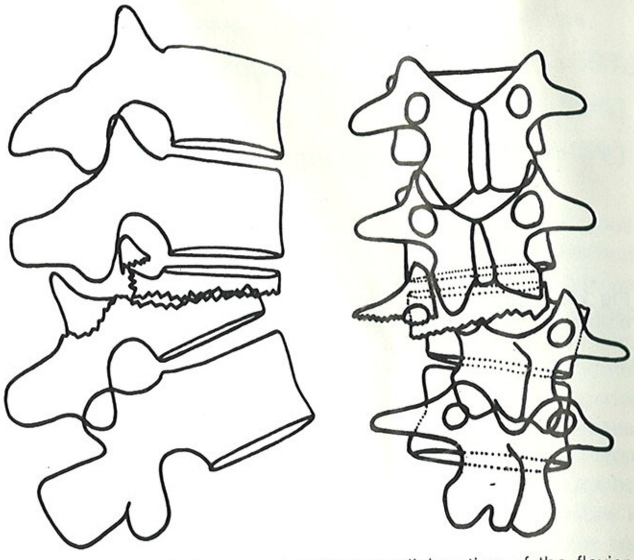

Fig 15B. Lateral diagram of a fracture-dislocation of the flexion-rotation type through bone (slice fracture). **C.** Anteroposterior diagram of a fracture-dislocation of the flexion-rotation type through bone (slice fracture). Note the difference in rotation between both spinal segments.

an unexplained neurological problem forces the spine surgeon to order finer radiological investigations.

Isolated facet and pars interarticularis fractures were not associated with any neurological symptoms, but their small number prevents drawing hasty conclusions as to the incidence of nerve damage in these cases.

Compression fractures were not directly responsible for any acute neurological damage. However, two patients with thoracic compression fractures presented with cervical cord injuries related to low cervical fracture dislocations. One patient presented with sciatic nerve injury, incurred in a posterior fracture-dislocation of the hip, and another had a lumbosacral plexus injury associated with a severe pelvic disruption with sacral fractures.

Seat-Belt Type Injuries. No neurological injury could be linked to this type of injury. One patient had a peroneal nerve palsy following a prolonged period of pressure over the posterolateral aspect of her knee while waiting to be extracted from her car after a severe motor vehicle accident.

Burst fractures were neurologically intact at first ex-

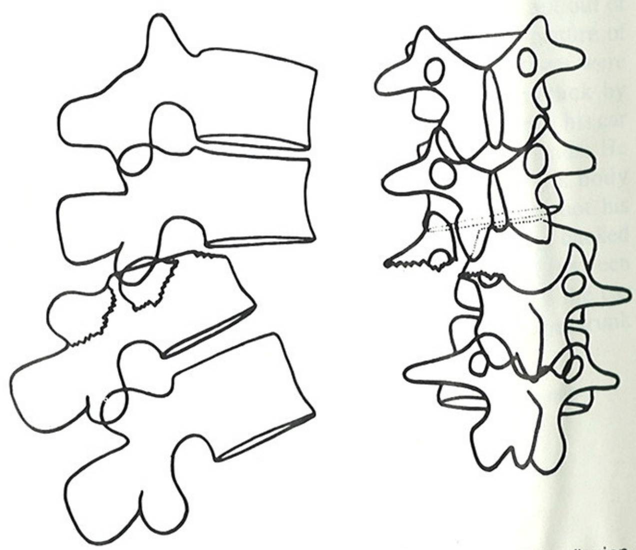

Fig 16A. Lateral diagram of a fracture-dislocation of the flexion-rotation type through the disc. Note the superior articular process fracture on one side only. **B.** Anteroposterior diagram of a fracture-dislocation of the flexion-rotation type through the disc. Note the fracture of the left superior articular process.

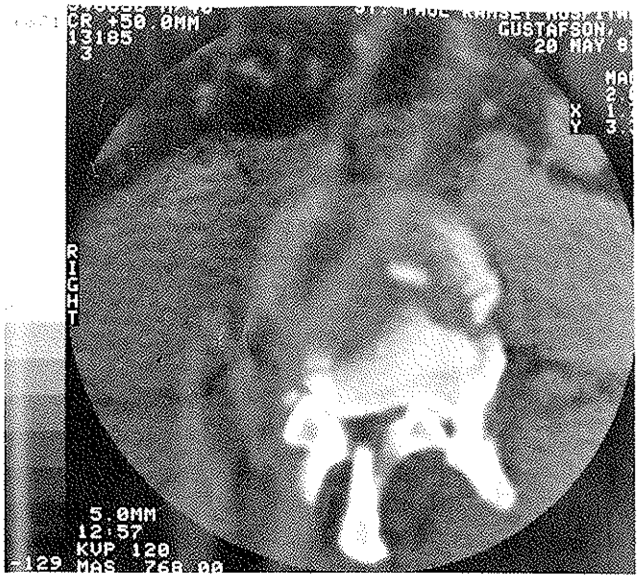

Fig 17. Computerized axial tomogram of an L2-3 lumbar fracture-dislocation of the flexion-rotation type. Note the fracture of the right superior articular process of L3 and the 80% neural canal obstruction resulting from the malalignment.

amination in 31 cases (52.5%). Among these patients, approximately one out of two remembers leg numbness, tingling, and/or weakness just after the accident, which subsided within one hour and was absent at the time of examination by the physician. This phenomenon, related to the impact to either the conus or the cauda equina, was investigated only in the last 15 cases of the series. It was present by history in eight of the 15.

Among the 28 cases with neurological deficits (47.5% of all burst fractures) only one case presented a complete paraplegia at a low thoracic level. None of the 30 operative cases presented dural tears at exploration. This high proportion of incomplete paraplegias (96.4%) in burst fractures compared to 47.6% in fracture-dislocations demonstrates the better neurological resilience of the former (Table 9).

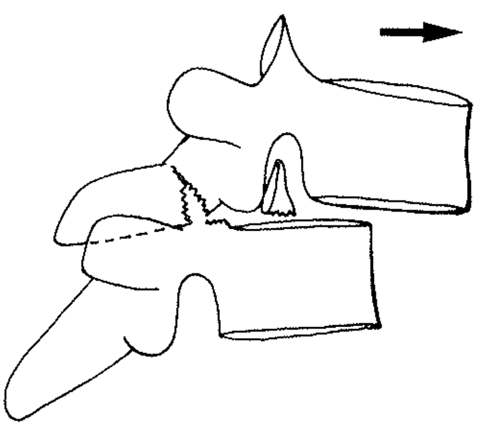

Fig 18A. Lateral diagram of a posteroanterior shear injury. Note the intact anterior vertebral bodies, the fracture of the superior articular facet which has been sheared off by the anterior displacement. The spinous process or entire posterior arch may be fractured by the same mechanism.

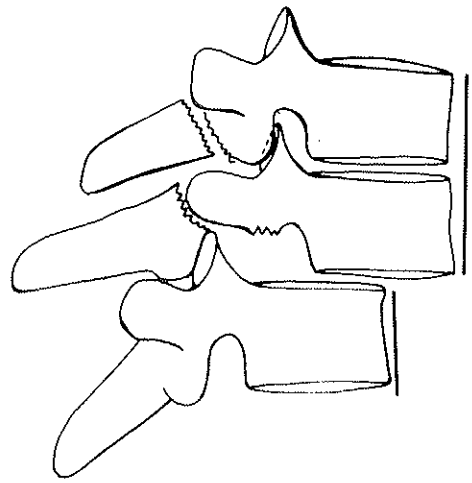

Fig 18B. Lateral diagram of a posteroanterior shear injury. A large part of the posterior arch may be left behind (floating lamina).

Fracture dislocations of the flexion rotation type were neurologically intact in 14 cases (25%). When neurologically injured, 52.4% of them were complete (39.2% of all cases).

Fracture dislocations of the shear type: All seven cases were complete paraplegics on admission

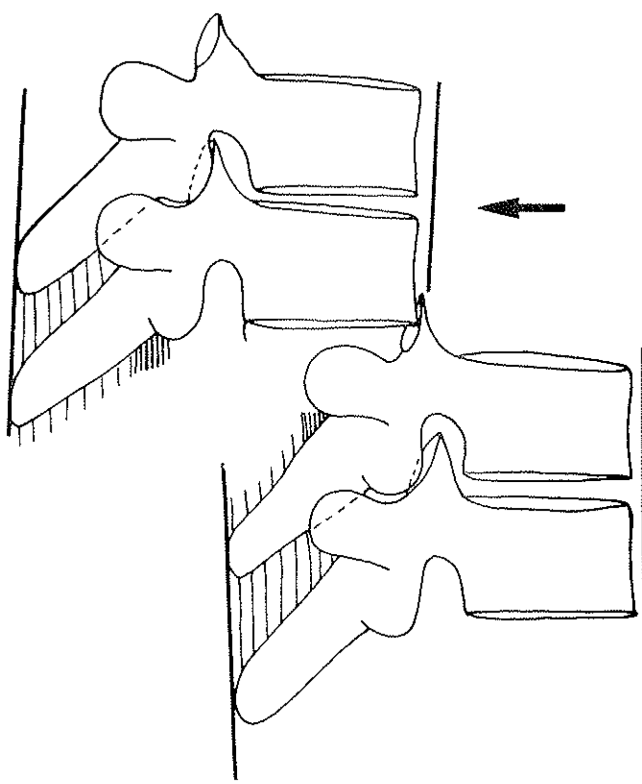

Fig 19. Lateral diagram of an anteroposterior shear injury. The posterior arches and anterior vertebral bodies may be entirely intact, but the three ligamentous columns are disrupted.

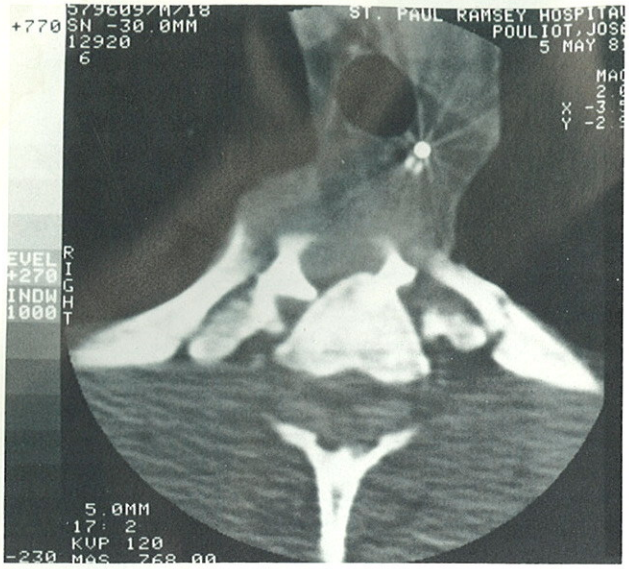

Fig 20. Computerized axial tomogram of a fracture-dislocation of the anteroposterior shear type. Note the anterior aspect of the superior vertebral body locked on the superior facets of the inferior vertebral body.

(Frankel A). All cases of posteroanterior shear had large dural tears.

Fracture dislocations of the flexion-distraction type were incomplete paraplegics in three cases (75%) and intact in one case (25%).

CORRELATION OF THE CLASSIFICATION WITH INSTABILITY AND BASIC RATIONALE FOR TREATMENT

The term "stable injury" should be applied to minimal and moderate compression fractures with an intact posterior column. These may then be treated by early ambulation with or without external immobilization, depending upon the degree of compression, the kyphosis and the age of the patient.

Instability of the first degree (*mechanical instability*) applies to cases in which the "spinal beam" may buckle or angulate. This mechanical instability is best represented by severe compression fractures and seat-belt-type injuries. In the former, disruption of the posterior ligamentous complex allows the spine to buckle around the hinge of the middle column. In the latter, flexion allows buckling around the hinge of the anterior column, both of the other columns being disrupted. This instability does not acutely threaten the neural elements. Therapeutic indications will, therefore, include at least external immobilization in extension during the healing period; in certain cases, open reduction and internal fixation will be required.

Instability of the second degree (*neurological instability*): In spite of the controversy, burst fractures are at risk, even when they present without neurological deficits:

1. The middle column, by definition, has ruptured under axial load.
2. Most of the neurological deficit comes initially from the traumatic impact and later from the continued compression by the fragment of the middle column against the neural elements when this one continues to obstruct the canal.
3. Early ambulation leads to axial load whether or not the patient is in a cast (the cast prevents flexion, extension and rotation to some extent, but not axial loading).
4. The meticulous observer of the burst fracture may see the increased interpediculate distance of the initial supine film increase a little further on the standing AP taken in the cast. This ominous sign explains why among 29 nonoperatively treated burst fractures, six patients developed a neurological deficit related to their fracture during follow-up (20.3%).

This appeared acutely in four of them (13.5%) and late in two (6.8%). Whether nonoperative treatment or preventive surgical stabilization is indicated in these fractures remains to be discussed and demonstrated. However, the physician in charge should inform the patient of the neurological risk and organize the rationale of his treatment around the potential complications.

Instability of the third degree (*mechanical and neurologic instability*): This represents typically the fracture-dislocation and the severe burst fracture with neurological deficit. Major secondary displacements and progression of neurological deficit may occur in both. Treatment will be aimed at the safest prevention of both complications. It includes surgical decompression and stabilization in the author's practice.

DISCUSSION

Lawrence Bohler[2] in 1944, had already identified five different mechanisms for spinal injuries; flexion,

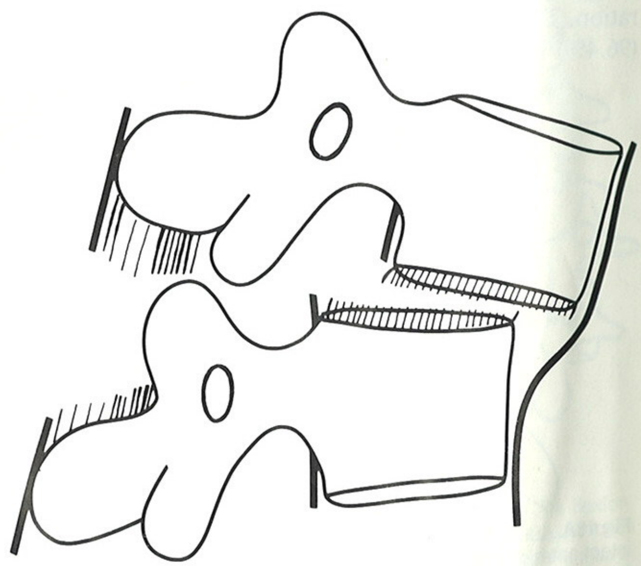

Fig 21. Lateral diagram of a fracture-dislocation of the flexion-distraction type. The posterior, middle, and anterior ligamentous columns are disrupted but for the anterior longitudinal ligament, which strips off the vertebral body below.

extension, rotation, shear, and axial load. Nicoll,[10] in a study of 166 thoracolumbar fractures in miners, demonstrated the importance of flexion rotation and lateral flexion mechanisms. Olof Perey[12] has carried out the most significant experimental work on burst fractures. Seat-belt injuries were well reviewed by Smith and Kaufer,[15] who added to the knowledge of their mechanisms. Reuber and Schultz[14] reported that posterior element destruction (posterior ligamentous complex and posterior arch) did not significantly alter the strength of the disc under compression, nor did it alter the disc bulge under compression, flexion, rotation, and shear. A recent study by Nagel[9] demonstrates also that flexion of the second lumbar vertebra on the first of about 20° or a lateral bend of 10° as seen on a routine roentgenogram without vertebral fracture indicates that all posterior ligaments and at least part of the annulus fibrosus must be disrupted. Bedbrook[1] advises the student of spinal injuries to spend an hour in a dissecting room with a few fresh specimens and a sharp knife in order to prove to themselves that dividing the entire posterior ligamentous complex does not interfere with stability. "It is not until the disc is cleanly divided by a sharp knife that the spinal column begins to show some potential instability." He ends this paragraph by stating that "it is not until the anterior longitudinal ligament is stripped (but not necessarily divided) that the vertebral column then becomes potentially unstable under the influence of stress." Computerized axial tomography has improved the clinician's ability to recognize the pathologic anatomy of spinal fractures.

Although not experiments, thousands of scoliosis operations are performed yearly in this country consisting of posterior spinal fusion and Harrington instrumentation. The technique consists in carefully detaching the supraspinous ligament, excising the interspinous ligament and the ligamentum flavum in order to allow insertion of the hooks; thereafter, all capsule and cartilage of the diarthrodial joints are carefully removed in an attempt to prepare them for facet fusion. Finally, the same motion segment is stressed with 40 to 80 kiloponds of distraction force, allowing correction of the spinal curvature. With Holdsworth's theory of spinal instability, each and every one of these thousands of cases should lead to catastrophic iatrogenic spinal instabilities.

The scoliosis literature does not report the occurrence of this complication.

The statement that rupture of the posterior ligamentous complex means instability may become accurate only if and when there is associated disruption of at least the posterior longitudinal ligament and posterior annulus fibrosus. Rupture of the posterior ligamentous complex in severe compression fractures may, however, lead to chronic instabilities with kyphotic deformities. This is particularly true in children. In the same way as rupture of the medial collateral ligament of the knee has only a modest role in knee stability when compared to the cruciate complex, the posterior ligamentous complex has only a modest role in spine stability when compared to the middle column complex.

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Abnormal Magnetic-Resonance Scans of the Lumbar Spine in Asymptomatic Subjects

A Prospective Investigation*

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ABSTRACT: **We performed magnetic resonance imaging on sixty-seven individuals who had never had low-back pain, sciatica, or neurogenic claudication. The scans were interpreted independently by three neuroradiologists who had no knowledge about the presence or absence of clinical symptoms in the subjects. About one-third of the subjects were found to have a substantial abnormality. Of those who were less than sixty years old, 20 per cent had a herniated nucleus pulposus and one had spinal stenosis. In the group that was sixty years old or older, the findings were abnormal on about 57 per cent of the scans: 36 per cent of the subjects had a herniated nucleus pulposus and 21 per cent had spinal stenosis. There was degeneration or bulging of a disc at at least one lumbar level in 35 per cent of the subjects between twenty and thirty-nine years old and in all but one of the sixty to eighty-year-old subjects. In view of these findings in asymptomatic subjects, we concluded that abnormalities on magnetic resonance images must be strictly correlated with age and any clinical signs and symptoms before operative treatment is contemplated.**

Magnetic resonance imaging is being used increasingly for the diagnosis of conditions causing acute low-back pain and sciatica. Some investigators have proposed that magnetic resonance imaging should replace, rather than supplement, myelography[12]. Several have reported that the sensitivity of magnetic resonance imaging for the diagnosis of herniated nucleus pulposus and spinal stenosis is equivalent to or better than that of computerized tomography, even when computerized tomography is combined with myelography or discography[2,5-8]. Magnetic resonance imaging is sensitive enough to detect a partial or complete tear of the anulus fibrosus that is undetectable with other non-invasive imaging modalities[14].

Despite the high sensitivity of magnetic resonance imaging, there is still a question about whether the modality is acceptably specific, especially when it reveals abnormal findings in the absence of clinical signs and symptoms[9]. Specificity is ordinarily defined by percentages of false-positive and false-negative results, and it is determined most often in symptomatic patients. However, a considerable number of abnormalities are found on the magnetic resonance images of asymptomatic subjects. An abnormal finding on magnetic resonance imaging in an asymptomatic subject is not necessarily a false-positive result, since such a lesion cannot be correlated with an anatomical lesion in subjects who are not operated on. Thus, in this report on asymptomatic subjects, we use the term magnetic-resonance positive to allow inference about the specificity of the findings and to allow calculation of the prevalence of abnormal findings.

Three studies have demonstrated high incidences (24 to 37 per cent) of abnormal findings on discograms, myelograms, and computerized tomography scans of asymptomatic subjects[3,4,13]. To our knowledge, analogous data have not been generated for magnetic resonance imaging. The purpose of this investigation was to determine the prevalence of positive findings on magnetic resonance images of the lumbar spine in asymptomatic subjects.

Materials and Methods

Magnetic resonance imaging of the lumbar spine was performed on sixty-seven volunteers, who ranged in age from twenty to eighty years (average, forty-two years). There were thirty men and thirty-seven women. The subjects were recruited through advertising in several general newspapers, and the respondents, as well as their spouses (when eligible) were chosen to obtain the correct balance of sex and age for three groups (Fig. 1). The volunteers were screened with a standardized questionnaire, and only those who had no history of pain in the back, sciatica, or neurogenic claudication were included in the study. Any episode of non-radiating low-back discomfort that had lasted more than twenty-four hours or had necessitated time off from work was grounds for excluding the candidate from the study. Volunteers were also excluded if they had had sciatica (pain or sensory abnormalities in the buttocks or

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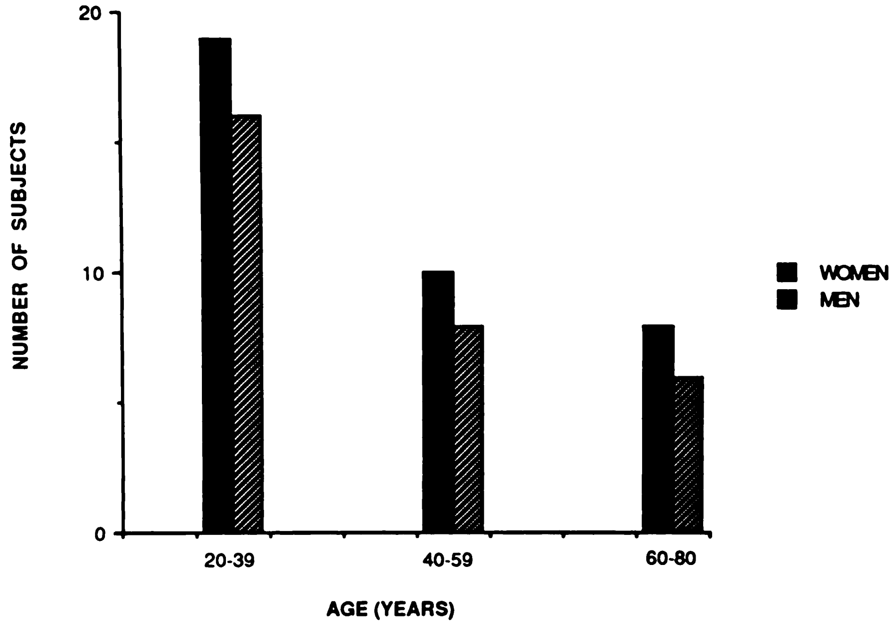

FIG. 1

Demographic data for sixty-seven asymptomatic volunteers.

lower limbs) or if walking caused pain or a sensory abnormality in a lower limb.

Once the subject was entered in the study, multiplanar magnetic-resonance imaging was done from the first lumbar to the first sacral vertebra with a 1.5-tesla imaging system (Signa, General Electric, Milwaukee, Wisconsin). A sagittal localizing series was performed with a repetition time of 400 milliseconds, an echo time of twenty milliseconds, a slice thickness of five millimeters with one-millimeter intervals, and a thirty-two to thirty-six-centimeter field of view. For the sagittal images (twenty-four-centimeter field of view), a multiple spin-echo technique was used, with a repetition time of 1000 milliseconds, to produce five-millimeter-thick slices at one-millimeter intervals after four excitations. Two echoes were generated; the first had an echo time of twenty milliseconds (T1 weighted) and the second, an echo time of seventy milliseconds (T2 weighted). For axial sequences, which were angled through the disc space, four-millimeter-thick slices at one-millimeter intervals were acquired with a repetition time of 600 milliseconds and an echo time of twenty milliseconds.

The sixty-seven studies of the asymptomatic subjects were mixed randomly with thirty-three scans that had been made with the same scanner on patients who had well defined clinical symptoms of either a herniated disc or spinal stenosis. Those symptoms correlated with an unequivocal abnormality on the magnetic resonance image, as previously interpreted by neuroradiologists who were not associated with the study. Thus, 100 scans were presented, in random sequence, to three of us who are neuroradiologists (D. O. D., T. S. D., and N. J. P.) and who had no information about the patients or the subjects. At the level of each disc, any important diagnoses (herniated nucleus pulposus and spinal stenosis) were identified, as were findings of less-certain importance (bulging and degeneration of a disc). In addition to rating the severity of the abnormality, the neuroradiologist rated his certainty about the diagnosis (definite, probable, or possible).

Since precise radiographic definitions of lesions in the lumbar discs remain subject to variations between readers, this study was designed to yield a spectrum of independent interpretations from three expert neuroradiologists. Herniated nucleus pulposus was considered to be an extrusion, mainly focal, of disc material beyond the osseous confines of the vertebral body, resulting in displacement of epidural fat, nerve root, or thecal sac. A bulge was defined as a diffuse, usually non-focal protrusion of non-osseous material beyond the normal disc space. The basic criterion for a diagnosis of stenosis of the spinal canal was non-discogenic loss of signal in the epidural fat with compression of neural tissues within the canal. Degeneration of the disc

TABLE I

CORRELATION OF AGE WITH ABNORMAL MAGNETIC-RESONANCE IMAGES OF THE LUMBAR SPINE IN SIXTY-SEVEN ASYMPTOMATIC SUBJECTS

	Percentage of Subjects Who Had an Abnormal Finding		
	20-39 Yrs. Old (N = 35)	40-59 Yrs. Old (N = 18)	60-80 Yrs. Old (N = 14)
All abnormal findings			
Reader 1	26	28	57
Reader 2	20	22	64
Reader 3	20	17	50
Average*	22 (7)	22 (3)	57 (7)
Herniated discs	21	22	36
Spinal stenosis	1	0	21

* Figures in parentheses represent the number of subjects in each age group for which the interpretations of all three readers were in complete agreement.

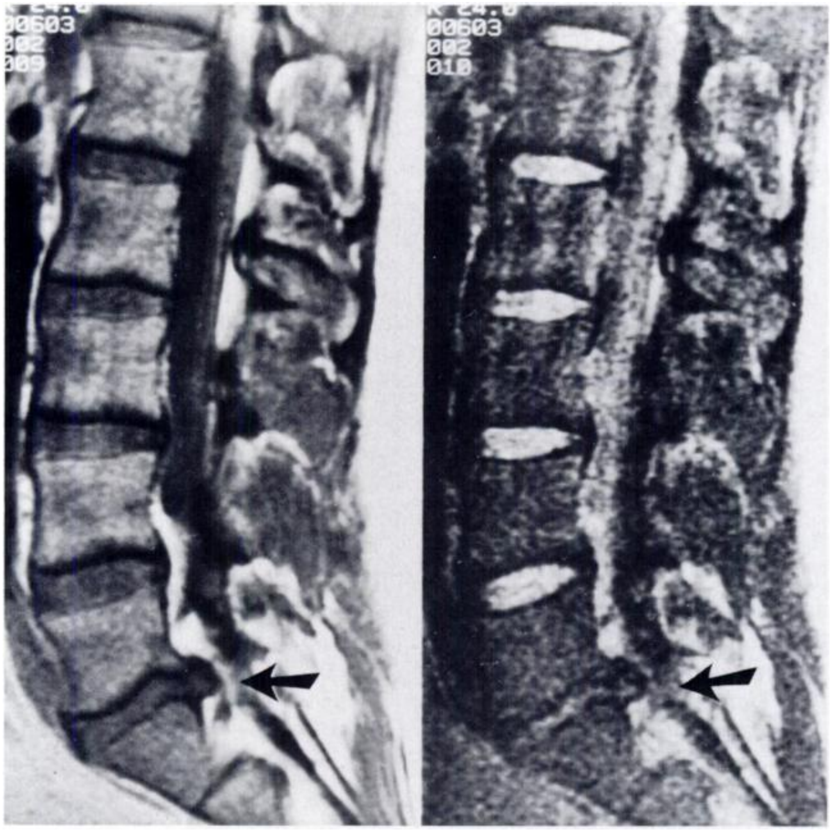

FIG. 2

Magnetic resonance image interpreted by three neuroradiologists as showing herniation of the disc between the fifth lumbar and first sacral vertebrae in a thirty-three-year-old subject who had never had low-back pain or sciatica.

was considered to be present when there was loss of height of the disc space and a decreased signal on T2-weighted sequences.

At the level of each disc, each neuroradiologist scored the findings of the magnetic resonance image quantitatively and objectively and assessed the importance of any abnormal finding subjectively. The results from each reader were averaged, and the diagnosis and the severity of the lesion were tabulated according to the subject's age. Only the findings that the interpreters had labeled as probably or definitely abnormal were recorded as abnormal findings. The over-all number of abnormal magnetic-resonance images included only those that were considered to demonstrate very substantial abnormalities. Findings that were graded as being less important to the diagnosis were tabulated separately. The consistency of interpretation among the neuroradiologists was also assessed. Finally, the percentage of asymptomatic subjects who had abnormal findings was calculated, thus establishing the prevalence of abnormal magnetic-resonance images of the lumbar discs of asymptomatic subjects.

Results

The three neuroradiologists independently interpreted the magnetic resonance images as being substantially abnormal for about 28 per cent (nineteen) of the sixty-seven asymptomatic subjects. Herniated nucleus pulposus was noted in about 24 per cent (sixteen subjects) and stenosis of the spinal canal, in about 4 per cent (three subjects). Three more subjects had evidence of herniated nucleus pulposus on the magnetic resonance image, but the average of the readings of the three neuroradiologists resulted in a rating of "less than probable". Therefore, these subjects were not included in the group that had an abnormal scan.

The prevalence of abnormal findings was the same in the asymptomatic men and women, but it varied according to the ages of the subjects (Table I). In the twenty to thirty-nine-year-old and forty to fifty-nine-year-old groups, the prevalence of abnormal scans averaged about 20 per cent (seven of thirty-five and four of eighteen, respectively). In the sixty to eighty-year-old group, however, it averaged about 57 per cent (eight of fourteen). The most common important abnormalities in the oldest group were herniated nucleus pulposus (about 36 per cent, or five of fourteen) and stenosis (about 21 per cent, or three of fourteen), whereas all but one of the subjects who were less than sixty years old and had an abnormality had a herniated disc.

Figure 2 shows a magnetic resonance image of a thirty-three-year-old subject who never had back pain. All three interpreters thought that the scan showed a substantially herniated disc between the fifth lumbar and first sacral vertebrae. Most of the herniated discs were between the fourth and fifth lumbar or the fifth lumbar and first sacral levels (Fig. 3).

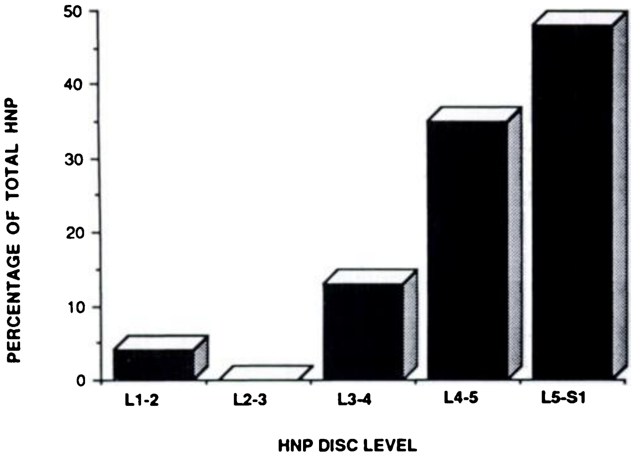

FIG. 3

Distribution of herniated nucleus pulposus (HNP) as seen on magnetic resonance images of the lumbar spine in asymptomatic individuals. Twenty-nine levels in twenty-one volunteers were involved.

At least one bulging disc was seen in about 54 per cent (nineteen) of thirty-five subjects who were less than sixty years old and in 79 per cent (eleven) of the fourteen subjects who were sixty years old or older. Similarly, at least one degenerated disc was noted in 34 per cent (twelve) of the thirty-five subjects in the youngest group and in all but one of the subjects in the oldest group (Fig. 4). In the subjects who were less than sixty years old, the degeneration involved an average of two levels, whereas in each of the subjects who were sixty years old or older, it involved an average of three levels. Approximately half of the degenerated discs also bulged, and this prevalence did not vary with age. In contrast, the proportion of bulging discs that were also degenerated increased from about one-third in the subjects who were less than sixty years old to about two-thirds in the older group.

In all but one of the thirty-three symptomatic patients, the findings on the magnetic resonance image correlated with the operative diagnosis. In the exceptional patient, who had spinal stenosis, one of the involved levels was not identified by two of the three readers.

The three neuroradiologists agreed regarding the presence or absence of abnormal findings on the magnetic resonance image at 99 per cent of the 500 disc levels (five in each subject) from both the symptomatic patients and the asymptomatic subjects. The subjective assessments of the severity of the findings varied somewhat, but over-all the three readers agreed completely on the exact diagnosis at 86 per cent of the levels, two agreed on the diagnosis at 98 per cent, and there was no consensus regarding the diagnosis at only 2 per cent of the levels. With regard to the 335 disc levels of the asymptomatic subjects alone, all three neuroradiologists agreed on the diagnosis at 90 per cent of the levels, and two agreed on the diagnosis at 99 per cent. When there was disagreement, it usually did not involve the presence or absence of an abnormality but rather the precise score of its severity and importance.

Discussion

Substantial percentages of individuals who never had low-back pain or sciatica but had abnormal myelograms (24 per cent), computerized tomography scans (36 per cent), or discograms (37 per cent) have been reported[3,4,13]. In the present study, about 30 per cent of an asymptomatic population had a major abnormality on a magnetic resonance image of the lumbar spine. The finding that an asymptomatic individual has more than a one-in-four chance of having an abnormal magnetic-resonance image emphasizes the danger of predicating a decision to operate on the basis of any diagnostic tests in isolation, without clinical information. A diagnosis that is based on magnetic resonance imaging,

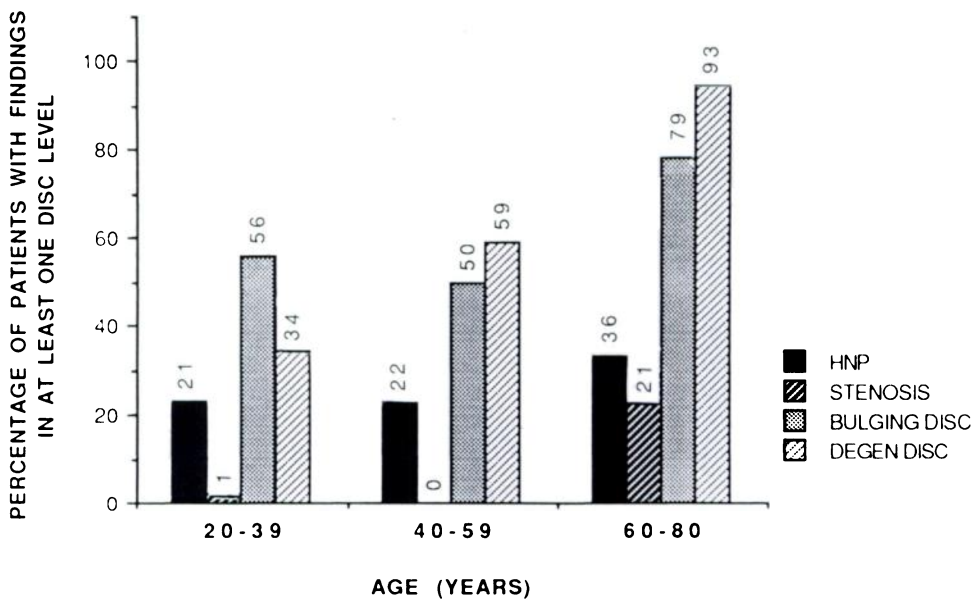

FIG. 4

Incidences of herniated nucleus pulposus (HNP), spinal stenosis, a bulging disc, and a degenerated disc on the magnetic resonance images of sixty-seven asymptomatic individuals.

in the absence of objective clinical findings, may not be the cause of the patient's pain, and an attempt at operative correction could be the first step toward disaster.

Comparison of the results of the present study with those of investigations of other types of imaging in asymptomatic subjects must be undertaken with caution. As we have noted, many abnormal findings are age-dependent. The study of discograms by Holt and the study of myelograms by Hitselberger and Witten differed from our study with regard to the mean age of the subjects. In fact, the results of the other two studies were not analyzed according to age. In contrast, Wiesel et al. studied computerized tomography scans in an asymptomatic population in which the distribution of age was comparable with that in ours. For the subjects who were less than forty years old, the incidences of abnormalities were similar in the two studies, but for the subjects who were forty or older, our data suggested that magnetic resonance imaging may yield fewer positive findings than computerized tomography does (approximately 35 per cent compared with approximately 50 per cent). Magnetic resonance imaging may be even more superior than the studies suggested because the computerized tomography was done at the fourth and fifth lumbar and the fifth lumbar and first sacral levels only, while the magnetic resonance images demonstrated herniated discs at the third and fourth lumbar levels as well. In fact, 13 per cent (four) of all twenty-nine herniated discs in our asymptomatic subjects were at these levels.

As with computerized tomography, subjects who were sixty years old or older were found to have a far higher percentage of abnormal magnetic-resonance scans than did those who were younger than sixty. Thus, an abnormal magnetic-resonance image in a younger patient is more likely to be a true indication of the cause of the complaints. For individuals who are sixty years old or older, it is less likely that the lesions demonstrated by magnetic resonance imaging are of clinical importance.

The interpretations of the three neuroradiologists in our study varied substantially less than those of the investigators of the computerized tomography scans[13]. In our study, the neuroradiologists agreed completely about 60 per cent of the scans, whereas the investigators did so about only 11 per cent of the computerized tomography scans. As noted earlier, the disagreements in our study mainly concerned the severity of the findings. Accordingly, one might infer that magnetic resonance imaging is better than computerized tomography for assessing the size and importance of lesions and of neural compression. However, that inference could be validated only if the same team of radiologists interpreted both computerized tomography scans and magnetic resonance images for the same group of patients.

The sensitivity of magnetic resonance imaging also enabled us to study the incidence and distribution of bulging and degenerated discs. In addition to the surprisingly high prevalence of those findings in asymptomatic subjects of all ages (twenty years old or older), the interrelationships of the two findings differed from what had been expected. Although many authors have considered bulging of a disc to be caused by degeneration[5,6], in our asymptomatic subjects only half of the degenerated discs bulged, and only half of the bulging discs were also degenerated. In addition, in the older subjects, the prevalence of degeneration was more increased than that of bulging. These relationships may suggest that factors other than degeneration result in bulging, or possibly that the T2-weighted magnetic-resonance-imaging sequences do not detect all lesions that are indicative of degenerated discs[15].

In analyzing the reliability of data like ours, it is important to consider the selection of subjects as related to the design of the study. For the asymptomatic subjects in this study, the distribution of age and sex (Fig. 1) was similar to the typical spectrum for patients who have low-back pain[1,10,11]. Our three groups contained approximately equal numbers of men and women (by design) and most subjects were less than sixty years old. In addition, in our study, the distribution of the levels of the herniated discs was similar to that in a large study of patients who were treated for herniation of a lumbar disc[11].

Another important aspect of our selection of subjects was the exclusion of those who had any history of back pain, sciatica, or neurogenic claudication. It is possible, especially with older patients, that an episode of pain in the back might be forgotten, but we tried to minimize this error by using a standardized questionnaire that elicited the necessary information with several different avenues of questioning. Subjects whose reliability was questionable or who had problems with memory were excluded from the study.

We designed the prospective study to maximize the reliability of the neuroradiologists' estimates of the abnormalities on the magnetic resonance images. The asymptomatic volunteers were examined with a complete and standardized imaging protocol that was identical to the one used for the symptomatic patients. Precautions were taken so that the scans of the asymptomatic subjects could not be distinguished on a technical basis from those of the symptomatic patients. We randomized the sequence in which the scans were read so that the neuroradiologists' interpretation would be blind and unbiased by knowledge of the clinical situation. The forced-choice design of the score sheet necessitated evaluation of each disc level for the four objective findings and was intended to minimize inadvertent underreporting of findings. Finally, our three neuroradiologists differed in training, experience, and type of practice (private or academic), so that the spectrum of interpretation for each scan would be as wide as possible.

In conclusion, the high incidence of bulging and degenerated lumbar intervertebral discs seen on the magnetic resonance images of asymptomatic subjects confirms observations that have been made with computerized tomography and myelography studies that these findings are part of a normal, or at least common, aging process. The finding of an abnormal lumbar disc on a magnetic resonance image is most reliable in symptomatic patients who are less than sixty years old. It is less reliable in older patients. In this study, the prevalence of abnormal magnetic-resonance images for asymptomatic subjects who were less than forty years old was comparable with that reported by Wiesel et al. for computerized tomography scans. Finally, the finding of substantial abnormalities of the lumbar spine in about 28 per cent of asymptomatic subjects emphasizes the dangers of predicating a decision to operate on the basis of diagnostic tests — even when a state-of-the-art modality is used — without precise correlation with clinical signs and symptoms.

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A System for the Surgical Staging of Musculoskeletal Sarcoma

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Historically, an adequate surgical procedure has been the most effective means of treating the majority of primary musculoskeletal sarcomas, and amputation has figured prominently in the surgical armamentarium.[4,7,9,19,21,29,41] The recent evidence that certain chemotherapeutic agents may have significant anti-sarcoma activity[2,15,17,38] and coincident technical advances in irradiation therapy, radiographic localization, and reconstructive surgery have fostered enthusiastic interest in extremity-saving treatments. Almost all such treatments emphasize limb salvage as an alternative to amputation and are usually performed under a protective cloak of adjunctive chemotherapy, irradiation or immunoactive agents.[20,23,24,30,37,39] Since neither chemotherapy nor irradiation therapy alone has been shown to assure long-term local control of bulk disease, surgical intervention remains an essential step in the overall management of musculoskeletal sarcomas.[3,9,17,18,29] Questions concerning the magnitude and timing of the surgical procedure are as unanswered as those relating to the most appropriate use of the adjuncts themselves. Increasingly, the surgeon and his patient are confronted with a bewildering array of therapeutic options, the long-term outcomes of which are unknown.

These relatively rare sarcomas increasingly are distributed among a variety of treatment protocols in which multiple parameters differ. This trend necessitates interinstitutional cooperation if sufficient numbers of patients are to be available for the timely evaluation of treatments in clinical use.

Such cooperation and even effective interinstitutional communication are seriously hampered by the lack of uniform language, so that meaningful comparison of treatments is currently impossible. Prime factors include the lack of a consistent definition of the surgery performed and a serviceable surgical staging system encompassing bone and soft tissue. Standard terminology will assure that like and unlike treatments are appropriately compared. Although an effective staging system should serve all members of the multidisciplinary team, the biologic behavior of musculo-

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skeletal sarcomas suggests that the most useful staging system will articulate with the surgical procedure.

SURGICAL STAGING

A surgical staging system for sarcoma should:

1. Incorporate the most significant prognostic factors into a system which describes progressive degrees of risk to which a patient is subject.
2. Delineate progressive stages of disease that have specific implications for surgical management.
3. Provide guidelines to the use of adjunctive therapies.

Since its organization in 1959, the American Joint Committee for Cancer Staging and End Results Reporting (AJC) has undertaken responsibility for developing clinically useful staging systems for many kinds of cancer. The intent of staging is to designate "the state of a cancer at various points in time and is related to the natural course of this particular type of cancer." The purpose is to: "provide a way by which this information can be readily communicated to others; to assist in decisions regarding treatment; and to be a factor in judgement as to prognosis. Ultimately, it provides a mechanism for comparing like or unlike groups of cases, particularly in regard to the results of different therapeutic procedures." The AJC philosophy expresses the idea that "for most types of cancer, the extent to which the disease has spread is probably the most important factor determining prognosis and must be given prime consideration in evaluating and comparing different therapeutic regimens." To this end, the TNM system, where T designates the local extent of disease (often translated into size) of the primary tumor, N designates nodal extent, and M, metastatic extent, has been consistently used.[22,31] In addition to anatomic extent, the histopathologic analysis and grade of the tumor are other recognized prime determinants.[6,13,14,16,19,22,26,27,28,31–33]

The single attempt to develop a staging system for sarcomas of bone by the Task Force on Malignant Bone Tumors of the AJC failed to yield a satisfactory system. They recommended that institutions with access to large numbers of patients, consistency in management, and long-term follow-up undertake this task.[11] The staging system for soft tissue sarcomas proposed by the AJC in 1977[31] and the recent modification suggested by Hajdu[16] have, in our experience, been of limited value in the surgical management of soft-tissue lesions.[12,13,37]

A surgical staging system for musculoskeletal sarcomas is most logically accomplished by assessment of the surgical grade (G), the local extent (T), and the presence or absence of regional or distant metastases (M).

The sarcomas for which this system was designed are those arising from the mesenchymal connective tissue of the musculoskeletal system. Lesions derived from the marrow, reticuloendothelial tissue housed within bone and mesenchymal soft tissue, and the skull are not included in this system because their natural history, surgical management, and response to treatment are quite different. Thus, leukemias, plasmacytoma, lymphomas, Ewing's sarcoma, undifferentiated round-cell lesions, and metastatic carcinomas are excluded.

SURGICAL GRADE (G)

From the standpoint of surgical planning, neoplasms of any histogenesis are divided into two grades: low (G_1) and high (G_2). The majority of low-grade lesions may be managed with relatively conservative procedures while the high-grade lesions require more aggressive procedures to achieve the primary goal of a definitive oncologic surgical procedure—local control.[12,13,28,29] In general, low-grade lesions correspond to Broder's I or II and have a low risk for metastases (<25%). Histologically, they are well-differentiated, have few mitoses, and moderate cytologic atypia. Their clinical course is marked by indolence. When they occur in bone, there is a tendency toward circumscription by reactive new bone.

High-grade lesions (Broder's III and IV) have a significantly higher incidence of metastases. They are characterized by poor differentiation, a high cell/matrix ratio, a high mitotic rate, necrosis, and microvascular invasion. Their clinical course is correspondingly marked by activity. Radiographically, the bone primaries are poorly marginated and have a permeated pattern. Angiographically, a reactive neovasculature usually rims the lesion.

The surgical grade may differ slightly from the purely histologic grade by consideration of clinical and radiographic features. Thus, the surgical grade may be weighted by the radiographic characteristics in chondrosarcoma, by the histologic appearance in fibrosarcoma, or by the clinical course in giant-cell tumor of bone. Usually there is good correspondence among the clinical, radiologic, and histologic findings.

The surgical grades (G) of a number of musculoskeletal sarcomas are given in Table 1. Each lesion ultimately is assessed on its own clinicopathologic features; not all parosteal osteosarcomas are low-grade,[1] nor are all intraosseous osteosarcomas high-grade.[40] In the absence of metastases, this method of separating lesions determines the stage: Stage I = G_1; Stage II = G_2. The stage is linked to surgical planning through providing information about what kind of surgical margin is required for definitive local control.

TABLE 1. Surgical Grade (G)

Low (G_1)	*High (G_2)*
Parosteal osteosarcoma Endosteal osteosarcoma	Classic osteosarcoma Radiation sarcoma Paget's sarcoma
Secondary chondrosarcoma	Primary chondrosarcoma
Fibrosarcoma, Kaposi's sarcoma Atypical malignant fibrous histiocytoma	Fibrosarcoma Malignant fibrous histiocytoma Undifferentiated primary sarcoma
Giant-cell tumor, bone	Giant-cell sarcoma, bone
Hemangioendothelioma Hemangiopericytoma	Angiosarcoma Hemangiopericytoma
Myxoid liposarcoma	Pleomorphic liposarcoma Neurofibrosarcoma Rhabdomyosarcoma Synovial sarcoma
Clear-cell sarcoma, tendon sheath Epithelioid sarcoma	
Chordoma	
Adamantinoma	
Alveolar cell sarcoma	Alveolar cell sarcoma
Other and undifferentiated	Other and undifferentiated

Surgical Site (T)

Just as the surgical grade is a measure of the overall biologic aggressivity of a lesion and indicates what kind of surgical margin is appropriate,[12,13,28,35] the anatomic extent or setting (T) indicates *how* the surgical procedure is most likely to be achieved[4,5,7,13,21-25,26,33,41] or even whether the desired margin can be achieved at all. The prime factor in determining *how* a surgical margin is accomplished is whether the lesion is within a well-delineated anatomic compartment or is diffusely infiltrating poorly demarcated adventitial planes and spaces. Therefore, the two stages are subdivided by whether the lesion is intracompartmental (A) or extracompartmental (B). Anatomic compartments have natural barriers to occult tumor extension: in bone, the barriers are cortical bone and articular cartilage; in joints, articular cartilage and joint capsule; and in soft tissues, the major fascial septae and the tendinous origins and insertions of muscles. In contrast, the ill-defined interfascial spaces and planes are limited only by loose areolar tissues that favor occult microextension. Because major neurovascular bundles lie in these interfascial extracompartmental tissues, a lesion involving these structures is by definition extracompartmental.

Both lesion size and its physical distance from vital structures are related to compartmentalization, but they are not determinants in surgical planning.[33] Although the larger lesions are more likely to become extracompartmental, neither large intracompartmental nor small extracompartmental lesions are unusual. Similarly, a lesion may be separated by only a few millimeters from a major nerve or vessel and yet be contained by a fascial septum that provides an adequate plane of dissection without sacrifice of the adjacent structures. Because satellite micronodules are routinely found in the pseudocapsular and reactive zones about all sarcomas, these zones must be considered an integral part of the lesion. Whether or not the lesion and its reaction is contained within a well-defined anatomic compartment more accurately indicates the feasibility of a local procedure than does the size or proximity to vital structures.[13]

The various surgical compartmental sites (T) are listed in Table 2. The left hand column lists the defined anatomic compartments: intraosseous, intra-articular, subcutaneous, paraosseous, and intrafascial. The skin and subcutaneous tissues are designated as an anatomic compartment because the deep fascia is a barrier to direct extension. In the same sense, the potential paraosseous space is a compartment; a lesion that has neither invaded the underlying bone nor penetrated the overlying muscle is intracompartmental. If a paraosseous lesion invades either the underlying bone or overlying muscle, it is extracompartmental.

Extracompartmental anatomic sites are listed in the right hand column of Table 2. A lesion is extracompartmental if it arises in these tissues or if it secondarily extends into them from an original intracompartmental site. Thus, a synovial sarcoma arising in the popliteal space is extracompartmental; an osteosarcoma of the femur extending into the quadriceps muscle is extracompartmental; and a fibrosarcoma of the quadriceps invading bone is extracompartmental. A superficial lesion which penetrates the deep fascia is extracompartmental, as is a deep lesion when it penetrates the fascia and becomes superficial. An intraosseous lesion that lifts periosteum from cortical bone or an intra-articular lesion that penetrates a joint capsule is extracompartmental. Surgical manipulation of a lesion without complete removal of the lesion places any tissue planes exposed to the lesion or post-surgical hematoma at risk for subsequent recurrence. Thus, most intracompartmental lesions are converted to extracompart-

TABLE 2. Surgical Sites (T)

Intracompartmental (T_1)	*Extracompartmental (T_2)*
Intraosseous	Soft-tissue extension
Intra-articular	Soft-tissue extension
Superficial to deep fascia	Deep fascial extension
Paraosseous	Intraosseous or extrafascial
Intrafascial compartments	Extrafascial planes or spaces
Ray of hand or foot	Mid and hind foot
Posterior calf	Popliteal space
Anterolateral leg	Groin—femoral triangle
Anterior thigh	Intrapelvic
Medial thigh	Mid-hand
Posterior thigh	Antecubital fossae
Buttocks	Axilla
Volar forearm	Periclavicular
Dorsal forearm	Paraspinal
Anterior arm	Head and neck
Posterior arm	
Periscapular	

mental lesions by any surgical manipulation which does not completely remove the lesion.

Detailed pathologic examination of specimens and surgical observations have documented that a reliable preoperative distinction between intra- and extracompartmental involvement may be made by the appropriate combinations of history, physical findings, roentgenograms, tomograms, angiograms, computed assisted tomography (CAT) scans, isotope scans, and other specialized studies.

Regional or Distant Extent (M)

The presence or absence of metastases is the third major factor related to both prognosis and surgical planning. In sarcomas the common route of hematogenous metastasis to the lung and the less common regional metastasis to lymph nodes have the same ominous prognostic significance. They indicate the failure of local control, and the presence of either indicates little chance for prolonged survival.[9,33,42]

SUMMARY OF STAGING

Based on these considerations, a Surgical Staging System (SSS) that stratifies both bone and soft-tissue lesions by grade (G_1 or G_2), anatomic setting (T_1 or T_2), and metastases (M_0 or M_1) has been constructed. The stages are based upon considerations of grade and metastasis. The stages are subdivided into A and B based upon the compartmentalization of the lesion. The stages and their subdivisions are summarized in Table 3. Stage I comprises those low-grade lesions shown in Table 1 (G_1); Stage II, the high-grade lesions in Table 1 (G_2); and Stage III lesions, those with either regional or distant metastases (G_1 or G_2, M_1). Stages I (G_1, M_0) and II (G_2, M_0) are further subdivided by the intra- (T_1) and extracompartmental (T_2) settings shown in Table 2. Thus, Stage IA is a low-grade, intracompartmental lesion with no regional or distant metastases (G_1, T_1, M_0); Stage IB is a low-grade, extracompartmental lesion without metastases (G_1, T_2, M_0); Stage IIA is a high-grade, intracom-

TABLE 3. Surgical Stages

Stage	*Grade*	*Site*
IA	Low (G_1)	Intracompartmental (T_1)
IB	Low (G_1)	Extracompartmental (T_2)
IIA	High (G_2)	Intracompartmental (T_1)
IIB	High (G_2)	Extracompartmental (T_2)
III	Any (G) Regional or distant metastasis	Any (T)

partmental lesion free of metastases (G_2, T_2, M_0); Stage IIB is a high-grade, extracompartmental lesion without metastases (G_2,T_2, M_0); and Stage III is of either grade and setting with metastases (G_1 or G_2, T_1 or T_2, M_1).

SURGICAL PROCEDURES

The articulation of the Surgical Staging System with surgical planning is accomplished by the link to a surgical procedure with margins that have predictable local recurrence rates.

Four types of margins based on the relationship of the surgical margin to the neoplasm and its pseudocapsular-reactive zone are recognized.[5,9,13,25,34–36] A descriptive summary of these margins and the anticipated residual disease is presented in Table 4. Since any of these margins may be accomplished by either a local procedure or an amputation, eight possible biologically significant surgical procedures result. These are summarized in Table 5 and detailed below.

1. Intralesional. An *intralesional* margin is accomplished by a procedure in which the dissection passes within the lesion. Macroscopic or microscopic tumor is left at the margins of the wound, and there is contamination of all the exposed tissue planes. Most commonly, local *intralesional* procedures are performed as a diagnostic incisional biopsy, by curettage of a presumably benign lesion, or by subtotal removal of a lesion to be managed by other means. An *intralesional amputation* is sometimes intended as a palliative procedure, but more commonly is done inadvertently because of occult microextensions of the lesion.

2. Marginal. A *marginal* margin is achieved by a procedure in which the lesion is removed in one piece. The plane of dissection is through the pseudocapsule or reactive tissue about the lesion, and when performed for malignant lesions, leaves microscopic disease at the margin of the

TABLE 4. Surgical Margins*

Type	*Plane of Dissection*	*Result*
Intralesional	Piecemeal debulking or curettage	Leaves macroscopic disease
Marginal	Shell out *en bloc* through pseudocapsule or reactive zone	May leave either "satellite" or "skip" lesions
Wide	Intracompartmental *en bloc* with cuff of normal tissue	May leave "skip" lesions
Radical	Extracompartmental *en bloc* entire compartment	No residual

* The plane of dissection used to achieve a particular margin is shown as well as the result of that margin in terms of residual lesion remaining in the wound.

TABLE 5. Surgical Procedures*

Margin	*Local*	*Amputation*
Intralesional	Curettage or debulking	Debulking amputation
Marginal	Marginal excision	Marginal amputation
Wide	Wide local excision	Wide through-bone amputation
Radical	Radical local resection	Radical disarticulation

* Classified by the type of margin they achieve and whether it is obtained by a local or ablative procedure.

wound in a high percentage of the cases.[4,5,-9,33] As a local procedure, *marginal excision* is usually described as excisional biopsy or "shell 'em out" of a presumed benign lesion. *Marginal amputation* is usually done as either a palliative procedure, an attempted definitive procedure constrained by anatomic inaccessibility, or as an adjunctive procedure.

3. Wide. A *wide* margin is accomplished by a procedure in which the lesion, its pseudocapsule and/or reactive zone, and a surrounding cuff of normal tissue are taken as a single block. The plane of dissection is entirely through normal tissue but within the involved compartment. No effort is made to remove the entire length of involved muscle from origin to insertion or bone from joint to joint. The local wide procedure probably corresponds to what is referred to as "wide local excision," "*en bloc* excision," and "radical *en bloc* excision." A wide margin is definitive surgical management for Stage I lesions and can usually be accomplished by a local procedure for IA lesions.[12,13] Because Stage IB lesions usually involve some combination of bone, soft parts, and neurovascular structures, amputation is more likely to be required.

4. Radical. A *radical* margin is achieved by a procedure in which the lesion, pseudocapsule, reactive zone, and the entire muscles or bone involved are removed as one block. Longitudinally, the plane of dissection goes through or beyond the joint proximally and distally to the bone involved and through the tendinous origin and insertion of involved muscles. Transversely, the dissection passes beyond the major fascial septa of the involved soft tissue compartments or beyond the periosteum of intraosseous lesions. A radical margin does not necessarily imply a greater distance from the lesion to the margin of the wound than a wide margin. A margin on the other side of the intermuscular septum of a lesion in the vastus lateralis will constitute a radical margin but may be considerably closer than a wide margin achieved by amputation. A radical margin is definitive for Stage II lesions. A *radical local resection* can often be done for a Stage IIA lesion. If a lesion involves more than one compartment, or extends into or arises in the extracompartmental planes or spaces, compartmental containment is lost, and a radical margin is usually not attainable with a local procedure. Thus, *radical amputation* is usually carried out to achieve a radical margin in Stage IIB lesions, and it often requires a disarticulation or amputation proximal to the joint in question. These various procedures are illustrated diagramatically in Figures 1 and 2.

A total myectomy for a lesion within a single muscle may be either a wide local excision or a radical local resection, depending upon the muscle involved. If the muscle also constitutes a compartment, *i.e.*, the deltoid, then myectomy accomplishes a radical local resection. If the muscle is one of several muscles separated by loose areolar tissue within a large fascially contained compartment such as the rectus femoris, then myectomy is radical in the longitudinal sense but only wide in the transverse sense and is, by definition, a wide local excision.

APPLICATION

The utility and general applicability of this surgical staging system has been evaluated in two quite different situations: (1) intramurally by the University of Florida musculoskeletal oncology service, and (2) extramurally by an interinstitutional pilot study conducted by the Musculoskeletal Tumor Society.

The intramural evaluation involved patients treated on the musculoskeletal oncology service at the University of Florida since 1959. The service has well-established patient referral patterns, effective mechanisms for patient follow-up, and a consistent, well-defined surgical philosophy. A great deal of prospective primary observational data have been collected since 1959 and is stored in computers. Histogenic classification and grading have been done prospectively since 1974. Cases treated prior to 1974 have been retrospectively reviewed and graded, allowing reclassification along the lines of new histogenic concepts. The surgical grade, site, and stage were estimated preoperatively for surgical planning. The final stage was assigned after pathologic review of the surgical specimen. Two-hundred-fifty-eight cases form the basis of the intramural evaluation of the staging system.

The extramural evaluation of the system was done among 13 institutions (M. D. Anderson Hospital, SUNY–Buffalo, UCLA, UCSF, Case Western Reserve, University of Chicago, University of Iowa, Massachusetts General Hospital, Mayo Clinic, Memorial Hospital for Cancer–New York, University of Miami, University of Minnesota, and Rizzoli Institute of Orthopaedics, Bologna). Many of the participants are established investigators with extensive experience in the management of musculoskeletal neoplasms. The spectrum of their surgical philosophies ranges from conservative to highly innovative. These 13 institutions each have their own pathologists, referral patterns, methods of follow-up and mechanisms for handling data, and therefore represent a reasonable sample of the spectrum of musculoskeletal surgical oncology practice as it exists today.

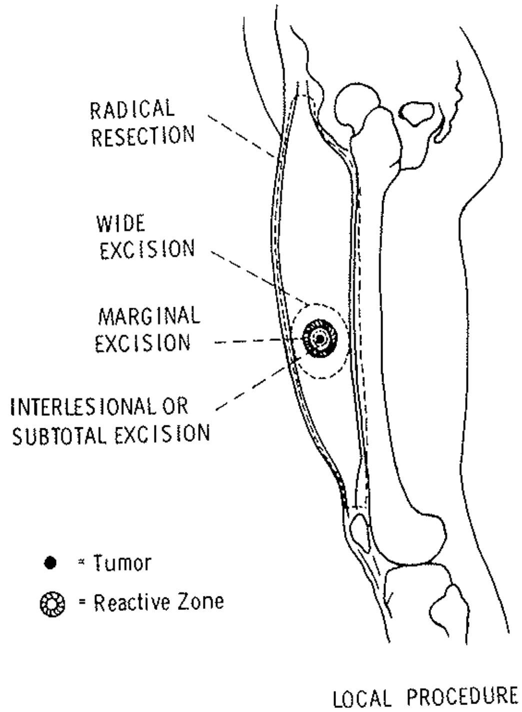

FIG. 1. The various local procedures are shown. The dotted lines indicate the plane of dissection and the amount of tissue removed to achieve the various procedures for a theoretical lesion within the anterior compartment of the thigh. Similar types of procedures may be done for bone lesions.

Each participant was mailed a questionnaire along with a précis of the staging system (Project Manager, Michael Simon, University of Chicago), and asked to retrospectively stage and submit ten consecutive cases of musculoskeletal sarcoma personally treated since 1970. The only restrictions were that the cases have a minimum two-year follow-up period. Patients could be entered without regard for treatment. This diverse group contributed 146 cases. Difficulty in utilizing the system was

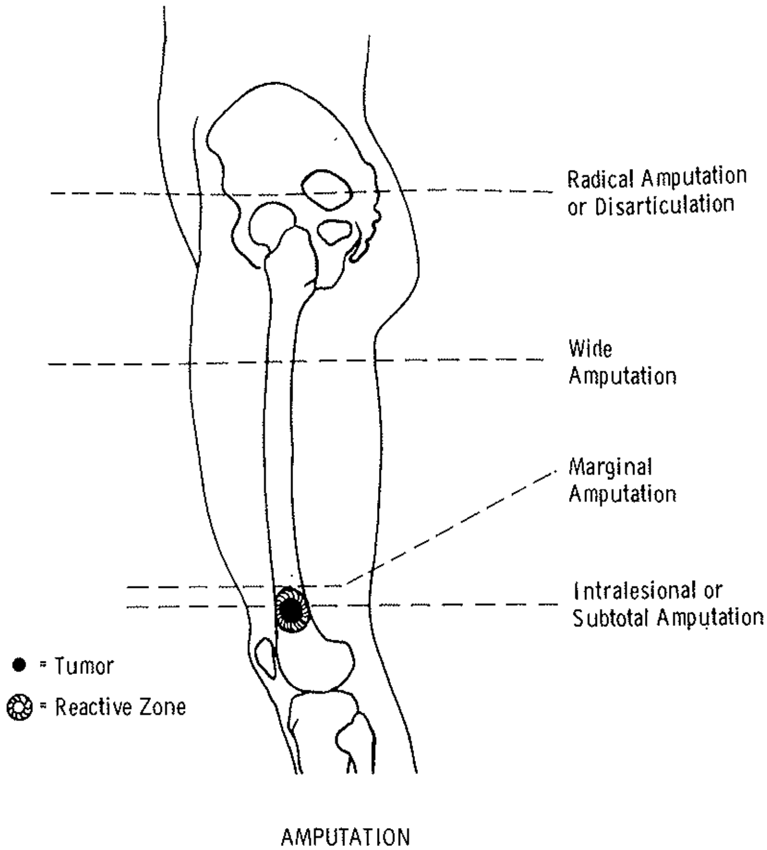

FIG. 2. The various types of amputations are shown for a theoretical lesion of the distal femur. Similar types of amputation may be done for soft-tissue lesions.

reported in 5.5% of cases, almost all problems being related to compartmentalization. Seven cases (5%) were excluded from analysis because of insufficient data. Bookkeeping errors were detected and corrected in 2.5% of the responses. The remaining 139 cases were studied.

Because of the limited amount of data in the extramural group, the survival probabilities were calculated by the method of Cohen for censored data.[10] The intramural data sets were analyzed both by the method of Cohen and by methods using absolute numbers of patients at risk for the time intervals studied.

RESULTS

The histogenic distribution for the total 397 cases is shown in Table 6, and the distribution by stage in Table 7. The histogenic distribution is comparable to other large series with the exception of the relative preponderance of malignant fibrous histiocytoma. There is a modest preponderance of bone lesions and a decided preoponderance of high-grade lesions.

The probability of survival as a function of stage for the extramural and intramural data sets is compared in Figure 3. The probability of survival by Cohen's method for the extramural group is no different from that of the intramural group (Fig. 3,A *vs*. Fig. 3,B). Moreover, it makes no difference whether the intramural data analysis is censored or based on absolute survival rates (Fig. 3,B *vs*. Fig. 3,C). This serves to validate the thesis that analysis of censored data provides a satisfactory estimate of the probability of survival and permits the combining of data for further analysis.

TABLE 6. Histogenetic Distribution

	Bone		*Soft Parts*	
Diagnosis	*MSK*	*UF*	*MSK*	*UF*
Chondrosarcoma	30	28	0	2
Chordoma	4	2	0	0
Clear-cell sarcoma	0	0	1	4
Fibrosarcoma	3	1	2	4
Liposarcoma, myxoid	0	0	6	12
Liposarcoma, pleomorphic	0	0	1	3
Malignant fibrous histiocytoma (MFH)	5	22	13	42
Neuroepithelial sarcoma	0	0	0	5
Classic osteosarcoma	43	40	0	0
Osteosarcoma, other	6	8	2	6
Parosteal osteosarcoma	7	8	0	0
Pleomorphic rhabdomyosarcoma	0	0	2	5
Synovial sarcoma	0	0	8	16
Unclassified	0	4	1	22
Other	2	6	3	18
Total	100	119	39	139

MSK = Musculoskeletal Tumor Society
UF = University of Florida

The probability of survival as a function of stage for the combined group of 397 cases of bone and soft-tissue sarcomas is shown in Figure 4. At each year of survival, there is a significant difference between the probability of survival for each stage ($p < .01$). Patients with Stage I lesions are at low risk and differ from those with Stage II lesions ($p < .01$). The difference between IA and IB lesions is not significant. Patients with Stage II lesions are at high risk ($p < .01$). The difference between Stage IIA and IIB is significant ($p < .01$).

The combined data were separated according to bone ($n = 219$) or soft parts ($n = 178$) origin. The probability of survival as a function of stage for each of these primary sites is illustrated in Figure 5. There is no difference in the survival of bone and soft tissue lesions that are of comparable stage.

The SSS and AJC systems for soft-tissue lesions were compared. The interinstitutional study did not provide sufficient information to retrospectively stage their soft-tissue lesions by the AJC criteria, and the comparative data were drawn from the intramural group. The results of comparing 139 soft-tissue primary lesions are shown in Figure 6. From one to five years, AJC Stages IA and IB are congruent. AJC Stages IA, IB, and IIA together are roughly equivalent to SSS Stage I. The AJC IIB is similar to SSS IIA. AJC Stages IIIA, IIIB, and IVA have considerable overlap at all periods of observation and their distinction is not meaningful. Together they are similar to SSS Stage IIB. The AJC IVB is comparable to SSS Stage III.

TABLE 7. Distribution by Surgical Stage (N = 397)

Stage	*Bone*	*Soft Parts*
IA	22	15
IB	48	33
IIA	10	31
IIB	123	86
III	16	13
Total	219	178

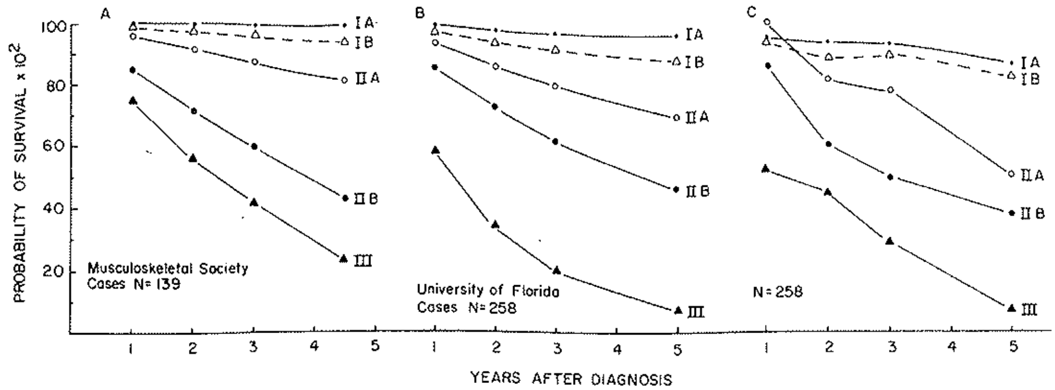

FIG. 3. The probability of survival for the extramural (A) and intramural (B) study group as well as the absolute survival for the intramural group (C) is shown by stages for a five-year period.

DISCUSSION

The Surgical Staging System in our experience has satisfactorily met the objectives. It has aided substantially in surgical planning and permits stratification of lesions in such a way that meaningful comparisons may be made between various treatment protocols.

The purpose of this article is not to describe what constitutes an appropriate surgical procedure in a given patient. Rather the purpose is to point out that in the design

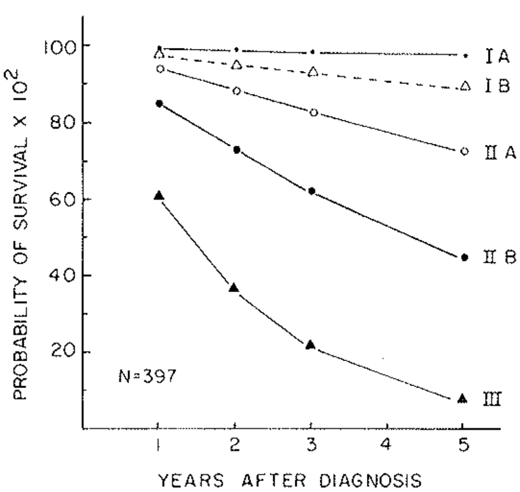

FIG. 4. The probability of survival by the various stages over a five-year period.

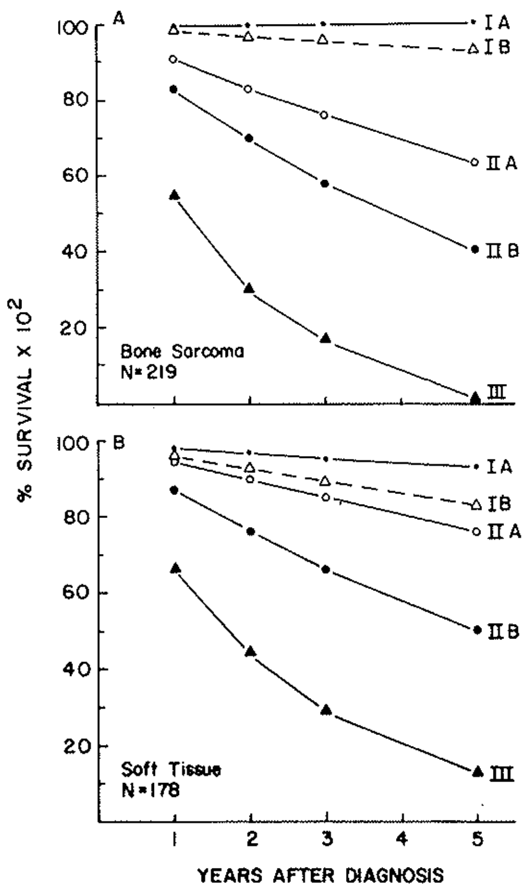

FIG. 5. The probability of survival by stages over a five-year period between bone (upper) and soft-tissue (lower) lesions.

of surgical procedures, the surgeon must meet two sometimes conflicting goals. One is local control of the lesion and the other is preservation of function. The Surgical Staging System, stratified on the basis of the risk factors associated with various surgical procedures, directly enhances treatment planning by permitting the formulation of alternative surgical plans in which the risk of recurrence for a given surgical procedure may be weighed against the benefit of retained function offered by each alternative. The patient's age, sex, expectations, and life style, coupled with the purpose of the procedure (palliative, diagnostic, curative, adjunctive), the surgeon's expertise, the availability of effective adjunctive therapy, and other facts lead to the final choice of operations.

The second objective is also well-served. In order to compare different methods of surgical treatment, the stage of the disease and adjunctive therapy must be the same. In order to compare the effectiveness of nonsurgical treatment, both the stage and the surgical procedure must be the same. It is inappropriate to compare the effectiveness of postoperative adjuvant chemotherapy between two patients with Stage IIB osteosarcoma when one has had a marginal local excision and the other a radical disarticulation. It is equally inappropriate to compare the effectiveness of postoperative irradiation therapy in synovial sarcoma when one patient had a Stage IA lesion with a wide local excision and the other had a Stage IIB lesion with a marginal local excision. Since the definitive surgical procedure is the single most important therapeutic maneuver, both it and the stage of the lesion must be comparable in order to assess the effectiveness of non-surgical adjuvants.

The AJC system is a complex system with four tiers. The system is based on assessment of histologic grade (G_1, G_2, or G_3), size (T_1 or T_2), in some cases, histogenesis, regional metastasis (N_0 or N_1), distant

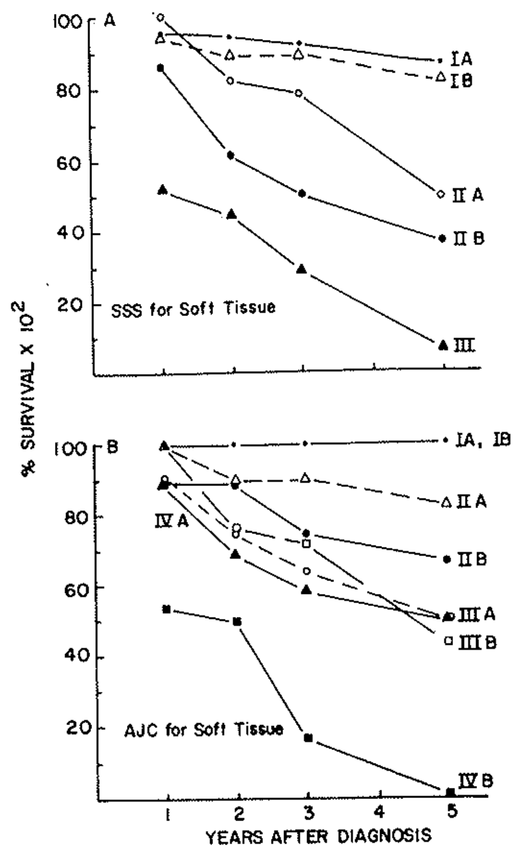

FIG. 6. The incidence of survival by stages over a five-year period. The upper figure shows the lesions staged by the Surgical Staging System while the lower figure shows the lesions staged by the AJC system for soft-tissue sarcomas.

metastasis (M_0 or M_1), and by the proximity of the lesion to neurovascular structures and bone. Although it has the merit of taking into account that histologic grade is a prime factor in the assessment of risk in soft-parts sarcoma, the proposal incorporates a number of conceptual premises that make its clinical use awkward:

1. Forty-seven per cent of the 1215 tumors upon which their proposal rests were located in the head and neck, retroperitoneum or other surgically inaccessible site. These lesions present such a different problem clinically, biologically, and surgically

that they should not be grouped with lesions of the extremities for analysis.

2. The division of sarcomas into three histologic grades is a histologic nicety. Although it is likely to have great appeal to the pathologist, it has little to offer the surgeon in terms of surgical guidance because there is no "middle" surgical procedure.

3. The T designation (local extent) is represented by lesion size. We believe that lesion size has prognostic significance that is a complex composite of anatomic setting, growth rate, and time to physician intervention. Since neither growth rate nor time to diagnosis can be quantitated, this variable in the AJC system would have more relevance if it reflected the extent defined by anatomic setting, *i.e.*, compartmentalization (or compartmental escape). The latter designation is more consistent with the natural biologic behavior of the sarcomas, and has meaning for the surgeon.

4. Appended to Stage III as IIIc are lesions with regional lymph node metastases. Lymph node involvement is so uncommon in the natural history of these lesions at the time of diagnosis as to not be worth a separate factor.[6,8,9,25,26,33,42] When this relatively rare phenomenon does occur, the prognosis is poor. If nodal metastases are given equal weight with other metastases, the surgeon knows that a contemplated procedure is likely to be palliative or must be supplemented with other treatment modalities to be curative.

5. "Gross involvement of a major nerve, artery, or bone" (T_3) is poorly defined, and the methods by which these judgments are to be made are not defined. Lesions with such involvement are assigned to a higher stage without regard for grade. Analysis of our soft-tissue sarcoma data by this method results in these Stage IVA lesions having a prognosis similar to AJC Stages IIIA and B lesions. Such involvement is a proper function of the anatomic setting (extent of the primary), and as such, does not require a separate category.

6. Lesions of certain histogenesis are assigned to at least Stage III because of their usual poor prognosis. This is a function of grade and should be treated as such. Occasional lower grades of these lesions do occur, and they should be staged accordingly.

The AJC system proposed for primary bone lesions is so complex that we have not retrospectively compared it with the Surgical Staging System. However, it is different from the AJC soft tissue system and if generally adopted would require the use of two complex systems that would not permit ready comparison between bone and soft-tissue sarcomas of the same histogenesis. Because definitive surgery is the primary treatment for sarcomas of both bone and soft tissue, and because the principles describing their biologic behavior and surgical procedures are the same for both groups, a common staging system for both groups would be more useful than two separate and different systems.

It is ironic that the essentials of the staging system proposed here were recognized by Quick and Cutler[28] over 50 years ago. They divided 75 tumors which they believed to be of neurogenic origin into three progressive histologic grades and correlated their microscopic observations with the clinical course and treatment. Their clinical rate of metastases reinforces our view that a simple division into high and low grade is practical and sufficient to define the risk of distant spread. Lesion size was not an important determining factor in survival but anatomic location and inadequacy of treatment were. They recognized the relationship between histologic grade and an adequate surgical procedure to patient survival. Their statement that "whereas wide local excision of the acellular fibrous tumors may result in a cure, this procedure is frequently followed by local recurrence and pulmonary metastasis in the highly cellular and malignant tumors (their Grades II and III)," is a precise statement of the principles of tumor surgery recapitulated at our institution.[13,28,36] They appreciated the occasional need for adjunctive therapies and attempted to elucidate factors in their appropriate use by comparing treatment results. The dilemma in treatment choices: "Tumors of the extremity in which amputation offers a chance of completely eradicating the disease present an important problem in treatment. The decision between amputation on the one hand and excision and radiation on the other is at times most difficult," is as unresolved now as it was then.

The Surgical Staging System for sarcomas of bone and soft tissues presented here is simple, clear cut, and has a high degree of compliance and accuracy. It is relevant to both surgical planning and end-result studies. It is quite clear that in comparing nonsurgical treatment protocols both the prognostic stage and the extent of the surgical procedure must be clearly defined and standardized before meaningful end-result studies can be made. The absence of a generally accepted staging system articulated with clearly defined surgical procedures has hampered the understanding of the proper role of various nonsurgical methods in managing musculoskeletal sarcomas. The surgical staging system and surgical definitions presented here form the basis for the ongoing interinstitutional studies currently being conducted by the Musculoskeletal Tumor Society.

SUMMARY

A surgical staging system for musculoskeletal sarcomas stratifies bone and soft-tissue lesions of any histogenesis by the grade of biologic aggressiveness, by the anatomic setting, and by the presence of metastasis. The three stages: I—low grade; II—high grade; and III—presence of metastases, are subdivided by (a) whether the lesion is anatomically confined within well-delineated surgical compartments, or (b) beyond such compartments in ill-defined fascial planes and spaces. Operative margins are defined as intralesional, marginal, wide, and radical, and relate the surgical margin to the lesions, its reactive zone, and anatomic compartment. The system defines prognostically significant progressive stages of risk which also have surgical implications. When the system is linked to clearly defined surgical procedures, it permits appropriate evaluation and comparison of the new treatment protocols designed to replace standard surgical treatment.

ACKNOWLEDGMENT

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KNEE JOINT CHANGES AFTER MENISCECTOMY

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This paper records an investigation of changes found in the knee joint at intervals ranging from three months to fourteen years after meniscectomy. In a search of the literature only one reference to these changes has been found. Vandendorp, Bastien, and Vandecasteele (1939–40) observed in a few subjects that there was narrowing of the joint space and broadening of the femoral and tibial condyles on the operated side of the joint, but they offered no explanation of their findings.

RADIOLOGICAL STUDY

After excluding all cases with definite osteoarthritis, a comparison was made between the pre-operative and post-operative X-ray films in one hundred and seven cases of meniscectomy. Owing to difficulty in securing identical views on separate occasions, the changes to be described were accepted as convincing only because they were seen repeatedly; and occasionally a film of the normal knee joint provided better comparison. The changes noted, alone or in combination, were of three types: formation of an antero-posterior ridge projecting downwards from the margin of the femoral condyle over the old meniscus site (Figs. 1 and 2); generalised flattening of the marginal half of the femoral articular surface—a reaction similar to but more diffuse than the ridge (Figs. 3 and 4); narrowing of the joint space on the side of operation (Figs. 5 and 6) which, after lateral meniscectomy, was occasionally accompanied by apparent widening of the opposite side of the joint; in three patients this was sufficient to cause symptoms suggestive of mild valgus strain of the knee. The lateral views showed nothing of significance; nor was any change observed in the tibia apart from slight sharpening of the articular margin, insufficient to be described as osteoarthritis. It must be noted that the femoral ridge may be seen even before operation, particularly in cases with long-standing lesions of the meniscus, and sometimes in apparently normal joints. The changes have been seen within five months of operation on many occasions, but they tend to become more obvious with the passage of time. No correlation was found between clinical and radiographic findings, many knee joints with the most marked radiographic changes being functionally perfect. The frequency of such changes after medial and lateral meniscectomy was:

	Total cases	No change	Ridge	Narrowing	Flattening
Medial meniscectomy	80	33 per cent.	43 per cent.	32 per cent.	18 per cent.
Lateral meniscectomy	27	50 per cent.	7 per cent.	40 per cent.	17 per cent.

Narrowing plus flattening were the commonest changes found in combination.

INVESTIGATIONS

It is submitted that these changes result chiefly from loss of the weight-bearing function of the meniscus—a function which has not been accepted universally. Before enlarging on the problem two points must be emphasized. 1) If the normal meniscus is to take part in weight-bearing it can do so only if there is a force which prevents it from slipping away like an orange pip squeezed between the fingers. The peripheral attachments are loose and they are not designed to provide this counter-force, but there is another retaining mechanism which will be described later. 2) The elasticity of articular cartilage shows certain peculiarities (Hirsch 1944). Articular cartilage is perfectly elastic only for small loads applied for a very short time. If the load is maintained, deformation (*i.e.*, compression) continues slowly, and is not complete even after half an hour (Fig. 7). Recoil on removing the load has similar characteristics: the longer the load has been maintained the smaller is the immediate rebound

FIG. 1

FIG. 2

Patient, aged forty years, before operation (Fig. 1) and six years after removal of the medial meniscus, showing formation of a ridge from the margin of the femoral condyle (Fig. 2).

FIG. 3

FIG. 4

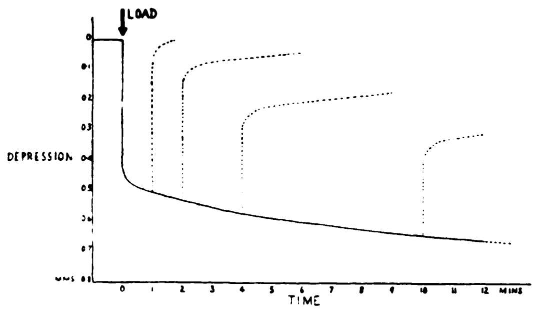
Patient, aged thirty-six years, before operation (Fig. 3) and seven years after removal of the medial meniscus, showing flattening of the femoral condyle (Fig. 4).

FIG. 5

FIG. 6

Patient, aged twenty-five years, before operation (Fig. 5) and five months after removal of the lateral meniscus, showing narrowing of the joint space laterally, and some widening medially (Fig. 6).

and the longer the gradual recovery phase; while if the load has been too great or too prolonged recovery is never complete. This is not the behaviour of a homogeneous substance. The structure of articular cartilage, with its fibrillar arcades (Benninghoff 1922, 1925), and the fact that local compression was seen to cause exudation of fluid from its surface, suggested that its elastic peculiarities might be comparable to those of a sponge. By using a simple modification of the elasticity apparatus designed by Bär (1926), strikingly similar curves were in fact produced from sponge rubber immersed in gylcerin (Fig. 8).



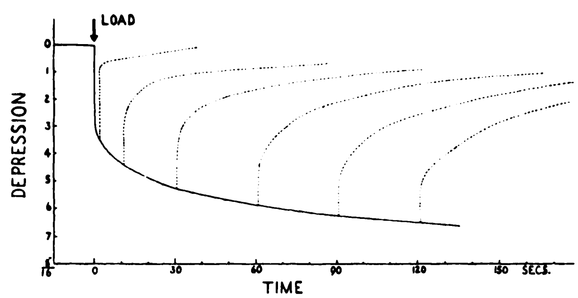
ELASTICITY CURVES OF ARTICULAR CARTILAGE (AFTER CARL HIRSCH)

FIG. 7

The dotted lines represent recovery curves when the load is removed after increasing intervals.

With this behaviour in mind, and in order to observe the degree of compression which occurs in the living joint, radiographs were taken of normal knee joints in full extension and in the upright position. Very careful precautions were employed to obtain identical views for three exposures: 1) in the morning before any weight had been placed on the limb, the muscles gently bracing the knee joint into extension, and all weight being on the other limb; 2) with full weight on the knee after standing for a few minutes; 3) with full weight on the limb at the end of the day. In only one of seven subjects was the first view strictly comparable with the others be cause the degree of rotation and of extension both tend to alter slightly when weight is borne. By measuring the joint space in each view it was shown that the space narrowed by approximately one millimetre when weight was applied; and that by the end of the day it narrowed by another millimetre. Thus, as might be expected from the elasticity experiments, progressive compression of articular cartilage had occurred (Figs. 9 and 10).

A micrometric survey was then made of those parts of the femoral and tibial articular surfaces which are normally apposed in full extension, using an apparatus devised with the generous aid of Professor Thom, Professor of Engineering at Oxford (Fig. 11). By means of the lathe traversing, to which it was bolted, the gauge could be moved in the horizontal plane either sagittally or coronally for known distances. It recorded any vertical movement of the hemispherical pelotte, which rested on the articular surface and slid over it as the gauge was moved. The bone was firmly screwed to the base block. By taking gauge readings at each millimetre shift of the traversing gear it was possible to plot the curvature of a regular series of sections, sagittal and coronal, on a very large scale. These have been arranged to give perspective views of the apposed condyles (Figs. 12 to 15). Two knees were thus surveyed. Both were macroscopically normal and came from autopsy cadavers of women aged thirty and thirty-three years. The figures show how surprisingly incongruous are the joint surfaces, particularly in the sagittal plane, where much of the medial tibial condyle is almost flat and the lateral tibial condyle actually convex.



ELASTICITY CURVES OF SPONGE RUBBER IN GLYCERIN

FIG. 8

Recovery curves of sponge rubber in glycerin for comparison with Fig. 7.

Fig. 16 represents diagrammatically a sagittal section through the lateral compartment of the knee joint. It is evident that until the articular cartilage has been compressed the femur cannot bear upon the meniscus as a whole. Fig. 17 shows the effect of such compression. Tracings of apposed sagittal sections of the lateral femoral and tibial condyles were superimposed so that their intersections took place at a distance equal to that between the central margins of the meniscus, in this case twelve millimetres. The compression was therefore just sufficient to bring the femur down on to the meniscus. The articular cartilages were then sharing a central compression of one millimetre, which by the same method could be shown to be approximately the same in the medial compartment of the joint.

As compression increases, whether from sudden strains or in consequence of normal weight-bearing throughout the day, the circumference of the meniscus must be forced centrifugally. But in so far as the two ends of the meniscus are firmly attached to bone this force is resisted by rising tension in the stretched and elastic fibrocartilage. The greater the degree of joint compression, the greater the circumferential tension in the meniscus. It is submitted that this tension resists extrusive forces and enables the meniscus to share in weight-bearing. That the tension is real was confirmed by stripping a knee joint of the outer soft tissues, while leaving the cruciate ligaments intact and the menisci in position but attached only by their central ends. In full extension the menisci remained slightly mobile until compression was applied, when the periphery of the menisci at once became hard and tense.

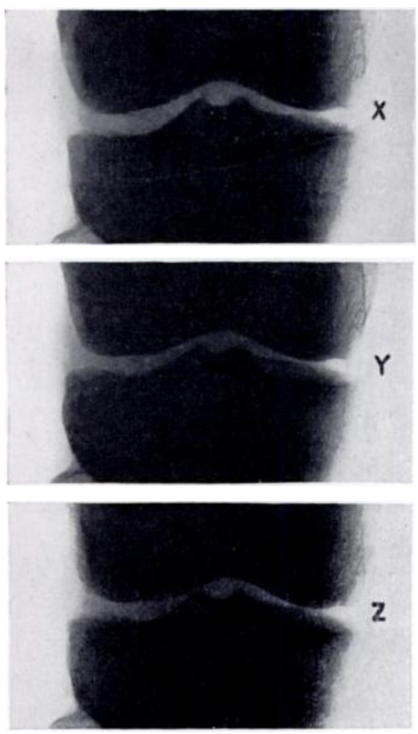


FIG. 9

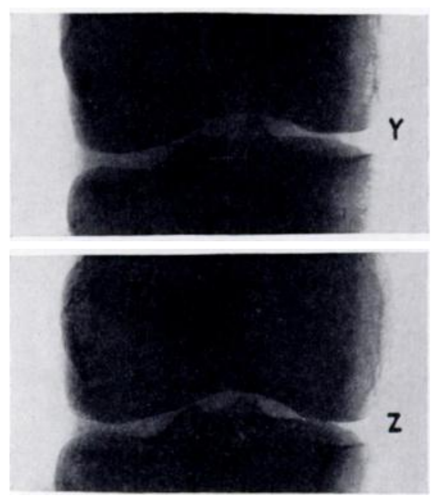


FIG. 10

Fig. 9 shows a normal knee joint after a night's rest without weight-bearing (X); after weight-bearing for two minutes (Y); and weight-bearing at the end of the day (Z).

Fig. 10 shows a normal knee, weight-bearing in the morning (Y) and in the evening (Z).

DISCUSSION

Meniscectomy must therefore result in relative overloading of the articular surfaces on that side of the joint, with increasing compression of the cartilage. But narrowing of the joint space after operation was seen in X-ray films of the recumbent patient, and if such narrowing is permanent, and radiographically demonstrable, it must be due either to structural

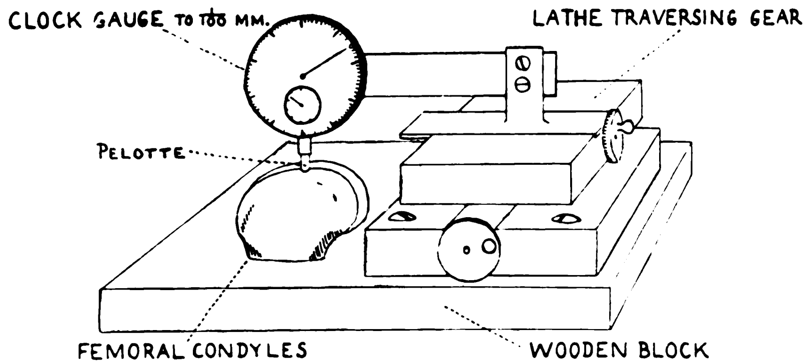


FIG. 11

Apparatus for articular survey (see text).

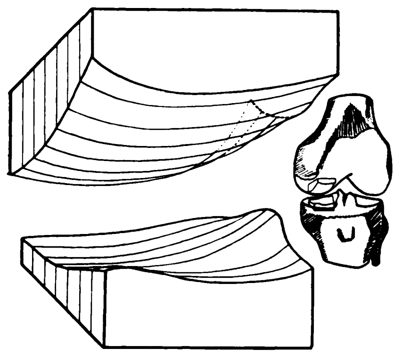


FIG. 12

Coronal section outlines of the medial condyles — interval between each section 3 mms.

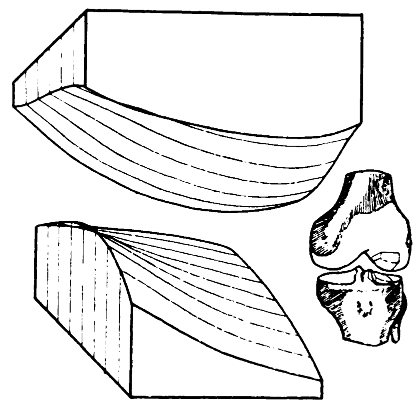


FIG. 13

Coronal section outlines of the lateral condyles—interval between each section 3 mms.

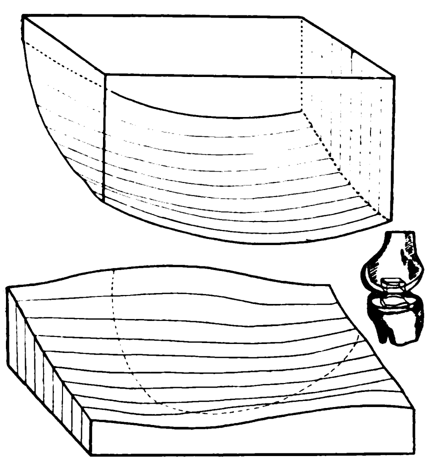


FIG. 14

Sagittal section outlines of the medial condyles—section intervals 2 mms. The dotted line on the tibial surface represents the central margin of the meniscus.

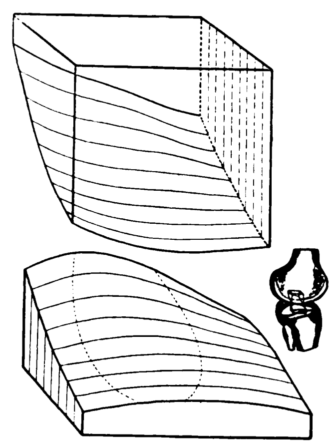


FIG. 15

Sagittal section outlines of the lateral condyles—section intervals 2 mms. The dotted line on the tibial surface represents the central margin of the meniscus.

changes in the articular cartilage which impair the power of recoil, or to actual loss of tissue. The method by which loss of articular cartilage from normal wear and tear is replaced, if it is replaced at all, is still in doubt. But the work of Elliott (1936) suggests that in the adult there is amitotic cell division occurring very close to the surface. The speed of this division is controlled by: 1) a nutritional factor which accounts for an increasing rate of cell division as the articular surface is approached; and 2) a mechanical factor, possibly associated with friction, which inhibits cell division and completely arrests it at the surface itself. Elliott's work was done on experimental animals and so far as can be ascertained it has not yet been confirmed in man, although this writer has made preliminary investigations. MacConaill (1932) stressed the importance of the meniscus as a lubricating mechanism and stated that loss of the meniscus caused a 20 per cent. increase in friction. It is reasonable to suppose that both nutritional and mechanical factors will be affected adversely when cartilage is overloaded, and the resulting interference with tissue replacement may account for the marked narrowing.

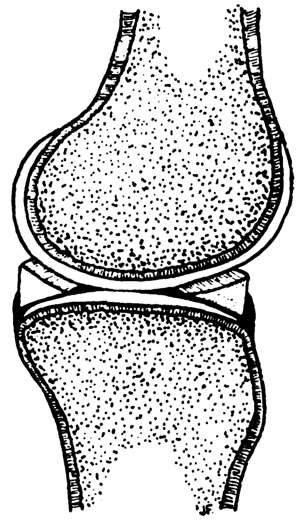


FIG. 16

Sagittal section to show that the femur cannot rest on the meniscus until compression of articular cartilage has occurred.

Flattening and ridge formation over the former site of the meniscus present another problem. These changes appear to be due to reaction in the overlying bone which is no longer subject to the pressure of the meniscus, although changes in the synovial blood supply at the margin may well be significant. We know that bone which is subjected to excessive pressure undergoes atrophy, and in the knee joint this may be seen in the lateral femoral condyle overlying a cystic meniscus. The condyle reacts in the opposite manner when normal pressure is removed; the mechanical effect is that of spreading the load of body weight.

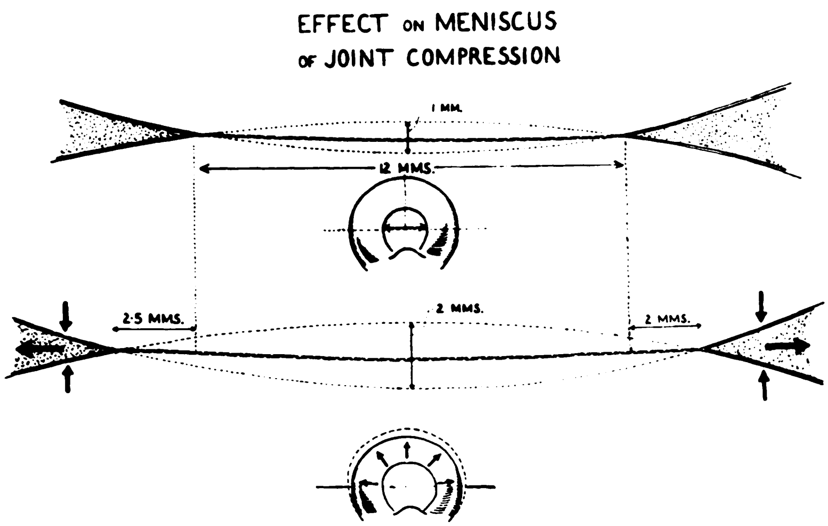


FIG. 17

Superimposed tracings of sagittal sections of the tibial and femoral condyles to show the effect of joint compression in producing centrifugal displacement of the meniscus (for explanation see text).

The final problem is why the findings should be inconstant. There appear to be two possible explanations: 1) variations in the reserve or safety factor of individual joints about which we know so little; 2) variations in the speed and completeness of regeneration of the meniscus. In this series, the results of investigation by arthrography have been inconclusive; a knee with no changes whatever in the articular cartilage or bone was shown to have almost no replacement of the meniscus, while another with ridge formation had fibrous replacement of the meniscus almost to the normal size. Arthrograms also suggested that the ridge consists solely of bone and that the articular cartilage may still have an even and normally curved surface, because the thickness of the cartilage diminishes rapidly as the apex of the bone ridge is approached. It is worth remarking that in dogs, Bruce and Walmsley (1937) found that regeneration of an excised meniscus was still progressing and not yet complete even after five months, while Pfab (1927, 1928), Dieterich (1931), and King (1936) found evidence of degenerative changes in the overlying femoral condyle.

SUMMARY AND CONCLUSION

Changes in the knee joint after meniscectomy include ridge formation, narrowing of the joint space, and flattening of the femoral condyle. Investigations suggest that these changes are due to loss of the weight-bearing function of the meniscus. Meniscectomy is not wholly innocuous; it interferes, at least temporarily, with the mechanics of the joint. It seems likely that narrowing of the joint space will predispose to early degenerative changes, but a connection between these appearances and later osteoarthritis is not yet established and is too indefinite to justify clinical deductions.

My thanks are offered to Sir Harry Platt, the staff of the Wingfield-Morris Orthopaedic Hospital, and in particular to Professor H. J. Seddon for much helpful advice; to Mrs Crossley of the Photographic Department and Miss Robins of the X-ray Department for their patience and skill; and to Professor Thom and Mr Lund of the Oxford University Engineering Laboratory for generous help in micrometric joint surveys.

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Prevention of infection in the treatment of one thousand and twenty-five open fractures of long bones: retrospective and prospective analyses

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Prevention of Infection in the Treatment of One Thousand and Twenty-five Open Fractures of Long Bones

RETROSPECTIVE AND PROSPECTIVE ANALYSES

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ABSTRACT: **In 673 open fractures of long bones (tibia and fibula, femur, radius and ulna, and humerus) treated from 1955 to 1968 at Hennepin County Medical Center, Minneapolis, Minnesota, and analyzed retrospectively, the infection rate was 12 per cent from 1955 to 1960 and 5 per cent from 1961 to 1968. In a prospective study from 1969 to 1973, 352 patients were managed as follows: débridement and copious irrigation, primary closure for Type I and II fractures and secondary closure for Type III fractures, no primary internal fixation except in the presence of associated vascular injuries, cultures of all wounds, and oxacillin-ampicillin before surgery and for three days postoperatively. In 158 of the patients in the prospective study the initial wound cultures revealed bacterial growth in 70.3 per cent and the infection rate was 2.5 per cent. Sensitivity studies suggested that cephalosporin is currently the prophylactic antibiotic of choice. For the Type III open fractures (severe soft-tissue injury, segmental fracture, or traumatic amputation), the infection rates were 44 per cent in the retrospective study and 9 per cent in the prospective study.**

Prevention of wound sepsis remains the prime objective in the management of open fractures. The reported infection rates in these fractures, which range from 3 to 25 per cent, are a challenge to every surgeon who treats them [6-8,10,14,15,21,22,26].

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There is universal agreement that open fractures require emergency treatment, including adequate débridement and irrigation of the wound. Beyond these two basic tenets, opinions differ as to the following:

1. Primary or secondary closure. If the wound is left open and secondary direct skin closure is not possible, when does one do skin-grafting, or create a cross-leg pedicle flap or a rotational flap?
2. Use of primary internal fixation. What are the indications for primary internal fixation and if internal fixation is delayed, when is the proper time for open reduction and internal fixation?
3. Use of antibiotics. Should they be used routinely? What antibiotics should be used and for how long?

In an attempt to answer these questions we carried out retrospective and prospective analyses of a total of 1,025 open fractures of all the long bones treated at Hennepin County Medical Center, Minneapolis, Minnesota, from 1955 to 1973.

Retrospective Study, 1955 to 1968

As previously reported [14,15], 673 open fractures of long bones in 602 patients were treated at Hennepin County Medical Center from 1955 to 1968. The data on these fractures were collected by review of the charts, follow-up letters, and telephone calls. Of the 673 fractures, 583 (86.6 per cent) were followed for at least one month until soft-tissue healing had occurred. The remaining ninety patients failed to return for any follow-up.

All patients were cared for by the general surgical or orthopaedic resident assigned to the Trauma Service with a member of the attending staff consulting. The management of these fractures was essentially the same throughout the period of this study, except for the antibiotics used. Treatment during this period included:

1. Adequate débridement and copious irrigation of the wound.

2. Primary closure whenever possible, regardless of the severity of the fracture and the soft-tissue injury.

3. Internal fixation used at the discretion of the surgeon and not in accordance with any rigid criteria. Some fractures treated by internal fixation could have been treated in a plaster cast alone or with pins above and below the fracture incorporated in a plaster cast.

4. Routine antibiotics. During the first five years (1955 to 1960), penicillin, 40,000 to 60,000 units, was given intravenously every four to six hours in combination with streptomycin, 0.5 to 1.0 gram twice daily, starting postoperatively and continuing for seven to ten days. From 1961 to 1966, penicillin, 600,000 to 1.0 million units, and Chloromycetin (chloramphenicol), 0.5 to 1.0 gram, were given intravenously every six hours starting one to three hours preoperatively and continuing for seven to ten days. From 1967 to 1968, penicillin, 1.0 million units every six hours, and oxacillin, 1.0 gram every four hours intravenously, were started one to three hours before operation and continued for seven to ten days. Occasionally, when the wound was severely contaminated, kanamycin, 0.5 gram twice a day, was also given.

Results

Infection Rate

The infections were usually evident during the first month after surgery, the majority being recognized during the first seven days. Drainage developed in thirty-eight (6.5 per cent) of the wounds, of which thirty-one had positive and five had negative cultures, and two were not cultured. All thirty-eight wounds were considered infected because of the purulent drainage and characteristic appearance of the wounds. Sensitivity studies were done on all pathogenic bacteria recovered and the antibiotic programs were changed as indicated. The common pathogenic organisms isolated were *Staphylococcus aureus* coagulase positive in twenty-six patients, *Escherichia coli* in three, Proteus in two, and Pseudomonas and a gram-negative rod in one each.

The over-all incidence of wound infections from 1955 to 1960 was 11.85 per cent and from 1961 to 1968, 5.24 per cent. These rates were considered low and appeared to justify the methods of treatment, considering the high incidence of infection reported in previous series of open fractures [6-8,10,14,15,20,21,26].

Primary Internal Fixation

The incidence of infection in open fractures of the femur and tibia treated by primary internal fixation was compared with that in fractures treated without internal fixation. The fractures were not matched or selected at random, a problem in all retrospective studies. However, we believe that the fractures treated with primary internal fixation could have been treated by plaster alone or by pins inserted above and below the fracture site and incorporated in a plaster cast. Fifty-two open fractures (thirty-four tibiae and eighteen femora) treated by primary nailing or plating had a 19 per cent infection rate, and 238 open fractures (194 tibiae and forty-four femora) were treated without internal fixation and had an infection rate of 5 per cent.

Primary Versus Secondary Wound Closure

In a retrospective study it is not possible to make statistically valid comparisons. Obviously some of the wounds that were left open were the most contaminated or had the most tissue loss. Of forty-four open fractures treated by initial débridement and secondary closure, 20 per cent became infected, while only 6 per cent of the 495 fractures treated by primary closure became infected. Because of these excellent results with primary closure, in 1966 we advocated primary closure for all open fractures except when the surgeon thought that the débridement and irrigation had not been entirely satisfactory. From 1955 to 1960, 18 per cent of the open fractures were left open; from 1961 to 1966, 4 per cent; and from 1967 to 1968, only 1 per cent.

These over-all results might suggest that primary closure is indicated for all types of open fractures. However, we observed that in the majority of the thirty-eight infected cases the injuries were segmental fractures, extensive soft-tissue lacerations, or traumatic amputations treated by primary closure. Furthermore, of the twenty-one patients with open segmental tibial fractures and associated extensive soft-tissue injuries treated from 1961 to 1968, the sixteen treated by primary closure (three of them by primary internal fixation as well) had an infection rate that was a staggering 44 per cent, while only one of the five treated by delayed closure had an infection.

The conclusions from this retrospective study, therefore, were that primary internal fixation increases the incidence of infection; that primary closure after segmental open fracture, open fracture with extensive laceration and avulsion of the soft tissues, or traumatic amputation results in a high infection rate; and that prophylactic antibiotic therapy is essential in the treatment of open fractures.

Prospective Study of 352 Open Fractures, 1969 to 1973

From 1969 to 1973, all open fractures were classified into three categories:

Type I — An open fracture with a wound less than one centimeter long and clean.

Type II — An open fracture with a laceration more than one centimeter long without extensive soft-tissue damage, flaps, or avulsions.

Type III — Either an open segmental fracture, an open fracture with extensive soft-tissue damage, or a traumatic amputation. Special categories in Type III were gunshot injuries, any open fracture caused by a farm injury, and any open fracture with accompanying vascular injury requiring repair.

Guidelines for the treatment of these fractures were established prospectively and followed with only minor alterations. These guidelines were as follows:

1. All open fractures were treated as emergencies.

2. Cultures were obtained routinely on admission and before wound closure or application of the postoperative dressing after 1971.

3. Oxacillin, 1.0 gram every four hours, and ampicillin, 1.0 gram every six hours, were given intravenously before, during, and for three days after surgery. Occasionally, when the wounds were severely contaminated, gentamicin, three to five milligrams per kilogram of body weight, was given instead of ampicillin to "cover" gram-negative bacteria. If the wound was left open, antibiotics were continued for more than three days in accordance with the finding by wound culture or the appearance of the wound. Usually, antibiotics were continued for three days after secondary wound closure in the Type III fractures.

4. Thorough débridement and copious irrigation were emphasized, and for the more recently treated Type III injuries jet lavage was used [13,16].

5. No primary internal fixation was employed except in rare cases in which vascular injury required repair. External skeletal fixation or traction was the preferred method of immobilization.

6. Primary closure was performed in Type I and II fractures and delayed closure, in Type III lesions.

From 1969 to 1973, 352 open fractures were treated at Hennepin County Medical Center according to the protocol described. Of these fractures, 81 per cent were Types I and II and 19 per cent, Type III. Follow-up for at least six weeks, sufficient to determine the incidence of all but the delayed infections, was possible for 326 of these fractures, of which seventy-eight were Type I; 181, Type II; and sixty-seven, Type III. Therefore, there was no follow-up at all on twenty-six of the 352 fractures.

Results

Bacterial Flora and Sensitivities

Bacteriological studies were complete in the 158 consecutive patients seen after 1971. Of these, eighty (50.7 per cent) showed a positive wound culture on admission, and thirty-one (20 per cent) had a negative culture initially, but a positive culture at wound closure following irrigation and débridement. Therefore, a total of 111 patients (70.3 per cent) had a contaminated wound as shown by a positive culture either on admission or at wound closure.

As shown in Table I, approximately fifteen organisms were isolated on 143 occasions. Eighty-six of the isolates were gram positive and fifty-seven were gram-negative organisms. Thirty-two of the 158 wounds yielded mixed bacterial growth.

TABLE I

Organism	No. of Isolates	Sensitivities*							
		Cephalothin	Penicillin	Oxacillin	Cleocin	Ampicillin	Gentamicin	Carbenicillin	Chloramphenicol
Gram positive									
Staphylococcus coag. pos.	12	100	20	100	100	—	—	—	—
Staphylococcus coag. neg.	41	100	57	85	95	—	—	—	—
Diphtheroids	14	—	—	—	—	—	—	—	—
Alpha Streptococcus, group D	1	100	100	—	—	—	—	—	—
Bacillus subtilis	11	—	—	—	—	—	—	—	—
Alpha Streptococcus	7	50	50	0	0	—	—	—	—
Gram negative									
Escherichia coli	4	86	—	—	—	50	100	—	100
Klebsiella enterobacter	20	83	—	—	—	6	100	—	100
Klebsiella species	1	0	—	—	—	100	100	—	100
Enterobacter species	6	0	—	—	—	17	100	—	100
Pseudomonas species	17	0	—	—	—	0	100	100	100
Proteus species	3	100	—	—	—	100	100	—	100
Herellea	3	0	—	—	—	66	100	—	100
Achromobacter species	2	—	—	—	—	—	—	—	100
Other gram-neg. rods	1	100	—	—	—	—	100	—	100

* The sensitivity studies were done by the Kirby-Bauer method. A dash indicates that no studies were done.

Based on the sensitivity studies of these organisms, the cephalosporins (cephalothin and cefalozin) appeared to be the most effective antibiotics for prophylaxis after open fractures. These agents are effective against all gram-positive organisms including *Staphylococcus* coagulase positive and negative, and the majority of *Escherichia coli,* Klebsiella, and Proteus, excluding Pseudomonas. We did not find that anaerobes were particularly significant in these studies, presumably because the anaerobic culture technique at our institution was not satisfactory prior to 1974.

Wound Closure

Of the sixty-seven Type III fractures, 19 per cent were treated by delayed secondary closure, either direct skin closure, skin-grafting, or allowing the wound to heal by granulation tissue. Early (at five days to three weeks) pedicle flaps were used in five cases.

Primary Internal Fixation

In the last five years, only two open fractures were treated by primary internal fixation. Both were comminuted supracondylar fractures, complicated by injuries to the popliteal artery requiring repair. Both wounds became infected. In seventeen femoral-shaft fractures (thirteen Type I and II and four Type III) treated by intramedullary nailing ten days or more after fracture, there were no infections.

Infection Rate

Eight (2.4 per cent) of the 326 fractures in the prospective study became infected compared with twenty-four (5.2 per cent) of the 458 fractures in the series from 1961 to 1968 and fourteen (11.8 per cent) of 135 fractures in the series from 1955 to 1960 ($p < 0.02$). Of the eight infections in the prospective series, six involved fractures of the tibial shaft and two, supracondylar fractures of the femur. Six were Type III and two, Type II. Three of the eight fractures were associated with vascular injuries, two of the popliteal (in one patient) and one of the posterior tibial artery. Five of these eight infections appeared to be secondary, developing when the wound cultures became positive after the wounds had been open for two weeks or more because we had failed to close them secondarily by repeated skin grafts. For the Type III fractures the infection rate in this series was 9.9 per cent in contrast to the 44 per cent rate in the group studied retrospectively ($p < 0.01$).

The three open fractures associated with vascular injury and extensive soft-tissue damage were treated by débridement (considered adequate at the time), copious irrigation, primary internal fixation, vascular repair, and packing the wound open. In the patient with bilateral supracondylar open fractures and bilateral lacerated popliteal arteries, the operative time was eight hours, while in the other patient with a comminuted open fracture in the proximal part of the tibia and laceration of the posterior tibial artery, the time was three and one-half hours. To our dismay, forty-eight to seventy-two hours later we found more soft-tissue necrosis in all three wounds, which required further débridement. Infection was evident several days later in each instance.

In the uninfected Type III wounds, delayed primary closure by either direct suture or split-thickness skin-grafting was done five to seven days after the primary procedure in all but five cases in which rotational or cross-leg pedicle flaps were created. Split-thickness skin-grafting was successful over exposed bone when the periosteum was intact; otherwise, we resorted to some type of flap coverage. To date we have tried delayed (five days to three weeks after injury) primary cross-leg pedicle grafts to cover large exposed areas of bone five times, all successful. This procedure appears to prevent delayed infection and provides better coverage of the bone.

Bacterial culture and sensitivities of the eight infected open fractures from 1969 through 1973 revealed that three had infections with gram-positive and gram-negative bacteria. The predominant organisms were Staphylococcus coagulase positive, *Klebsiella enterobacter, Escherichia coli,* Proteus, and Staphylococcus coagulase negative.

Fracture Healing

Of the 352 fractures in the prospective study, 197 were followed with roentgenographic and clinical evaluations for at least six months after injury. The other 155 had not been followed for six months, had been transferred to private care, or were lost to follow-up at the time of writing. Of the 197 fractures which were followed, 170 (86.4 per cent) united uneventfully and twenty-seven (13.6 per cent) failed to unite and required bone-grafting.

Discussion

Adequate Débridement and Copious Irrigation

Scully and co-workers described criteria for muscle viability called the four C's: (1) color, (2) capacity to bleed, (3) contractility, and (4) consistency. In our experience color was a reliable guide and the other three C's correlated well with muscle viability. However, adequate débridement remains a difficult technical problem. *If there is the slightest doubt in the surgeon's mind as to whether there has been adequate débridement of the wound after an open fracture, the wound should not be closed regardless of the type of open fracture. For the surgeon who manages only an occasional open fracture, the safe rule is not to close the wound.*

Copious irrigation implies that the wound is irrigated with normal saline solution in large amounts in conjunction with débridement in order to remove all dirt and foreign material as well as all devitalized tissue. In our institution, the residents use an average of ten to fourteen liters of normal saline solution for open fractures of long bones. Recently use of jet lavage, particularly in Type III fractures, accomplished this task more effectively in a shorter time and with about half as much irrigating solution.

Rationale for Routine Use of Antibiotics

In our institution, every open fracture is now considered a severely contaminated wound and, therefore, more likely to become infected than a wound made in a clean, elective surgical procedure. Studies by Patzakis and associates and our own study (Table I) showed that open fractures are contaminated. In our series, 70.3 per cent of the open wounds yielded positive cultures. Therefore, we consider the routine use of antibiotics in open fractures as therapeutic rather than prophylactic, and we think that subsequent changes in antibiotic coverage should be guided by the sensitivity of the organisms isolated from the infected open fractures. Use of Chloromycetin was dis-continued in the early phase of the study because of the rare complication of agranulocytopenia.

Since our culture and sensitivity studies of the bacterial flora in open fractures and of the bacteria isolated from the infected wounds suggested that the best single antibiotic for prophylaxis is a cephalosporin (cephalothin or cefalozin), in 1974 we began using cephalosporins exclusively as the antibiotics for open fractures.

The dosage and duration of antibiotic administration remain unsettled questions. Antibiotics were given most commonly for seven to ten days in all previous studies, including our own. We could find no evidence to support this practice. The rationale appears to be that the wound heals in seven to ten days. On the other hand, recent clinical reports [2,22] have shown that prophylactic antibiotics given for a shorter time, such as three to five days, are probably just as effective in preventing wound infection and have the advantage that if infection develops, it will be manifest while the patient is still in the hospital. In our present regimen prophylactic antibiotics for open fractures are given one to three hours before surgery, during surgery, and for three days thereafter. They are then stopped whether the patient is febrile or not. If the wound becomes infected, gram stain and culture are obtained, and surgical débridement and irrigation are done immediately. The appropriate antibiotic is administered as soon as the sensitivities of the bacteria are known.

If the wound is left open initially, antibiotics are continued depending on the appearance of the wound and the results of its culture. It is difficult to keep a large open wound sterile for a long period of time, and it should be closed secondarily with either a skin graft or a cross-leg pedicle flap as soon as possible. If a wound is not closed, secondary contaminants such as Pseudomonas and other gram-negative bacteria, for which the antibiotics used are not effective, appear and become pathogenic.

The aminoglycosides (kanamycin and gentamicin) may be used occasionally in severely contaminated open fractures, primarily for gram-negative bacteria, but the patient must be watched carefully for nephrotoxic effects. The serum creatinine and blood urea nitrogen values should be determined daily. In patients who have had multiple trauma with severe open fractures, the aminoglycosides predispose to acute renal shutdown. These drugs should be used only if the anticipated beneficial effects are deemed essential after careful weighing of the potential benefits and dangers.

Unresolved Problems

During the last five years we have focused our attention on Type III fractures characterized by extensive soft-tissue loss, instability, and large areas of exposed bone requiring soft-tissue coverage. In these cases thorough débridement of the devitalized tissue is absolutely essential, and during the process large areas of bone are exposed. Use of the jet lavage apparatus certainly helps in cleaning these wounds, reducing the amount of irrigating solution and also shortening the operating time. At the end of the procedure the wound is packed open, and five to six days later split-thickness skin grafts are applied, followed if need be by repeated skin grafts as a good base of granulation tissue develops.

During the long intervals that such wounds are open, secondary infections, usually with gram-negative organisms, may be a problem since these organisms are usually difficult to control by antibiotics alone. Prolonged aminoglycoside therapy, particularly for Pseudomonas, is dangerous and of questionable value. Daily soaks of the open wound with solutions such as 0.25 per cent silver nitrate, hydrogen peroxide, and acetic acid, or with plain normal saline, help to control these infections and enhance the formation of good granulation tissue. A cross-leg pedicle flap or rotational flap to cover any exposed bone or large soft-tissue defect, done early, may prevent secondary contamination and subsequent infection. We treated five patients with cross-leg pedicle flaps to cover extensive soft-tissue defects in the leg five days to three weeks after injury, while extraskeletal fixation was used to immobilize the unstable open fractures. The results were satisfactory in all five patients.

Another major problem is the comminuted open fracture with vascular injury and extensive soft-tissue damage. This injury usually requires extensive débridement and primary repair of the damaged blood vessels. In the past it has been our policy to fix all fractures associated with arterial injury internally, in order to provide stability for the repaired vessel. To do this, however, increases the operating time as well as the amount of dissection around the fracture site, with consequent additional surgical trauma which predisposes to wound sepsis.

The danger of vascular disruption from unstable fracture fragments prompted many authors to advise internal fixation of the fracture prior to arterial repair in patients with combined bone and arterial injuries. However, experience with injuries treated during the Vietnam war raised questions about the necessity for internal fixation in severely traumatized limbs [11,18,24]. A study of civilian femoral and tibial fractures by Connolly and co-workers [4] also did not substantiate the need for internal fixation, since 4.5 to 6.8 kilograms of skeletal traction was shown to immobilize these fractures safely and effectively after arterial repair, especially when there was a severely contaminated wound or when the blood flow had to be restored as soon as possible. The method of managing the fracture, therefore, probably should not take precedence over treatment of the related serious soft-tissue injury [5].

In open fractures with arterial injury it is difficult to determine the extent of avascular and devitalized tissue initially. In our experience, despite prompt arterial repair, non-viable and necrotic tissues not recognized at the initial procedure were found two to three days later. This oversight was obviously the result of inadequate circulation not evident initially.

Therefore, we now recommend in such cases that a complete débridement be carried out, as is done in all open fractures, the damaged blood vessels repaired, and the fracture immobilized in traction, leaving the wound open to be closed secondarily by direct closure, split-thickness skin-grafting, or a cross-leg pedicle flap.

The use of large metallic fixation devices such as plates and intramedullary nails may be indicated rarely to provide stability and to facilitate wound care so that the soft tissues around the fracture site may be preserved. In only one patient, treated in 1974, was a Lottes nail used for a Type III fracture of the tibia associated with an extensive, almost circumferential degloving soft-tissue wound of the thigh. By stabilizing the tibia, care of the thigh and leg wounds, which otherwise would have been very difficult, was made much easier. We do not close wounds primarily when large metallic devices are used in the initial care of fractures, and we advocate strongly that extraskeletal fixation devices, such as pins incorporated in plaster, a Roger Anderson device, or a Müller apparatus, be used whenever stability is needed to facilitate care of an open wound.

It is worthy of note that there have been no cases of gas gangrene in over 1,000 patients treated at Hennepin County Medical Center. The method of treatment advocated is believed to have helped in the prevention of this complication.

Conclusions

1. Open fractures require emergency treatment, including adequate débridement and copious irrigation.

2. Primary closure is indicated for Type I and II open fractures, but delayed primary closure, including split-thickness skin grafts or appropriate flaps, should be used for Type III open fractures.

3. Internal fixation by plates or intramedullary nails should not be used. External skeletal fixation by skeletal traction, pins above and below the fracture site incorporated in a plaster cast, or such devices as the Roger Anderson or Müller apparatus is recommended.

4. Open fractures associated with arterial injury requiring repair should be treated in skeletal traction whenever possible instead of by primary internal fixation.

5. Antibiotics should be administered before and during surgery, the antibiotics of choice currently being the cephalosporins in therapeutic doses. If the wound is closed primarily, the antibiotics are stopped on the third postoperative day. If the wound is closed secondarily, the antibiotics are continued for another three days after this procedure.

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Treatment of Scoliosis: Correction and Internal Fixation by Spine Instrumentation

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Treatment of Scoliosis

Correction and Internal Fixation by Spine Instrumentation *†

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The development of the treatment of scoliosis to be described began in 1947 with a study of the anatomy of the spine and the problem of scoliosis as seen in approximately 3,000 patients with poliomyelitis. It was thought that a metal device for the correction of the scoliotic curve and for the maintenance of the correction could be implanted, and in the period between 1949 and 1954 such a device was used in nineteen patients (Table I). Thirty-five modifications in the

TABLE I

GROUP I

Name	Sex	Age	Diagnosis	Fusion: Yes	Fusion: No	Results: Better	Results: Same	Results: Worse	Number of Operations	Severity of Curvature: Mild	Severity of Curvature: Moderate	Severity of Curvature: Severe	Cast: Yes	Cast: No	Complications: Pseudo-arthrosis	Complications: Surgical Shock	Complications: Bone Erosion	Complications: Instrument Fracture	Complications: Instrument Dislocation	Complications: Radiculitis	Complications: Infections	Complications: Metal Reactions	Complications: Progression 2nd Curve	Complications: Ileus: Mild	Complications: Ileus: Medium	Complications: Ileus: Severe	Death	Remarks
BB	F	19	I	X			X		3			X			X			X										
VB	F	14	PP	X		X			2			X					X	X										
MC	F	33	PP	X		X			2			X						X										
JC	M	12	PP		X		X		4		X						X	X										
JE	F	11	I		X			X	2	X																		
JF	M	16	I	X		X			1		X				X													
DH	F	20	PP	X			X		11			X			X		X	X										
RH	M	9	PP					X	1		X						X					X						
KL	F	16	PP	X		X			3			X																
IM	F	25	PP	X		X			2		X				X		X	X										
GP	F	14	PP	X		X			3		X						X	X										
CQ	F	14	PP	X				X				X					X	X										
JR	F	12			X		X		3		X						X	X										
LS	F	16	PP	X		X			2		X																	
HS	M	15	PP	X		X			1	X																		
SW	F	12	PP		X		X		3		X						X	X										
JW	M	14	PP			X			4			X						X										
AW	F	18	I	X		X			2	X							X											
LW	F	13	PP		X	X			1		X																	
19			19	13	6	11	5	3	53	3	9	7	0	0	4	0	10	11	0	0	0	1	0	0	0	0	0	0

DIAGNOSIS KEY

PP—POST POLIO
I—IDIOPATHIC

Table I represents the nineteen cases in Group I of the study in which the major instrument development took place. The complications of bone erosion, instrument fracture, and pseudarthrosis dominated this series. Note that no casts were used and that fusion was used in nearly all cases eventually to acquire reasonable results.

* Read in part at the Annual Meeting of The American Orthopaedic Association, Hot Springs, Virginia, June 2, 1960.

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device were made during this five-year period. Many problems were encountered; and the period between 1955 and 1960 saw the development of other modifications, principally of the instrumentation, but also of the surgical approach and clinical application of the original idea (Table II). Forty-six patients were operated on in this phase of the study, and twelve modifications of the device were made in this period. During 1960, sixty-eight patients were treated by the method as perfected up to that point (Table III). A description of the method presently in use is the main subject of this article.

TABLE II

GROUP II

NAME	SEX	AGE	DIAGNOSIS	FUSION		RESULTS			NUMBER OF OPERATIONS	SEVERITY OF CURVATURE			CAST		COMPLICATIONS									ILEUS			DEATH	REMARKS
				YES	NO	BETTER	SAME	WORSE		MILD	MODERATE	SEVERE	YES	NO	PSEUDO-ARTHROSIS	SURGICAL SHOCK	BONE EROSION	INSTRUMENT FRACTURE	INSTRUMENT DISLOCATION	RADICULITIS	INFECTIONS	METAL REACTIONS	PROGRESSION 2nd CURVE	MILD	MEDIUM	SEVERE		
CB	F	17	I	X		X			2			X												X				
JB	M	15	PP	X		X			3		X						X							X				
JB	F	23	PP	X		X			2			X												X				
PB	M	14	PP	X		X			4			X					X	X						X				
TB	M	15	PP	X		X			3		X						X							X				
DB	F	18	PP										NO OPERATION YET															
JB	M	11	I	X		X			3			X												X				
SB	F	11	PP		X			X	3		X						X	X						X				
TC	M	10	PP	X				X	4		X						X	X							X			
C	M	—	PP										NO OPERATION YET											X				
CC	F	20	PP	X		X			1	X														X				
TC	F	11	PP	X		X			2		X													X				
SC	F	—	I		X			X	1	X							X							X				
RC	F	14	PP	X		X			1		X						X							X				
EC	F	13	PP	X				X	3			X					X	X							X			
BC	M	—	PP										NO OPERATION YET															
JC	M	13	PP		X			X	3			X					X	X						X				
SC	F	8	PP		X		X		2		X						X							X				
BE	M	12	PP	X		X			2			X					X	X						X				
JE	M	12	PP		X		X		2			X					X	X						X				
CF	M	11	PP		X		X		4	X							X							X				
DH	F	20	PP	X			X		11			X			X		X	X						X				
JH	F	16	I	X		X			2			X											X	X				
SH	M	12	PP		X		X		3		X											X–18 MONTHS			X			
LJ	F	13	PP		X		X		2		X													X				
BJ	F	12	I	X				X	3		X				X		X						X	X				
BJ	F	13	PP	X			X		1	X														X				
KL	F	16	PP	X		X			3			X												X				
FL	M	18	PP	X		X			1			X												X				
GM	M	15	PP	X			X		1		X													X				
BMc	M	11	PP	X			X		3			X					X	X						X				
BM	F	15	PP	X		X			1			X												X				
KM	F	10	PP		X	X			3		X													X				
FM	M	11	PP	X		X			2		X													X				
DN	M	8	PP	X		X			2									X						X				
PP	F	14	PP	X		X			4		X				X			X						X				
LP	M	15	PP		X			X	3			X					X	X						X				
RP	M	18	PP	X		X			1			X												X				
FR	F	13	PP	X		X			2		X						X							X				
JR	M	10	PP		X			X	1			X					X	X						X				
RR	F	7	PP		X	X			1			X					X							X				
JS	F	10	PP	X		X			3			X					X							X				
LS	F	16	PP	X		X			2		X													X				
HS	M	15	PP	X		X			1	X														X				
PVs	F	—	PP										NO OPERATION YET												X			
JW	M	14	PP	X		X			4			X					X	X						X				
			46	30	12	25	9	8	105	5	16	20	0	0	3	0	22	14	0	0	0	1	2	37	4	0	0	0

DIAGNOSIS KEY

I—IDIOPATHIC
PP—PARAPLEGIC

This table represents Group II, or the research group which was supported by a National Foundation grant, and consists of forty-six patients, forty-two of whom were operated on from 1955 to 1960. Note that fusion was used extensively to accomplish better results and that no casts were used. The instrument design and force application became better and greater, and bone erosion increased as well. Instrument fracture became less frequent than in Group I. The number of operations to reach a reasonable result was less in this group than in Group I.

The device includes several component parts, all made of S Mo 18–8 stainless steel. The device is designed to exert (1) a primary corrective force on the curve, using distraction on the concave side and compression on the convex side of the scoliotic spine (Fig. 1) and (2) a supplementary secondary stabilizing force on the lumbosacral spine when indicated (Fig. 4). The distraction rod is a prestressed rod (one-quarter of an inch in diameter). Rods ranging from three and three-quarters to fifteen and three-quarters inches in length, in one-inch increments, are

TABLE III

GROUP III

NAME	SEX	AGE	DIAGNOSIS	FUSION		RESULTS			NUMBER OF OPERATIONS	SEVERITY OF CURVATURE			CAST		COMPLICATIONS												DEATH	REMARKS
				YES	NO	BETTER	SAME	WORSE		MILD	MODERATE	SEVERE	YES	NO	PSEUDO-ARTHROSIS	SURGICAL SHOCK	BONE EROSION	INSTRUMENT FRACTURE	INSTRUMENT DISLOCATION	RADICULITIS	INFECTIONS	METAL REACTIONS	PROGRESSION OF CURVE	ILEUS MILD	ILEUS MEDIUM	ILEUS SEVERE		
R.B.	M	16	I		X		X		2			X		X	X				X					X				
M.B.	F	15	F	X		X			1		X			X														
M.B.	M	30	P	X		X			2		X			X							X							
S.B.	M	13	PP		X	X			1			X		X														
J.B.	F	14	PP	X		X			2			X		X										X				
DaB.	F	10	I		X	X			1			X																
Di B.	F	14	PP		X		X		3			X		X														
D.C.	F	13	I	X		X			1			X	X											X				
J.C.	M	10	PP	X		X			1			X		X										X				
P.C.	M	23	PP	X					2	X				X										X				
L.C.	M	8	EXPIRED—NO SURGERY ATTEMPTED																									
R.C.	M	14	I		X	X			1	X			X															
S.C.	F	6	PP	X				X	1		X			X													X	*
P.De	F	8	PP	X		X			2		X		X															
R.D.	M	16	PP	X		X			2		X		X															*
M.D.	F	57	P	X			X		3		X			X	X						X							
C.F.	F	10	PP	X		X			2			X	X						X				X					*
J.F.	M	32	P	X		X			1	X				X														
L.G.	M	33	P	X		X			1			X		X														
I.G.	F	24	PP	X				X	1			X		X	EXPIRED — DAY 6, POST OPERATION												X	*
R.G.	M	19	PP	X			X		1	X				X														
H.H.	M	22	PP	X		X			1	X				X														
R.H.	F	37	LS	X			X		1					X														
T.H.	M	34	MS	X		X			1		X		X												X			
C.H.	F	55	F	X		X			2	X				X														
P.H.	F	18	I	X		X			1	X				X														
C.H.	F	14	I		X		X		2		X			X			X											
B.K.	M	22	P	X		X			1	X				X														
A.K.	F	18	I	X		X			1			X	X											X				
S.K.	F	20	PP	X		X			2			X		X										X				
L.L.	F	14	I	X		X			1		X		X											X				
M.M.	F	12	PP	X		X			1				X											X				*
D.R.	M	24	PP	X		X			3			X		X										X				
M.R.	F	15	PP		X	X			1			X		X										X				
D.R.	F	35	PP	X		X			2		X		X											X				*
A.R.	F	19	PP		X	X			1					X										X				
B.R.	F	13	PP	X		X			2		X			X			X		X				X	X				
M.R.	F	11	PP	X		X			1		X			X										X				
R.J.	M	45	P	X		X			1		X			X										X				
O.P.	M	18	PP	X		X			1			X		X										X				
G.P.	F	14	PP	X	X		X		3		X						X	X	X									
E.P.	F	40	CH	X		X			2			X		X										X				
K.P.	M	9	PP		X	X			2			X	X											X				*
S.P.	F	15	PP	X		X			1		X		X											X				
F.P.	F	45	PP	X		X			1		X		X											X				
B.P.	F	14	I	X		X			1		X		X											X				
J.P.	F	20	P	X			X		1			X		X	X			X	X									
R.S.	F	17	I	X		X			1		X		X											X				
D.S.	M	18	PP		X	X			1					X									X	X				
A.S.	F	14	I	X	X	X			3			X	X						X	X								
B.S.	F	38	I	X		X			2		X			X										X				
N.S.	F	15	I	X		X			1			X	X											X				
B.S.	F	16	I	X		X			1		X		X											X				
W.S.	M	15	PP	X		X			1		X		X											X				
H.S.	M	35	PP	X			X		2			X		X										X				
G.S.	M	35	P	X		X			1			X		X														
H.S.	M	12	PP	X		X			2			X	X											X				
F.S.	M	20	PP	X		X			1			X		X										X				
B.S.	F	16	I	X		X			1		X			X			X							X				
B.S.	F	12	I	X		X			1			X	X											X				
D.S.	F	17	PP	X		X			1			X	X											X				
R.T.	M	22	SCH	X		X			1			X	X											X				
J.T.	M	20	P	X		X			1			X		X														
K.W.	F	18	I	X		X			1		X		X											X				
G.W.	M	15	PP	X		X			1			X	X											X				
P.W.	F	25	AMY	X		X			1			X	X											X				
S.W.	F	19	PP	X		X			1		X			X										X				
B.W.	M	15	CONG	X		X			1		X			X										X				
L.W.	M	23	PP	X		X			1		X			X														
				59	12	57	9	2	95	8	28	29	26	40	3	0	4	2	6	1	2	0	3	40	1	0	2	

DIAGNOSIS KEY

AMY.—AMYOTONIA
SCH.—SCHUERMANN DISEASE
M.S.—MARIE STRUMPELL
P—PARAPLEGIC
PP—POST POLIO
I—IDIOPATHIC
CH—CHARCOTS DISEASE
F—FRACTURE (UNCOMPLICATED)
L—LUMBO-SACRAL INSTABILITY
CONG.—CONGENITAL

This table represents the patients in Group III—1960. Fusion was performed at the initial correction with instrumentation. Casts were used more frequently. Postoperative management (immobilization) was prolonged. Instrument fracture and bone erosion were greatly reduced.

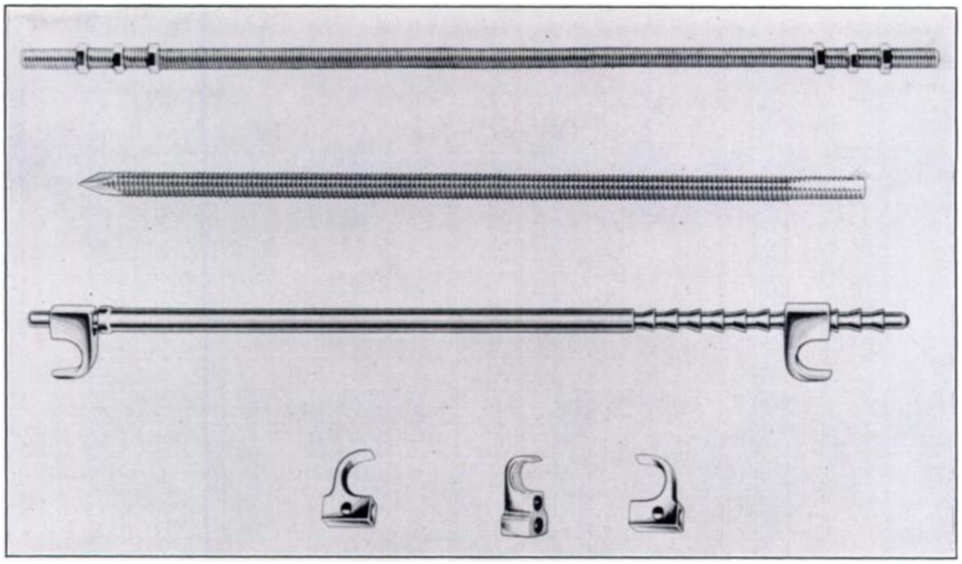

FIG. 1

The basic stainless-steel instruments used to apply compression and distraction forces to the spine. From top to bottom: a threaded rod for the compression system; a sacral bar; a distraction bar with purchasing hooks adjusted by the ratchet principle; and two compression hooks facing each other with a universal hook between them.

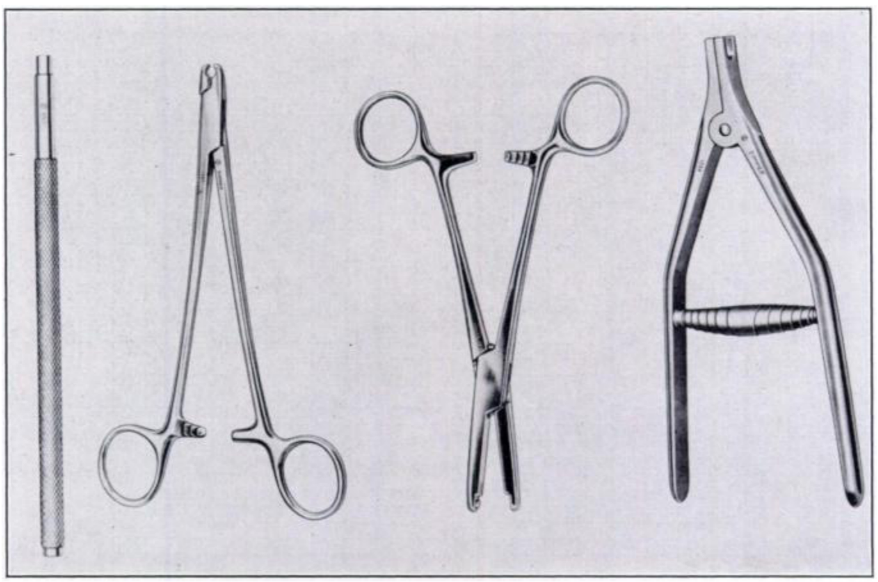

FIG. 2

The application instruments. These instruments are used to insert and to adjust the instrumentation once it is implanted. From left to right are a hook driver, threaded rod holder, hook holder, and spreader.

available. At the lower end of the rod, there is a reduced section three-quarters of an inch long which fits securely in the hole in the inferior hook. At the upper end of each rod there is a series of circumferential grooves so designed that the upper distraction hook will tilt slightly to engage on the shoulder of each groove and hence will not slip down the rod when axial compression is applied to the hooks. The rod therefore provides a ratchet system for progressive distraction of the two vertebrae engaged by the hooks at either end of the rod.

The hooks are one-half an inch thick and have a semicircular notch three-

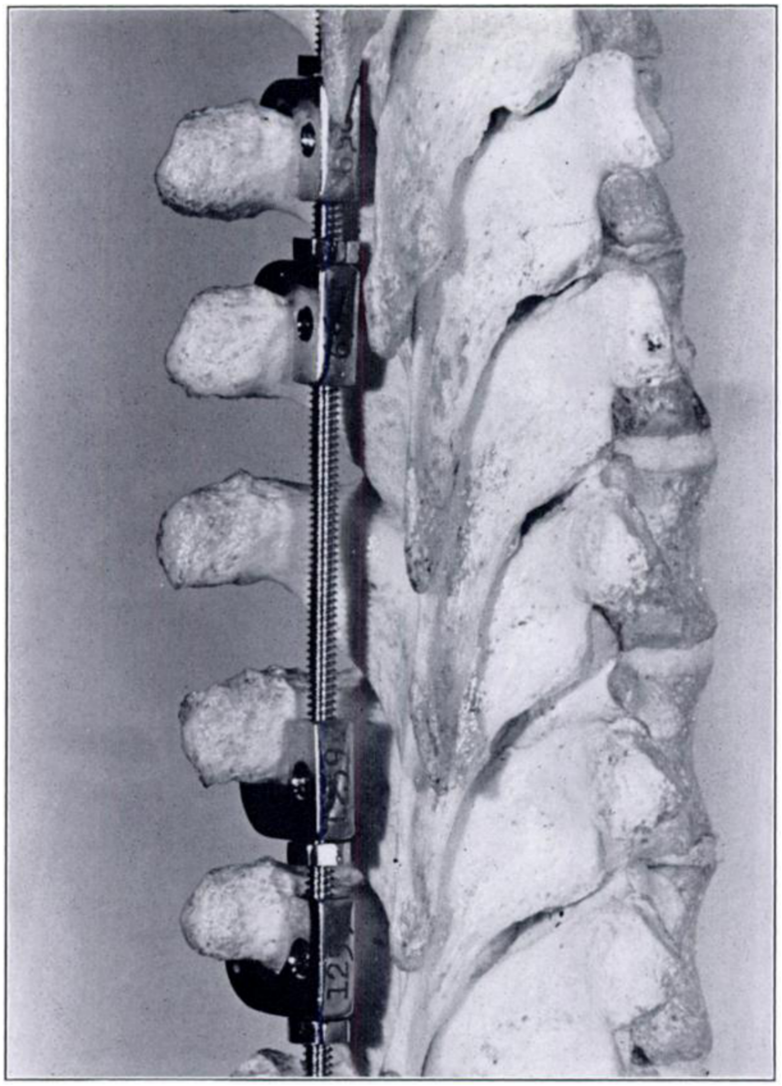

FIG. 3

A four-hook compression assembly properly placed at the base of the transverse processes of four thoracic vertebrae.

eighths of an inch in diameter. There is an axial hole through the hub of each hook; this hole will accept the reduced section of either end of the distraction rod. Another perforation at right angles to the axial hole accepts the stud on each jaw of the handling forceps and makes it possible to hold the hook firmly during insertion (Fig. 2). Within the axial hole of the large hook, there is a small shoulder which will slide over the circumferential ridges of the distraction rods, but which will also engage on the circumferential ridge when the distraction rod is under axial compression. The hook tilts somewhat and holds its engaged position.

The compression device, also of stainless steel (S Mo 18-8), consists of a threaded rod, hooks with axial holes into which the rod fits snugly, and hexagonal nuts of suitable size (Fig. 17). Two sizes of rods are provided, three-sixteenths of an inch and one-eighth of an inch in diameter, respectively. The larger rod is rigid; the smaller one is flexible and can be bent around a curve.

The sacral bar is a threaded rod one-quarter of an inch in diameter with one tip pointed for drilling purposes and a flat surface to prevent it from twisting out of

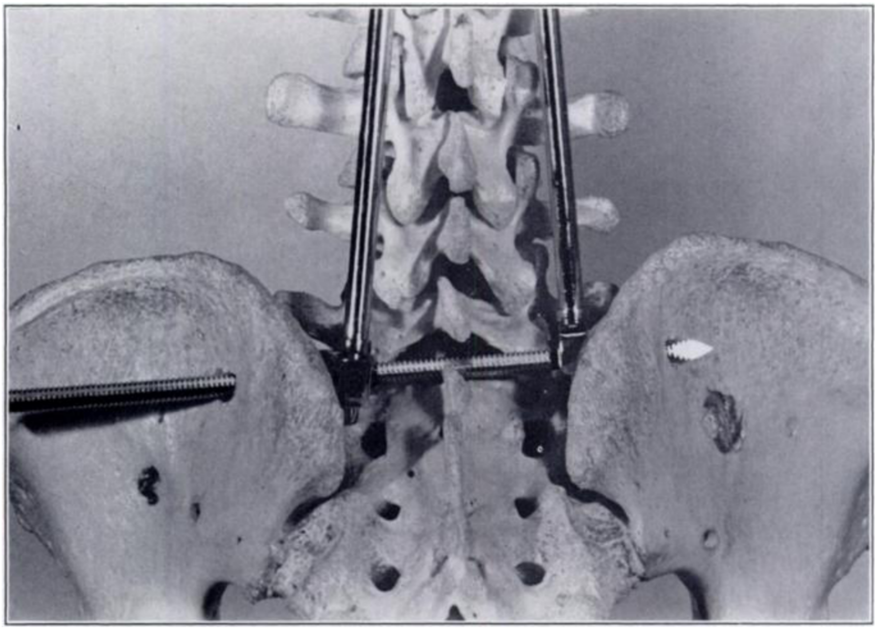

FIG. 4

A sacral bar with two distraction bars attached. Note the left purchasing hook has the hub posterior, whereas the right purchasing hook has the hub anterior. The flat surface on the threaded sacral bar is to prevent the bar from being rotated by the action of the purchasing hooks which are eccentrically loaded by the distraction bars.

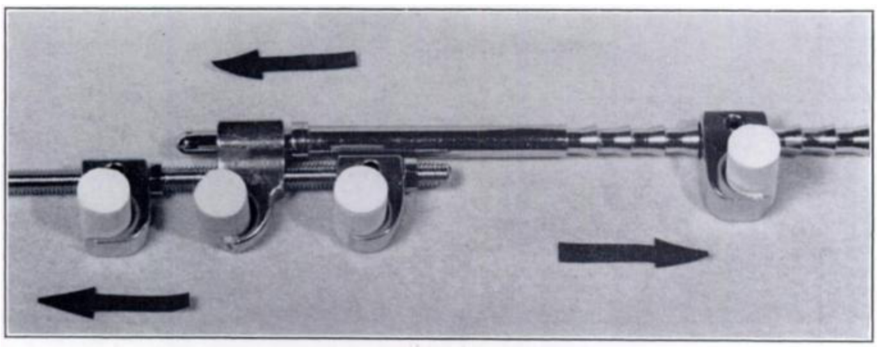

FIG. 5

Schematic representation of the use of a universal hook in the supplementary instrumentation system.

the bone (Fig. 4). Universal hooks are used when a distraction force is to be applied to one curve and a compression force to the adjacent curve on the same side, both forces being applied to the same vertebra (Figs. 5 and 15-B).

The instruments used to hold and manipulate the apparatus (Fig. 2) include a hook driver, a threaded rod holder, a hook holder, and a force-applying spreader.

The manner of application of the device depends in large measure on the location, extent, flexibility, and other individual characteristics of the scoliotic curve to be corrected. The apparatus described may be used for any curve between the first thoracic segment and the sacrum. Either distraction, compression, or both may be applied. The eight-inch distraction rods of the device have a yield point of approximately 400 pounds on axial loading and over 200 pounds on eccentric loading. The actual force which may be applied to a spine is limited not so much by the strength of the device as by the strength of the bone into which or on which the hooks are set. The hooks may be attached to either the laminae,

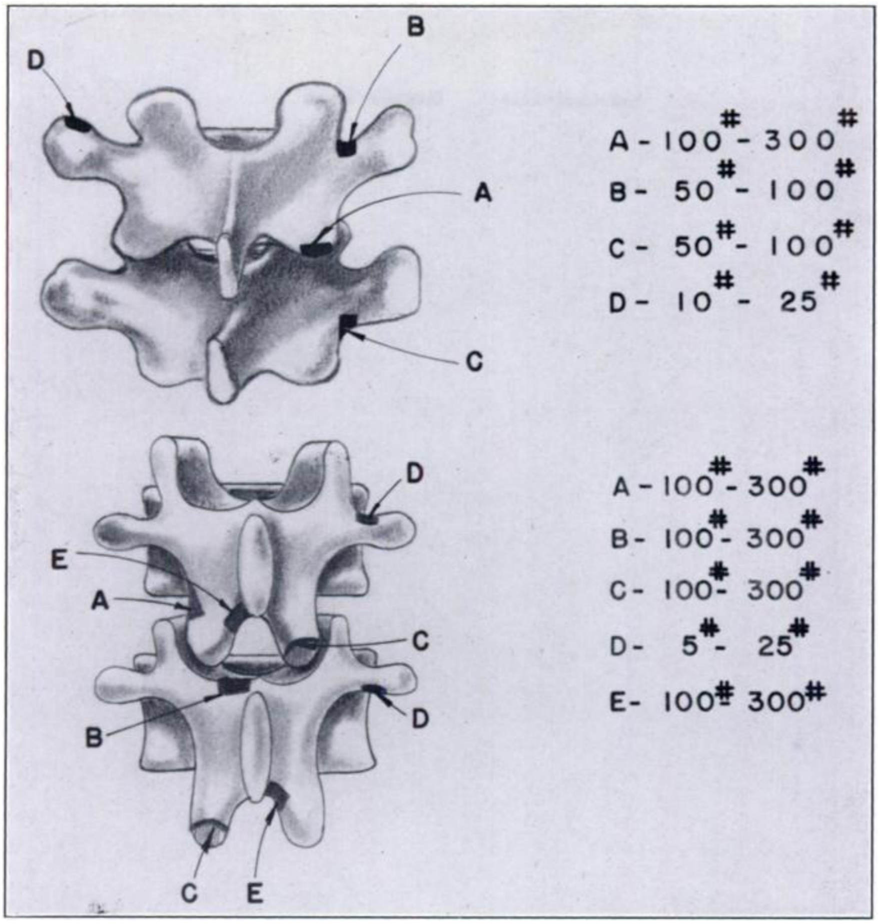

Fig. 6

The purchase sites in the thoracic (above) and lumbar (below) vertebrae used when applying the metallic system for compression or distraction.

transverse processes, or articular processes. These portions of the vertebra have a wide range of strength. The actual amount of force which they can withstand varies between twenty and 300 pounds. In Figure 6, the usual sites of application of the hooks are illustrated with the ranges of compressive and distractional force which each will tolerate. These ranges were established by a dynamometer gauge attached to the force-applying spreader. The values given indicate the order of magnitude of the mechanical strength of those sites where the hooks may be placed. In a given patient, there is no way to measure the load which can be tolerated by specific sites. The surgeon must estimate the degree of compression or distraction he is applying by feel and intelligent observation. Care should be taken not to reach the fracture point of the bone. Fracture of the bone at the site of application of a hook is catastrophic; therefore, the hooks should be carefully seated before correcting force is applied, and the correcting force should not exceed the yield point of the bone. When multiple hooks are used on one compression rod (Fig. 7-B), fracture of bone at one site may not be serious. In this situation, it is not necessary to reapply the hook at a new site, since the other hooks will suffice. The hook on the fractured bone may be left in place but no pressure should be applied to it. In our hands, fracture of bone at purchase sites is infrequent, and the desired pressure can be reached if the surgeon, by feel, applies small increments of pressure to the several purchase points in an orderly sequence

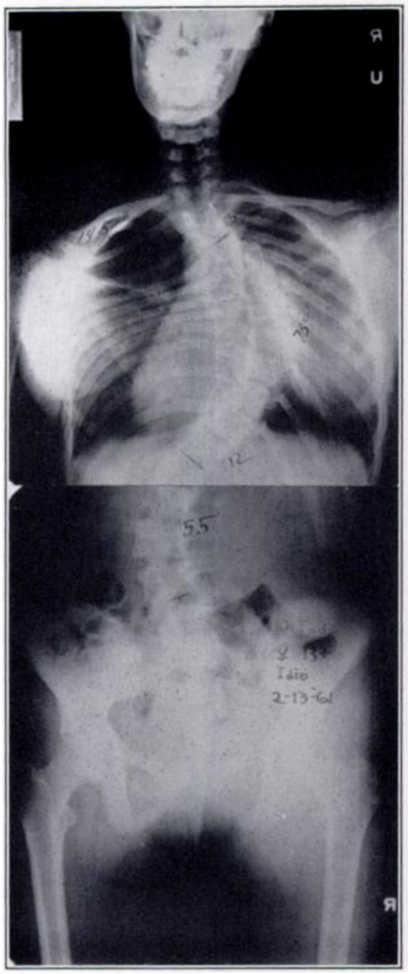

FIG. 7-A

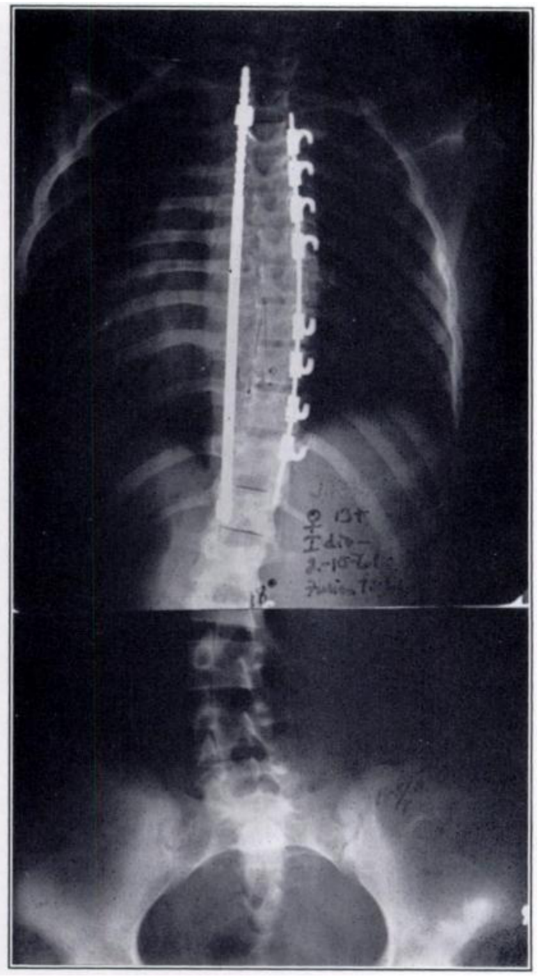

FIG. 7-B

Fig. 7-A: J. T. A standing roentgenogram of a thirteen-year-old white girl with an idiopathic right thoracic curvature measuring 75 degrees and a left lumbar curvature measuring 55 degrees. The Harrington factor (the degrees by the Cobb method divided by the number of vertebrae in the curve) was 8.3 for the thoracic curve and 10.5 for the lumbar curve.

Fig. 7-B: Roentgenogram of patient made in the supine position on the day of operation reveals a compression assembly of eight hooks and a distraction assembly of two hooks correcting the thoracic spine curvature of 75 degrees to 12 degrees. The spontaneous correction of the lumbar curve from 55 to 18 degrees is believed to be the result of altering the geometry of the spine as a whole.

until the combined forces in the whole system are brought to the desired level.

As the distraction force is applied, it encounters resistance from the soft tissues. After a few minutes of constant tension, the soft tissues stretch and more distraction can be achieved until the limit of the elasticity of the soft tissues is reached. When the normal elastic properties of the soft-tissue limits have been reached, a secondary tissue resistance is encountered. Elongation and deformation of this secondary resistance take place within twelve hours by tissue fatigue and microscopic rupture. When this occurs in the instrumentated spine, the abnormal forces which could cause erosion are non-existent. Resorption of bone under the stimulus of too much compression has not been a frequent complication in the recent cases where proper precautions were taken (Fig. 8).

The total force on the spine and on the apparatus is markedly increased by motion and by gravity. Although some erosion of bone is inevitable wherever bone is in contact with metal and under stress, excessive erosion is to be expected

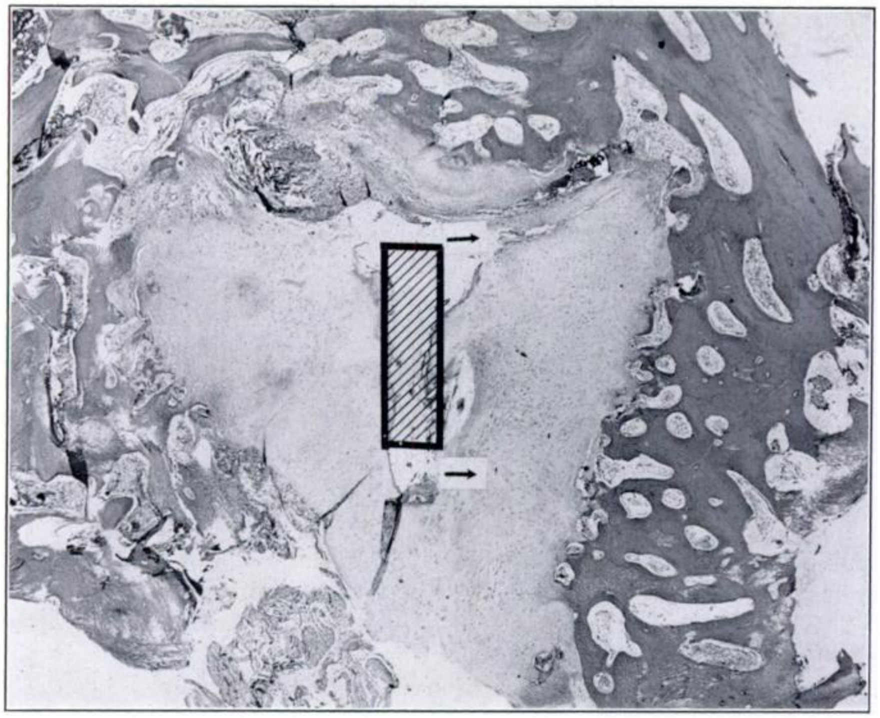

FIG. 8

Photomicrograph of section made through site from which a compression hook was removed six months after correction and fusion. The location of the hook is indicated by the rectangular shaded area; the direction of the pressure is shown by the arrows. Note fibrous tissue surrounding the location of the metallic implant and the increased density of the bone in the area subjected to pressure from the hook (hematoxylin and eosin, × 12.5). Histological studies of the implantation sites of the spine instruments in patients [9] demonstrated that the metallic device was walled off by the fibrous tissue reaction in six weeks, that new bone resembling callus was formed by ten weeks, and that mature firm bone was present by twelve weeks.

only when the stress is increased inordinately. In our patients between 5 and 15 degrees of correction was usually lost because of this erosion. However, if the patient assumed the erect position too soon after operation or moved his back excessively, more erosion occurred.

CLINICAL CONSIDERATIONS

The patients originally chosen for treatment by this new method were predominantly from a group of 3,000 patients with poliomyelitis, 400 of whom had scoliosis. A few patients with idiopathic scoliosis were also included in this early group. During the phase of the investigation ending in 1960, the method was applied to the treatment of scoliosis due to a variety of causes (Table III) and to the treatment of scoliosis of different degrees of severity in patients from four to forty years of age. Even the goal of treatment varied in this latter group. In several patients with amyotonia congenita and paraplegia so treated, the goal was to improve their sitting or standing endurance, whereas the goals of treatment in other patients were improvement of cardiorespiratory function, improvement in appearance, relief of pain, and the like. Because the clinical indications for therapy are still being worked out, they will not be discussed in detail at this time. However, several details in the selection of patients for treatment by this method deserve comment.

When a curve is progressing, I have found that the decision as to when to resort to surgical correction is simplified if a factor of my own devising is used (the

Harrington factor). This factor is determined by dividing the number of degrees of the primary curve, as determined by the Cobb method, by the number of vertebrae in the primary curve. If this factor is five or more, surgical treatment is usually indicated. Thus in the patient shown in Figures 7-A and 7-B, the preoperative factor for the thoracic curve was 8.3 (seventy-five divided by nine) and for the lumbar curve the factor was 11 (fifty-five divided by five), whereas after operation these factors were 1.2 and 3.6, respectively.

The significance of the Harrington factor varies with age. If the iliac epiphysis is still open and further growth of the spine will occur, a Harrington factor of five indicates that the curve will increase. In a young child with an increasing scoliosis and a Harrington factor of less than five and more than three, a Risser localizer jacket or Milwaukee brace will stop progression but rarely correct the deformity. If symmetry is maintained during growth, the spine will remain stable after maturity is reached.

In general, the following rules governing therapy are applicable when treatment with the device described is contemplated:

1. A Harrington factor of 5 or more should be present, with one or more of the following signs or symptoms: progression of the curve (in children); increasing pain or fatigue (in adults); and progressive cardiopulmonary decompensation.

2. The major curve and its transitional vertebrae should be identified on a roentgenogram made with the patient standing unsupported. The number of vertebrae, including the transitional vertebrae, is determined by the Cobb method.

3. The sites where primary and supplementary forces are to be applied are selected before operation. The primary forces, both distraction and compression, are applied to the primary curve. Distraction is applied to the concave side of the upper transitional vertebra or to the vertebra above this and to one or two vertebrae below the lower transitional vertebra. Compression is applied on the convex side to multiple vertebrae between the transitional vertebrae. Supplementary forces are applied to the lumbosacral spine according to the following rule:

Secondary forces are considered supplementary forces and are applied by the following rules relative to the triangle formed by the two lumbosacral facets (composing the base of the triangle) and the centroid of the vertebra being purchased on by the main distraction force:

1. Sacral triangle(isosceles). If the centroid of the vertebra being purchased on by the main distraction force forms an isosceles triangle with the lumbosacral articulation (the apex is over the base), the system will not need supplementation;

2. Sacral triangle (obtuse). If the centroid of the vertebra being purchased on by the main distraction force forms an obtuse triangle with the lumbosacral articulation (the apex is not over the base), the system will need supplementation.

SURGICAL PROCEDURE

This is an extensive procedure which is made possible only by modern surgical techniques and anesthesia. The limitations of the operation and the possible complications should be thoroughly discussed with all concerned before operation is undertaken.

Under endotracheal anesthesia, the patient is placed prone with the spine slightly flexed over lateral chest rolls. After suitable sterile preparation of the skin, the surgical field is covered with an adherent plastic drape; and, after the usual draping, the field is further sealed off with a plastic seal drape.

The usual exposure for spine fusion is carried out with special precautions

TABLE IV

BLOOD LOSS DURING SURGERY

(MEASURED IN CUBIC CENTIMETERS)

NAME	AGE	STAGE I	STAGE II	STAGE III	STAGE IV	STAGE V	SUCTION BOTTLE	TOT. BLOOD SALIVE	NORMAL SALIVE	TOTAL BLOOD LOSS
PH	14	24	212	101	96	128	460	1021	230	791
SP	14	10	205	248	0	105	362	930	350	580
PC	15	28	192	102	0	56	225	603	58	545
PN	15	12	172	100	0	57	485	826	92	734
DW	15	13	68	112	48	112	350	703	454	249
JC	16	14	56	10	10	26	110	226	106	120
HS	16	28	100	45	0	50	462	685	200	485
KK	18	43	164	67	0	38	273	585	195	390
KS	18	10	110	26	0	140	50	336	30	306
LS	19	46	484	196	76	85	1260	2147	710	1437
CF	19	20	243	132	116	26	860	1147	182	1265
PF	20	16	492	218	48	56	900	1730	0	1730
LR	20	20	260	162	30	261	720	1453	330	1123
VH	23	70	290	614	92	260	660	1986	341	1645
KA	25	56	175	74	34	40	664	1043	40	1003
PL	25	24	120	60	36	126	375	741	298	443
RB	26	80	295	215	0	38	550	1178	80	1098
DC	28	56	400	278	34	80	930	1778	670	1108
JW	33	22	174	88	48	36	600	968	648	320
RA	35	5	165	276	32	38	800	1236	610	626
DK	38	14	193	75	48	0	490	820	100	720
CA	39	24	277	288	745	208	1050	2582	498	2084
JT	40	20	174	68	43	54	270	629	114	515
BT	40	17	202	97	47	0	630	993	127	866
AVERAGES		28cc	217cc	152cc	66cc	86cc	564cc	1308cc	271cc	840cc

This table describes the blood loss in cubic centimeters recorded in the five stages of spine instrumentation and fusion on twenty-five consecutive patients. These cases are arranged in order of age to allow age correlation at a glance. Stage I is skin to periosteal dissection. Stage II is subperiosteal exposure of the intended operative site. The minimum exposure was ten vertebrae; the maximum was fourteen. Stage III is instrument application. Stage IV is spine fusion. Stage V is closure of the operative site.

to minimize blood loss. In the thoracic region, the exposure is carried out to the tips of the transverse processes; in the lumbar region the articular processes are fully exposed. By careful subperiosteal dissection, which proceeds beneath the capsule of each right and left posterior articulation, the arteries, veins, and nerves to the paraspinal muscles that emerge through the notch caudad to the inferior articular process of each vertebra can be spared.

Periodically throughout the procedure, the sponges are weighed to determine blood loss and the loss replaced by transfusion. The blood loss recorded in the operations performed has ranged from 200 to 2,000 milliliters (Table IV).

After the exposure is completed the sites for the placement of the hooks are determined by identifying the anatomically unique characteristics of the posterior elements of the twelfth thoracic vertebra. The site for the superior distraction hook is prepared by fashioning a notch (Figs. 9-A and 9-B) in the tip of the inferior articular process of the chosen vertebra. The inferior distraction hook is always seated in a lumber vertebra; the notch for this hook is made through the lamina where it meets the base of the inferior articular process (Figs. 10 and 11). After the notch has been prepared, a one-quarter-inch straight osteotome which is directed caudally and medially is driven through the inferior facet into the corresponding superior articular process of the vertebra below. After the notch has been thus prepared, the hook attached to the driver is driven in at such an angle that its tip enters the superior articular process and the rest of the hook is lodged between the superior and inferior articular processes. If the inferior articular process does not appear to be adequate to hold the hook, a notch can be prepared in the superior border of the lamina just lateral to the base of the spinous process. When this site is used care must be taken not to injure the dura.

Once the hooks for the distraction apparatus are in place, the previously

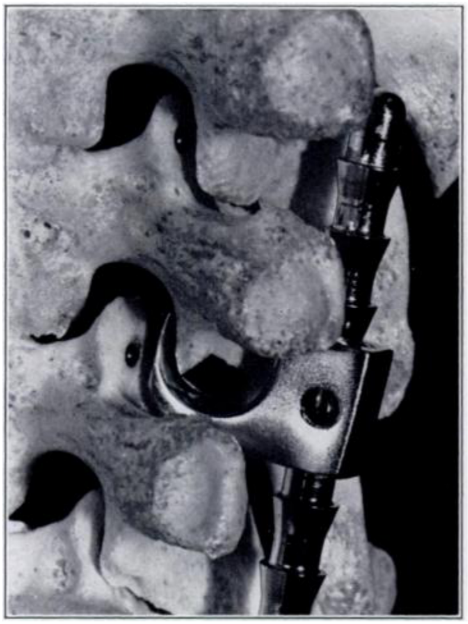

FIG. 9-A

FIG. 9-B

Fig. 9-A: Lateral view of several thoracic vertebral segments showing the relationship of the upper distraction hook, the ratchet rod, and the articular processes where they are engaged. The notch of the hook is inserted into the margin of the inferior articular process in the black shaded area within the notch of the hook in this picture.

Fig. 9-B: Posterior view of the upper distraction hook and ratchet rod in position on the thoracic spine.

FIG. 10

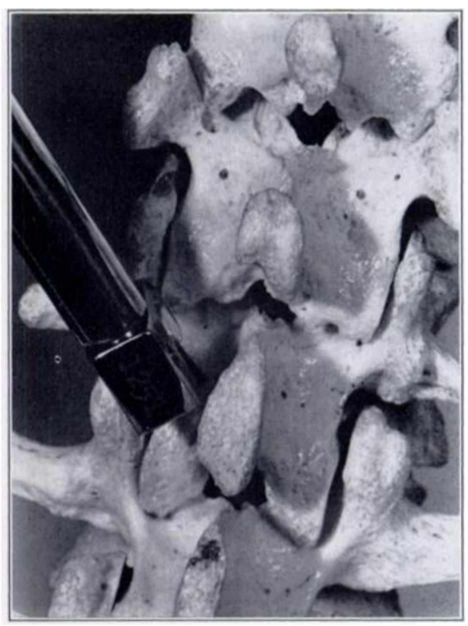

FIG. 11

Fig. 10: Posterior view of the lumbar spine to show location of the osteotomy that is made in the posterior cortex of the inferior articular process to allow insertion of the lower distraction hook.

Fig. 11: Posterior view of the lumbar spine and distraction hook on a driver showing the direction in which the hook is driven into the previously prepared notch (Fig. 10) in the inferior articular process. It is essential that the hook be driven in at the proper angle.

selected sites for the compression hooks are prepared. Each hook is held rigidly in the hook holder and dissected into place around the base of the appropriate transverse process as close to the pedicle as possible. The sharp edge of the hook makes it possible to dissect the costotransverse ligament off the bone as the hook is worked into place. Once in place, the hook holder is removed and the hook is left *in situ* for orientation when the compression assembly is inserted. At the caudad end of the compression system, the hooks are frequently on lumbar vertebrae. Here the hooks are inserted under the laminal arch or under the tip of the inferior articular process of the vertebra selected. A hook is never placed in a lamina directly over the spinal canal except below the level of the second lumbar vertebra because of the risk of penetration of the dura in the region of the caudal extremity of the spinal cord. When all the compression hooks are in place, a compression rod with nuts and hooks at the appropriate levels is assembled (Fig. 3) using the large rigid or small flexible rod as indicated. Starting at the top, the previously placed orientation hooks are removed, and the hooks on the compression assembly are inserted serially. At first this procedure may prove difficult. If the direction of insertion of the previously placed orientation hooks is kept in mind, the procedure is simplified. When the hooks on the rod are introduced they should be kept in exactly the same position as the orientation hooks. Also if the hooks used for orientation are inserted several times first, it is easier to place the less easily adjusted hooks that are on the rod. During insertion of the compression assembly each hook is held by the holder while the threaded rod is held in the holder designed for this purpose (Fig. 2). The rod holder is particularly useful to hold the assembly after the upper hooks have been placed and the lower hooks are being put in position. It is most disconcerting to work a set of hooks into place only to find that they have slipped out during the placement of other hooks. With a little planning before the compression assembly is inserted and practice the procedure is not difficult. Initially an assembly with two or four hooks should be used. Once the insertion of such an assembly is learned, the reward of the greater correction and stability afforded by multiple hooks is too attractive not to invite the use of the maximum number of compression hooks on every compression assembly that is inserted.

As soon as the compression apparatus is in place, the hooks are moved to the tight position by advancing the hexagonal nuts. At this point the wound is irrigated and the placement of all apparatus reviewed prior to the most gratifying phase of the operation, the application of the corrective forces.

The first step is to prepare for the application of the distraction force. This is done by threading a distraction rod of proper length through the hole in the previously placed superior hook in a cephalad direction until the inferior end of the rod engages the lower distraction hook. As this is done it should be noted if the rod will block access to the posterior articulations on the concave side of the curve. If it appears that these joints will be covered by the rod and spine fusion is thought indicated, a fusion of the facet-block type [13] is performed on this side before the rod is placed. The articular surfaces are gouged out and grafts from the spinous processes are placed in the defects so created. The fusion procedure completed, the lower end of the ratchet rod is firmly seated in the lower hook and distraction is applied using the spreader (Fig. 2). The curve is corrected slowly, one notch at a time. In doing this the surgeon must develop a sense of the proper amount of force to be applied; and, as distraction is accomplished, he must observe the hooks to make sure that they do not slide before they become firmly seated. Once well seated, they do not as a rule slide if the upper ratchet hook has been well seated. However, if shifting or sliding does take place, a loop of wire is placed

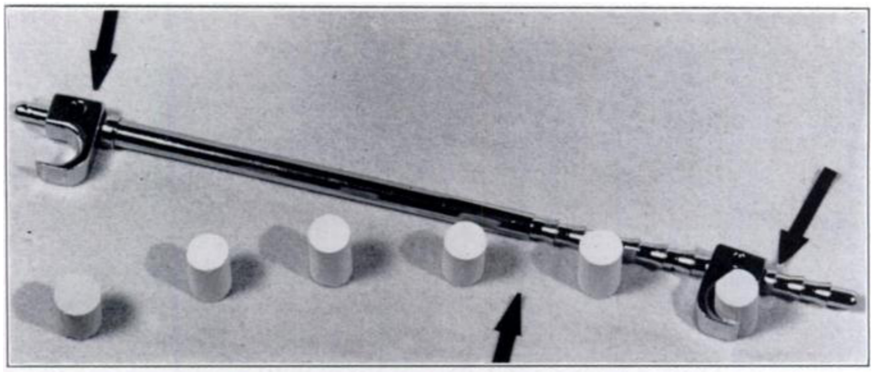

FIG. 12

Schematic representation of the distraction assembly being applied to a kyphotic deformity. The white cylinders represent ribs; the arrows indicate the forces involved in the placement of the assembly in proper position.

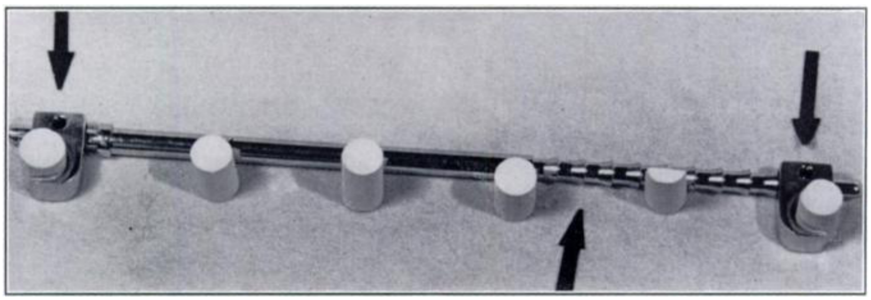

FIG. 13

Schematic representation of the distraction assembly in place on a spine with a kyphotic deformity (compare with Fig. 12). The assembly is manipulated into the correct position by springing it downward and engaging both hooks or, if need be, by osteotomy (as indicated by the half cylinder) of one or more ribs to provide room to displace the rod forward bringing the hooks into the desired position.

around the hook and corresponding spinous process to prevent further displacement. The lower distraction hook is particularly prone to slide and should be watched closely. This is the weakest feature of the whole procedure. A new device is being designed to provide a more secure purchase on the lumbar articular process. It should be noted here that an apparently insurmountable problem may arise during the placement of the distraction rod in severe scoliosis with some kyphosis. Here the deformed ribs at the apex of the curve on the concave side may hold the lower end of the distraction rod several inches away from the inferior hook as the rod is inserted through the upper hook (Fig. 12). One possible solution to this problem is to lever the rod down over the ribs once the upper ratchet hook has been well seated. However, if the upper hook is not seated firmly or if the force applied is too great, the facet and lamina in which the upper hook is engaged may break as the surgeon attempts to pass the rod through the hole in the caudad hook. The anesthetist can often help by lifting the head and shoulders of the patient until the rod has been inserted into the hole in the inferior hook and the distraction force adjusted. If difficulty is still encountered, osteotomy of one or two of the prominent ribs can be done (Fig. 13). Another way to overcome this difficulty in a severely scoliotic patient is to start with a short distraction apparatus near the apex of the curve and then introduce a second longer distraction system once the initial one is well seated and the curve partially corrected.

The distraction and compression systems are tightened gradually in orderly sequence until both mechanisms are tight. The wound is then irrigated; and the

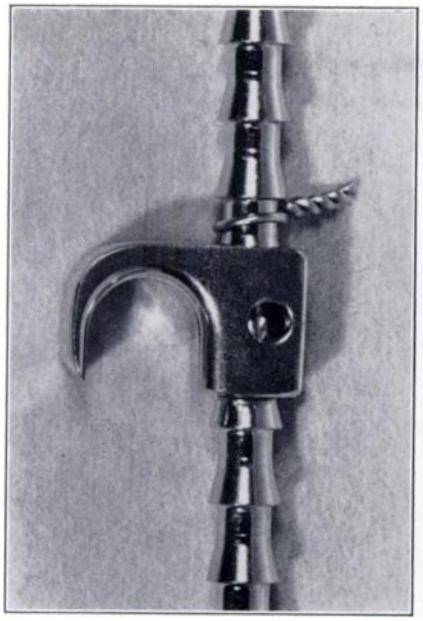

FIG. 14-A

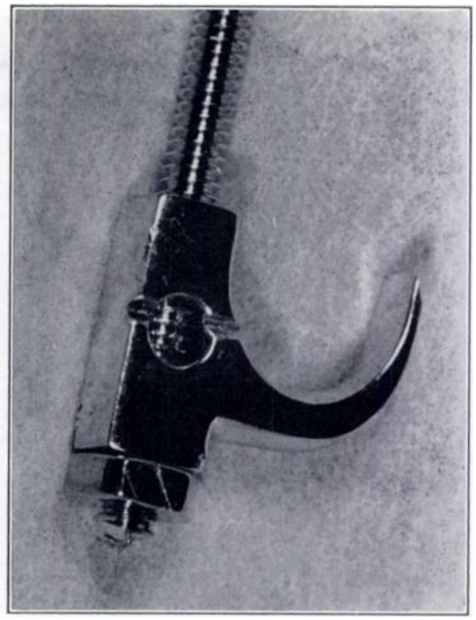

FIG. 14-B

Fig. 14-A: Distraction hook and ratchet rod showing locking wire in place.
Fig. 14-B: Photograph of compression hook and threaded rod after the hook has been crimped and the rod has been cut close to the hexagonal nut to lock the hook in position.

patient's trunk is twisted and shifted from side to side, and the moderately flexed table is straightened. After several minutes have passed, the entire mechanism is readjusted. Care must be taken at this point not to fracture any of the sites of purchase. When the system is found to stay tight, the operator attempts no further correction. At this point all the assembly hooks are locked by crimping the hooks of the compression assembly (Fig. 14-A) and by using a loop of wire to lock the ratchet of the distraction device (Fig. 14-B).

The surgeon must now decide whether spine fusion is to be performed to supplement the instrumentation. If the patient's condition will withstand the additional surgical procedure and if a fusion has been contemplated preoperatively, a Hibbs type of fusion should be done. If it is decided not to fuse the spine at this time, the wound is closed.

If supplementary stabilizing forces are necessary, as indicated by the presence of an obtuse sacral angle, as previously described, the sacral bar and distraction rods are introduced. These supplementary forces are not corrective but are used to hold the lower spinal segments in a stable position (Fig. 4). The lumbosacral junction should always be exposed well to allow a three-dimensional visualization of the region as the sacral bar is introduced through a stab wound in one buttock. The sacral bar is inserted with a motor-driven drill. The sharp point of the bar makes it possible to insert it accurately in the uneven inclined surface of the ilium; and the threads of the bar advance it in the proper line, preventing any shift in the direction of the bar once it is introduced. There is a flat side on the sacral bar to prevent torsional working caused by the hook of the distraction apparatus. The application of the sacral bar and its relation to the distraction bars which are attached to it are illustrated in Figure 4.

A universal hook is used, as already described, when overlapping distraction and either a compression or a stabilizing force are needed. The overlap of the two devices must extend for at least four vertebrae or the spine with the attached

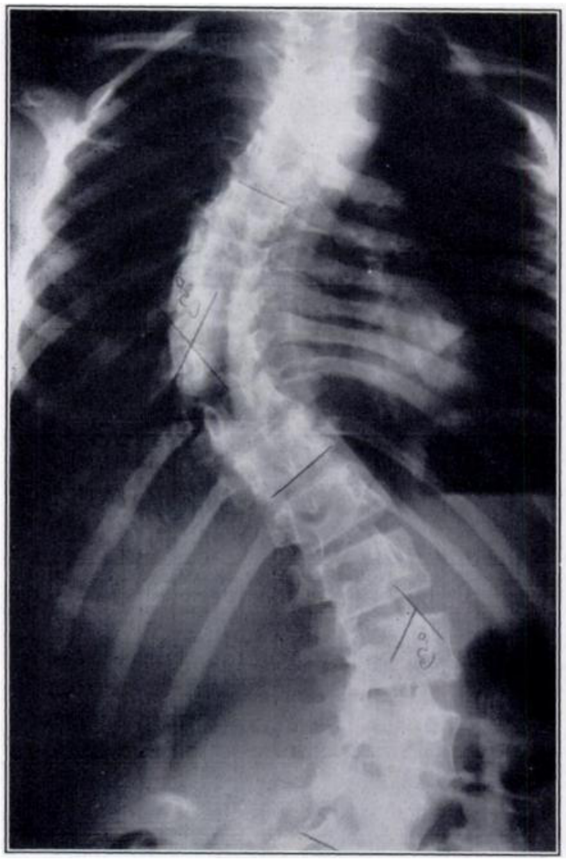

FIG. 15-A

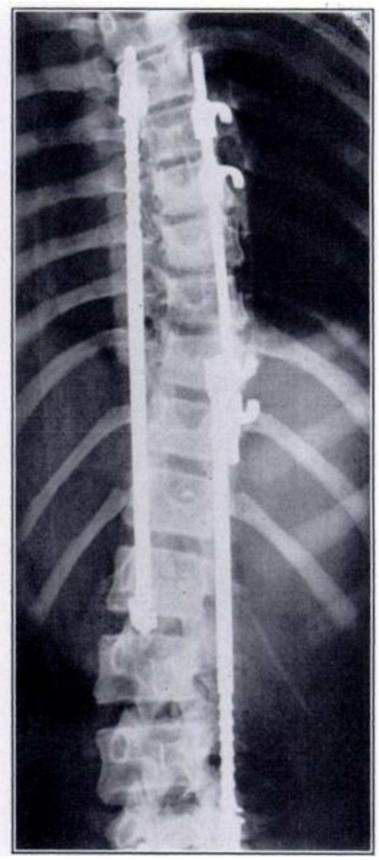

FIG. 15-B

Fig. 15-A: L.L. Postero-anterior roentgenogram of a right thoracic left lumbar idiopathic scoliosis in a girl, thirteen years old. The thoracic curve is 65 degrees and the lumbar curve is 65 degrees as measured by the Cobb method.

Fig. 15-B: Postero-anterior roentgenogram after correction by spine instrumentation using compression and distraction assemblies on the thoracic curve and a distraction device on the lumbar curve with overlapping of the compression and distraction devices on the right side of the spine accomplished by means of a universal hook. Spine fusion was performed from the fifth thoracic to the fourth lumbar vertebra.

apparatus will buckle posteriorly at this point. In a paralytic spine, more extensive instrumentation must be used to prevent tilting of the spine at the upper or lower end of the apparatus.

At the conclusion of the operation, an elastic adhesive compression bandage, laminated over foam rubber (one-half of an inch by three inches by the length of the wound), is applied and left in place for at least five days. A roentgenogram is obtained and the patient is kept supine for six hours; he may then be gently logrolled to either side at regular intervals. This is the patient's only activity until the tenth to fourteenth day, when the sutures are removed and a well molded plaster body cast is applied. After a few days of adjusting the cast, the patient is sent home. Recumbent posture is maintained with logrolling for an additional six to eight weeks. The patient is then allowed to stand and walk for a few minutes in his cast, maintaining erect posture, three times a day. Sitting is not permitted. The activity time is doubled at five-day intervals until a period of forty minutes of walking and standing three times a day is reached. The patient may then sit for meals and toilet necessities and start walking half a mile three times a day. A roentgenogram of the spine with the patient standing in the cast is obtained in the anteroposterior plane and compared with the immediate postoperative

FIG. 16-A

FIG. 16-B

Fig. 16-A: C.B. Postero-anterior roentgenogram of a severe idiopathic curve in a girl, fifteen years old.
Fig. 16-B: Preoperative photograph made in 1958.

roentgenogram. If more than 10 degrees of correction is lost, the cast is kept on an additional month in patients under fifteen years of age. Patients from fifteen to twenty-five years of age wear the cast a minimum of four months; those from twenty-five to thirty-five, a minimum of five months, with reasonable activity as time progresses. After removal of a cast, restricted activity is allowed for three months and reasonable activity (no athletics or physical education) for an additional three months, when a roentgenogram should reveal the final results.

RESULTS

The purpose of this article is to describe a method for the treatment of scoliosis indicating how the method has been developed and improved rather than attempting to analyze the results obtained. The over-all results of the treatment of scoliosis can only be evaluated by considering many factors. In the present series with the many modifications of the apparatus introduced, the inevitable difficulties attendant upon the development of any new surgical procedure of this magnitude, and the variety of conditions treated, a true evaluation of the results is not as yet possible. Three illustrative cases are shown in Figures 7-A, 7-B, 15-A, 15-B, and 16-A through 16-G. The results were graded roughly according to the following system.

The patient was considered *better* if the curve was decreased; if progression of the curve in a child was arrested; if function was improved (improved tolerance

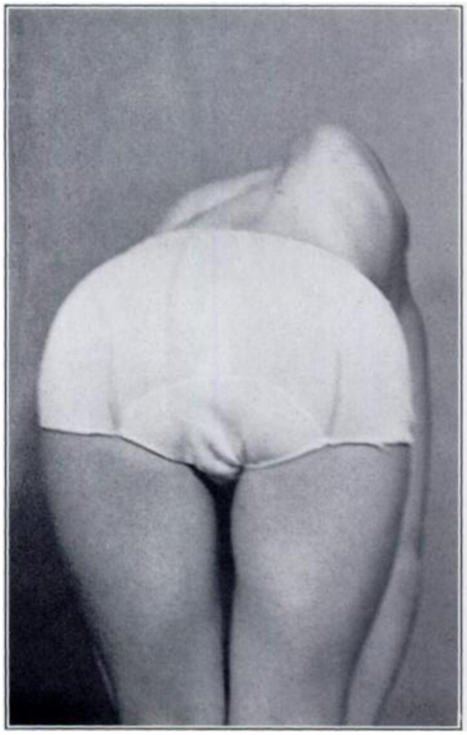

FIG. 16-C

FIG. 16-D

Fig. 16-C: Preoperative photograph of the sabre-back deformity in flexion.
Fig. 16-D: Postero-anterior roentgenogram made in 1958 after correction by instrumentation and spine fusion. The patient was supported in a body jacket after operation, and in 1959 a rib resection was performed.

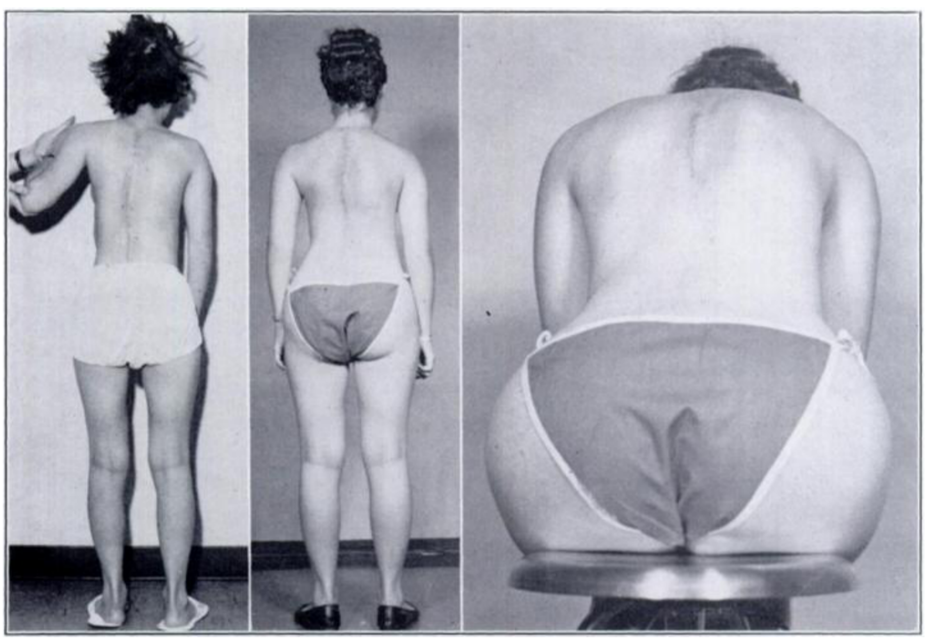

FIG. 16-E FIG. 16-F FIG. 16-G

Fig. 16-E: Photograph made in 1958, twelve days after operation.
Fig. 16-F: Standing photograph made in 1960.
Fig. 16-G: Photograph made with the patient sitting in flexion to show residual back deformity.

for activities of living and decreased instability of the back); if fatigue, pain, and respiratory distress were reduced; and if the psychosocial effects of the deformity were reduced.

The patient was rated the *same* if some of the aforementioned benefits were realized but they were offset by persistent imbalance, lack of functional improvement, persistence of fatigue, and so forth.

The patient was judged *worse* if secondary curves developed requiring repeated surgical procedures or if there was failure of the apparatus, bone erosion, or progression of the secondary curves. Also included in this category were the two patients who died.

TABLE V

GROUP I-II-III

	CASES	AVERAGE OPERATIONS	FUSION	NO FUSION	INSTRUMENT FRACTURE	ERO-SION	BET-TER	SAME	WORSE
GROUP I	19	3.0	12	5	11 58%	10 52%	11 58%	5 26%	3 16%
GROUP II	42	2.4	30	12	14 33%	22 52%	25 59%	9 21%	8 20%
GROUP III	68	1.3	58	10	2 3%	4 6%	57 84%	9 13%	2 3%

This table correlates the pertinent results in all three study groups. It reveals that spine fusion combined with instrumentation and prolonged immobilization in a plaster jacket (Group III) gave better results than those obtained with no cast and no immobilization in Groups I and II. The results indicate that spine instrumentation is a useful tool in the treatment of spine instability.

The results graded according to this system during the different phases of the development of the apparatus are indicated along with the complications in Tables I, II, and III. The over-all trend of the results is shown in Table V. The legend of Table V explains the advantage of initial fusion and postoperative cast immobilization.

The complications encountered in the patients treated so far are also indicated in the tables, but they deserve special mention. Two deaths occurred in the total series of 129 cases, the first due to obstructive bronchial edema four hours after intubation, the second six days after operation as a consequence of cardiac failure and cor pulmonale of nine months' duration. Breakage of the bar occurred in eleven of the first nineteen patients (Table I). With the redesigning of the instrument, breakage occurred in four of the forty-six patients in the second series (Table II); with the bars as now made, there were only two instances of breakage in the last fifty-nine patients. The other complications are also listed in the tables; they include pseudarthrosis after attempted fusion, dislocation of the hooks, radiculitis, progression of the secondary curve, and bone erosion at the site of purchase of the hooks. Some of these complications might be expected with this type of treatment; others might occur with any type of surgical treatment of scoliosis.

DISCUSSION

The results in the three groups show a gratifying improvement associated with increasing experience and refinement of the apparatus. With the newer apparatus and longer periods of immobilization after operation, the incidence of complications and instrument failure have been markedly reduced. It is significant that in the last group, spine fusion at the time of spine instrumentation was performed more frequently.

On the basis of my experience to date, I believe that a progressive scoliosis in a child less than ten years old can be managed with the apparatus alone without fusion, whereas in a child more than ten years old fusion should usually be done at the time of the initial correction. No form of treatment including the method described here with or without spine fusion can be considered definitive in a child whose axial skeleton is still growing.

The techniques, criteria for use, and the problems of metallic instrumentation of the malformed or unstable axial skeleton have been presented. Results have been given in table form by recording a simple classification of the results and the frequency of observed complications. The general conclusions from experience in the use of this surgical method in 129 patients over a period of eight years are:

1. The axial skeleton can be gratifyingly corrected from a malformed state in a growing child and adult by a prestressed metallic system in direct contact with it;

2. The axial skeleton can be stabilized by a prestressed metallic system in direct contact with it, especially if spine fusion is performed within the span of the instrumentation;

3. Metal (S Mo 18–8) is tolerated in the body and can be used in direct contact with the axial skeleton for a reasonable length of time (one to five years);

4. A sincere respect for the extent of the surgery required to apply instrumentation demands an organized procedure by a trained surgical team;

5. The importance of postoperative management must be fully realized and a program of management provided which takes into account the etiology of the condition and the period of active growth remaining. A well molded plaster-of-Paris body cast should be applied after surgery for twelve weeks or longer in almost all cases.

Complications occur, but they are correctable and have been minimized with time through changes in design, alterations of postoperative immobilization, and refinements in surgical technique. The rules of application are simple and all-inclusive. They apply to the spine from the first thoracic segment to and including the pelvis. The variables of age (four to forty years), etiology (paresis, idiopathic, or congenital), and time (growth) only add to the complexity of the problem. The extent to which a patient can be benefited lies within a total understanding of the problem (disease process) by the surgeon and the patient. Good results are the reflection of effort and understanding applied through a prolonged period of time.

SUMMARY

A new method for the treatment of scoliosis is described in which a metal system of rods and hooks is implanted, and distraction and compression forces applied, to correct the curve and stabilize the treated segments in the corrected position by skeletal fixation. The technique and principles of this method of treatment and a summary of the preliminary results obtained are given.

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Traumatic Arthritis of the Hip after Dislocation and Acetabular Fractures: Treatment by Mold Arthroplasty: AN END-RESULT STUDY USING A NEW METHOD OF RESULT EVALUATION

WILLIAM H. HARRIS
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Traumatic Arthritis of the Hip after Dislocation and Acetabular Fractures: Treatment by Mold Arthroplasty

An End-Result Study Using a New Method of Result Evaluation*

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Arthritis of the hip secondary to trauma severe enough to produce dislocation of the hip or fracture of the acetabulum presents a problem in treatment which may be compounded by avascular necrosis of the femoral head, sciatic-nerve involvement, severe disruption of the acetabulum, and serious musculoskeletal injuries in other parts of the body. These adverse features are frequently offset, in part, by the absence of systemic disease, the relative youth of the patients who usually have this condition, and the fact that, as a rule, only one hip is involved.

The usual operative treatment is either hip fusion or arthroplasty. In order to judge the efficacy of these two therapeutic measures, long-term end-result studies in large series are necessary, but no such studies have been reported. Waring and Anderson found the best results after Crawford Adams cup arthroplasties in twelve patients, but the traumatic arthritis and avascular necrosis in some of their patients followed femoral-neck fractures. Stewart and Milford, in their series of fracture-dislocations, had nine cup arthroplasties and eleven fusions. Of the other recorded cases of traumatic arthritis treated by mold arthroplasty, Stinchfield and Carroll had two, Law ten, and Aufranc and Sweet nine. (These nine cases are included in the current report.)

In Westerborn's paper on the use of mold arthroplasty in six cases of central dislocation, the longest follow-up was three years. Kelly and Lipscomb in a study of eight cases of posterior dislocation of the hip with associated fracture of the femoral head, found that primary mold arthroplasty yielded satisfactory results in seven.

Rowe and Lowell in their study of fracture of the acetabulum at the Massachusetts General Hospital found twelve patients with traumatic arthritis. Of these twelve, eight were treated by cup arthroplasty, two had spontaneous fusions, and two had surgical fusion. Three of the eight treated by cup arthroplasty were ward patients and were not included in this report; the other five were included.

Lipscomb and McCaslin reported eighty-four fusions for traumatic conditions of the hip but they included patients with slipped epiphysis, avascular necrosis, ununited fractures of the hip, and failure of arthroplasty. Stinchfield and Cavallaro did not include any cases of traumatic arthritis in their series of fusions and Watson-Jones and Robinson did not identify the cases of traumatic arthritis in their report. Stone and Mortens and Jensen included only one case of traumatic arthritis each in their series.

This study reports the follow-up results of thirty-nine mold arthroplasties in a consecutive series of thirty-eight private patients with traumatic arthritis of the hip treated at the Massachusetts General Hospital between 1945 and 1965. Only private

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patients were included in order to reduce the variables attributed to the individual surgeons. Only three surgeons were involved in these thirty-eight cases (M. N. Smith-Petersen, Otto E. Aufranc, and Morton Smith-Petersen).

Methods and Materials

In this series, only patients with fractures of the acetabulum, dislocations of the hip, or both were included. Patients with femoral-neck fractures and their sequelae were excluded since, for a variety of reasons, including age of the patient, other skeletal diseases, and associated debilitating diseases, these patients present a different problem. Patients who had pre-existing disease or hip symptoms were also excluded, as were patients who had had other forms of hip reconstruction prior to their mold arthroplasty or who had a mold arthroplasty done elsewhere.

A recent follow-up examination was made of thirty of the thirty-eight patients. Five of the current examinations were performed by other orthopaedic surgeons because the patients lived at a great distance. Of the eight patients who were not seen recently, three had died and five were lost to follow-up. The last recorded data on these patients obtained, respectively, at one, one and one-half (three patients), two, two and one-half, four and one-half, and five years after operation were used in this analysis.

Preoperative and postoperative data for all patients were analyzed by the methods of Shepherd [15,16] and Larson and also by a new method for the assessment of the results of hip surgery.

Method of Result Evaluation

The new system was formulated in an effort to encompass all the important variables into a single reliable figure which is both reproducible and reasonably objective. The system was also designed to be equally applicable to different hip problems and different methods of treatment.

The Shepherd system [15] is difficult to use because it does not integrate function with motion and because it does not assign a single over-all value for the rating. Comparison of the status of different patients or of the status of the same patient at different times is complex. Recognition of the inability to resolve the data into one rating is implicit in having two separate rating categories, namely, rating *as a hip* and *as an arthroplasty.*

The Larson system [10], although it does give a single over-all rating figure, appears to favor arthroplasty over other procedures and to lack sensitivity. For example, it is possible for a patient to obtain ninety-eight of one hundred possible points and yet require the use of a cane full time. Only six points are deducted for the use of two crutches full time.

Rationale of New Method of Evaluation

Pain and functional capacity are the two basic considerations. They constitute the indications for surgery in the vast majority of patients with hip problems, and hence receive the heaviest weighting. In specific cases, correction of deformity or restoration of motion may be of prime importance but such cases are uncommon.

Based on this reasoning a point scale with a maximum of 100 points is used with the following maximum possible scores:

Pain	44
Function	47
Range of Motion	5
Absence of deformity	4
Total	100

The gradations of pain, because of its subjective nature, are inevitably imperfect but the following gradations have proved workable and satisfactory:

Amount of Pain	Description	Points Allotted
None		44
Slight	Occasional ache or awareness of pain of low grade, no compromise of activities	40
Mild	No effect on average activities, rarely may have moderate pain following unusual activities, may take aspirin	30
Moderate	Pain tolerable but patient makes concessions to his pain, some limitation of ordinary activities but able to work regularly, may require pain medicine stronger than aspirin occasionally	20
Marked	Severe pain at times, but ambulatory; serious limitation of activities; takes pain medicine stronger than aspirin usually or frequently	10
Disabled	Severe pain even in bed; pain forces patient to bed; crippled by pain; bedridden	0

Although patients do not describe their pain exactly in these terms, reasonable assessment of the level of pain can be made with these guidelines.

Function is broken down into daily activities (fourteen points) and gait (thirty-three points). Although many functional activities could be graded, the following selected tasks give a very satisfactory profile.

	Daily Activity	Points Allotted
Stairs	Foot over foot without use of banister	4
	Foot over foot using banister	2
	Stairs in any manner	1
	Unable to do stairs	0
Transportation	Able to enter public transportation	1
Sitting	Comfortable in any chair for one hour	5
	Comfortable in a high chair for one-half hour	3
	Unable to sit comfortably in any chair	0
Shoes and socks	Puts on socks and ties shoe with ease	4
	Puts on socks and ties shoe with difficulty	2
	Unable to put on socks or tie shoe	0

Gait presents a problem in assessment. Excluding pain, which is considered separately, gait can be characterized in terms of support, limp, and distance that can be walked. Because the support needed and the amount of limp depend on the distance walked in certain cases, gait assessment is based on the support necessary to walk six to nine blocks (about one mile) and the appearance of the gait after walking this distance. Eleven points are assigned each to limp, support and distance walked.

Gait

Description	Points Allotted
Limp is rated as follows:	
None	11
Slight	8
Moderate	5
Severe	0
The support required to walk comfortably and smoothly is rated as follows:	
None	11

Single cane for long walks	7
Single cane most of the time	5
One crutch	3
Two canes	2
Two crutches	0
Not able to walk at all	0 (must specify reason)

Distance walked is rated as follows:

Unlimited	11
Six blocks	8
Two or three blocks	5
Indoors only	2
Bed and chair	0

The Trendelenburg test is obviously an important way to assess one aspect of hip function. It is recorded but not rated in this system, because, in a sense, it is a static rather than a dynamic test. It is possible for many patients to demonstrate a single negative test and yet be unable to walk without a Trendelenburg gait after the first few steps. What the patient can do functionally, as recorded in the rating of gait, is more important than the test itself.

Motion is important only as it affects function. Therefore, in this analysis motion in itself is given minor emphasis, with a maximum possible score of only five points out of the one hundred. Gade maintained that only active motion is significant but one has only to observe a paraplegic standing and then sitting down, to realize the importance of passive motion under certain circumstances.

All types of motion are not of the same utility. Ferguson and Howorth introduced the idea of rating certain motions preferentially, using an index factor and Gade pointed out that the first 45 degrees of flexion is of decidedly more value than the arc from 90 to 130 degrees. However, in Gade's system a patient could have flexion from 0 to 90 degrees, abduction to 15 degrees, internal rotation to neutral from 15 degrees of external rotation, and adduction to 10 degrees—an extremely useful range of motion—and still receive only sixty out of the possible one hundred points which he allots for motion. For this reason a more specific rating of the range of motion is used here with more emphasis on the functionally important aspects of motion.

	Arc of Motion		Index	Maximum Possible Value
Flexion	0–45°	(45°)	1.0	45
	45–90°	(45°)	0.6	27
	90–110°	(20°)	0.3	6
	110–130°	(20°)	0.0	0
Abduction	0–15°	(15°)	0.8	12
	15–20°	(5°)	0.3	1.5
	20–45°	(25°)	0.0	0
External rotation in extension	0–15°		0.4	6
	Over 15°		0.0	0
Internal rotation in extension	Any		0.0	0
Adduction	0–15°		0.2	3
	Over 15°		0	0
Extension	Any		0	0

Total Motion Point Value = 100.5

To determine the rating for motion the number of degrees of motion in each designated arc is multiplied by the corresponding index factor. For example, a patient with a 30-degree flexion contracture who has further flexion to 100 degrees but lacks rotation and has no motion in the abduction-adduction range would be rated for motion as follows:

15 degrees in the 0 to 45-degree range of flexion (that is, from the 30-degree flexion contracture further to 45 degrees of flexion), or 15 × 1.0 (index value) = 15 points;

45-degrees in the flexion arc from 45 to 90 degrees, or 45 degrees × 0.6 (index value) = 27 points;

10 degrees in the flexion arc from 90 to 110 degrees, or 10 × 0.3 (index value) = 3 points;

No points for rotation or abduction-adduction;

Total point score is forty-five.

The sum of the point scores for the individual arcs is then multiplied by 0.05 to obtain the number of points for the over-all evaluation of the range of motion. This patient would receive 0.05 × 45 or 2.3 points for motion. All of these calculations can be performed automatically during data processing so that the surgeon need only record the range of motion in the usual way.

The final four points of the over-all total of one hundred are given for the absence of deformity. Any of the following constitutes a significant deformity and eliminates these four points: A permanent flexion contracture greater than 30 degrees, fixed adduction of more than 10 degrees, fixed internal rotation of more than 10 degrees or a limb-length discrepancy of more than 3.2 centimeters.

Synopsis of The Evaluation System

I. Pain (44 possible)

- A. None or ignores it 44
- B. Slight, occasional, no compromise in activities. 40
- C. Mild pain, no effect on average activities, rarely moderate pain with unusual activity, may take aspirin 30
- D. Moderate pain, tolerable but makes concessions to pain. Some limitation of ordinary activity or work. May require occasional pain medicine stronger than aspirin. 20
- E. Marked pain, serious limitation of activities. 10
- F. Totally disabled, crippled, pain in bed, bedridden 0

II. Function (47 possible)

- A. Gait (33 possible)
  - 1. Limp
    - a. None 11
    - b. Slight. 8
    - c. Moderate 5
    - d. Severe 0
  - 2. Support
    - a. None. 11
    - b. Cane for long walks. 7
    - c. Cane most of the time 5
    - d. One crutch 3
    - e. Two canes. 2
    - f. Two crutches 0
    - g. Not able to walk (specify reason). 0
- B. Activities (14 possible)

1. Stairs
   a. Normally without using a railing 4
   b. Normally using a railing 2
   c. In any manner 1
   d. Unable to do stairs 0
2. Shoes and Socks
   a. With ease 4
   b. With difficulty 2
   c. Unable 0
3. Sitting
   a. Comfortably in ordinary chair one hour 5
   b. On a high chair for one-half hour 3
   c. Unable to sit comfortably in any chair 0
4. Enter public transportation 1

III. Absence of deformity points (4) are given if the patient demonstrates:

A. Less than 30° fixed flexion contracture
B. Less than 10° fixed adduction
C. Less than 10° fixed internal rotation in extension
D. Limb-length discrepancy less than 3.2 centimeters

IV. Range of motion (index values are determined by multiplying the degrees of motion possible in each arc by the appropriate index)

A. Flexion 0–45 degrees × 1.0
   45–90° × 0.6
   90–110° × 0.3
B. Abduction 0–15° × 0.8
   15–20° × 0.3
   over 20° × 0
C. External rotation in ext. 0–15 × 0.4
   over 15° × 0
D. Internal rotation in extension any × 0
E. Adduction 0–15° × 0.2

To determine the over-all rating for range of motion, multiply the sum of the index values × 0.05. Record Trendelenburg test as positive, level, or neutral.

Material

Thirty-one of the thirty-eight patients were male. The left hip was involved in eighteen; the right, in twenty-one. One patient required bilateral arthroplasty for bilateral traumatic arthritis.

Automobile accidents accounted for thirty-two of the thirty-nine injuries. Train accidents caused three, falls two, and skiing one. In one no information was available.

The types of injury to the hip were: posterior fracture-dislocation in eighteen (three with fracture of the femoral head), posterior dislocation in eight (one with fracture of the femoral head), central dislocation in six, bursting fracture in five (one with femoral-head fracture), and posterior fracture without dislocation in two.

The initial treatment consisted in closed reduction in twenty-two cases, open reduction in five, open reduction and internal fixation in four, closed reduction followed by open reduction in one, and traction in the remainder. In four of the ten hips treated by open reduction, postoperative intra-articular infections developed. The organism in three was *Staphylococcus aureus* and in one instance, streptococcus. The sciatic nerve had been injured in four patients, resulting in marked permanent

FIG. 1-A

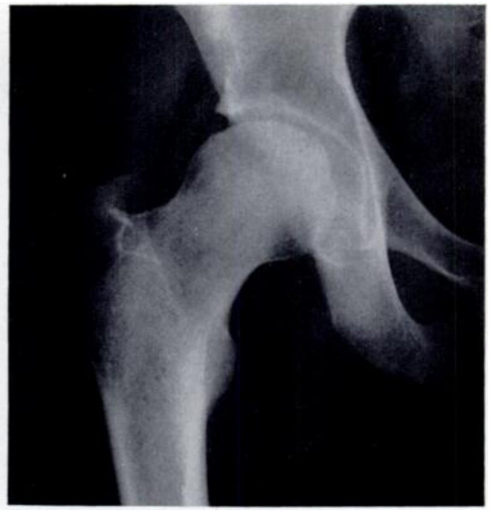

FIG. 1-B

Figs. 1-A through 1-D: P. M., a man, twenty-five years old, dislocated his right hip in a skiing accident. Nine years after the injury he had severe avascular necrosis of the femoral head. Mold arthroplasty was performed and eight years later, he had no pain and was able to ski, play tennis, and run six miles.

Fig. 1-A: Right hip two years after dislocation. The femoral head appears to show increased density.

Fig. 1-B: The right hip, five years later, shows slight loss of sphericity and increased density of the femoral head.

FIG. 1-C

FIG. 1-D

Fig. 1-C: Nine years after dislocation, the femoral head shows segmental collapse and cyst formation secondary to avascular necrosis.

Fig. 1-D: Six years after mold arthroplasty.

loss of sciatic function in three and partial peroneal palsy in the other.

Twenty-one of the patients had no other significant musculoskeletal injury and seventeen had the following concommitant traumatic lesions: fracture of the ipsilateral femur in three, fracture of the ipsilateral patella in four (one requiring patellectomy), fracture of the ipsilateral tibia in three, fracture of the ipsilateral foot or ankle in one, fracture of the contralateral femur in two, fracture of the contralateral patella in one, fracture of the contralateral knee in one, fracture of the contralateral

Fig. 2-A

Fig. 2-B

Figs. 2-A and 2-B: R. B., a man, sixty-two years old at the time of injury, sustained a central dislocation of his hip. Increasing pain and loss of motion led to arthroplasty two years later.

Fig. 2-A: Anteroposterior roentgenogram of the hips and pelvis shows severe disruption of the right acetabulum with central dislocation of the femoral head.

Fig. 2-B: Anteroposterior roentgenogram of the right hip four and one-half years after arthroplasty. The mold was placed against the periphery of the acetabular rim, rather than seating it deeply to the full depth of the acetabulum. He had no pain, an excellent gait, 130 degrees of flexion, and walked two miles without support.

tibia requiring fusion of the knee and ankle in one, fracture of the contralateral ankle in one, contralateral above-the-knee amputation in one, fracture of the forearm in four, crushed chest in one, sciatic-nerve injury in four, and fracture-dislocation of the other hip in two.

The average time between injury and reconstruction was 7.7 years with a range of from two months to thirty years. The mean age of the patients when the hip was reconstructed was forty-seven years with a range of from twenty-two to seventy-one. Thirteen of the thirty-eight patients were over fifty-five; nine, under forty; and seven, over sixty.

The arthroplasty was performed in thirty-four of the patients because of complaints of pain, in two because of pain and limited motion, in one patient because of stiffness, and in two because of persistent dislocation of the hip. One of the persistently dislocated hips had avascular necrosis of the femoral head. Altogether twelve hips showed roentgenographic evidence of avascular necrosis (Figs. 1-A through 1-D). The acetabulum showed severe changes in thirty-seven. Prior to surgery the Trendelenburg test was positive in thirty-four of the hips and negative in four. The result was not recorded in one instance.

The operative procedure, carried out through an anterior incision in thirty-seven cases and through a Kocher incision twice, took an average of 3.4 hours with a range from two to 5.5. All of the procedures were standard arthroplasties with decortication and reaming of both the head and acetabulum except for two in which the cup was placed on the mid-portion of the femoral head and two in which the cup was seated against the periphery of the acetabulum in preference to inserting it more deeply into an exploded socket (Figs. 2-A and 2-B). Of these latter two, one was rated excellent and one good at the follow-up examination. An average of 3.7 units of blood (range one to eight units) was used for each operation.

The duration of patients' stay in the hospital ranged from one month to 3.5 months with a mean of 1.7 months. One patient discarded his crutches two months after operation while another remained on crutches for forty-eight months until her death from metastatic carcinoma of the lung. On the average, two crutches were used postoperatively for 9.8 months (the mode and the median). All of the six patients who used crutches for over one year had some additional problem such as a contralateral above-the-knee amputation, metastatic malignant tumor, non-union of a fracture of the distal portion of the femoral shaft, additional trauma to the hip, and the like. The average duration of follow-up was 5.8 years with a range from one to fifteen years.

Results

All thirty-nine hips were evaluated by all three systems. In assessing pain the proposed new system and the Shepherd system are similar but the Larson system is quite different:

Pain Categories and Valuation in Three Systems

Larson		Shepherd	Proposed	
None	35	None	None	44
Pain only with fatigue	30	Ignores	Ignores	40
Pain only with weight-bearing	20	Makes concession	Mild	30
Pain at rest but not with weight-bearing	15	Disabling	Moderate	20
Pain sitting or in bed	10		Marked	10
Continuous pain	0	Crippling	Disabled	0

The categories, identified as *none*, *ignores*, and *totally disabled . . . bedridden* in the proposed evaluation system, are usually easy to define. Because patients in the intermediate groups are more difficult to categorize, this part of the pain classification has been expanded from two categories (*concession* and *disabling*) in the Shepherd system to three (*mild*, *moderate*, and *marked*) in the new scheme. This change makes classification of individual patients easier in the proposed system than in the Shepherd method. While the Larson system has six categories, the definition of the categories and the allotment of points are not consistent with my experience in interviewing patients. For example, it is very rare to find a patient who has pain at rest but not on weight-bearing. Also it is often hard to distinguish between a patient who has pain at rest (fifteen points) and one who has pain sitting or in bed (ten points) or has continuous pain (0 points).

Because the Shepherd system does not use a single over-all rating value, comparison of this method with the other two was difficult. In addition, the Shepherd system rates the result *as a hip* as distinct from the rating *as an arthroplasty*. The complex functional assessment is done by ascribing a series of *black marks* for functional limitation, improvement being recognized by a decrease in the number of black marks. For example, if the number of black marks is five or less before operation and decreases by three or more after operation or if the number is between six and ten before operation and decreases by five or more after operation, the functional result is deemed excellent. If, however, the number of black marks is four or more before operation and decreases by two or one or not at all after operation or increases by one, the functional result is fair. A *good* rating in the functional category is given if there are three black marks or less and the number decreases after operation or if there are four to thirteen black marks and a decrease of three marks or more occurs after operation.

Weighted equally with this functional assessment are (1) active motion using the Gade system, (2) the patients assessment, and (3) the rating of pain. Objections to the Gade assessment of motion and to the use of only active motion have been discussed previously. The weighting of the subjective response of the patient's own assessment so heavily and the weighting of motion in itself so heavily are questionable. For all these reasons the Shepherd system did not seem to be useful in this study.

The end-result ratings of the thirty-nine hips, evaluated by Larson and the new method were as follows:

Total	Larson Rating		New Rating	
Points	Preoperative	Postoperative	Preoperative	Postoperative
90–100		16		18
80–89	1	17		7
70–79	10	3	3	9
60–69	17	3	7	2
50–59	8		9	2
40–49	2		14	1
30–39	1		3	
20–29			3	
10–19				
0–9				

Comparison of the two rating schemes shows that hips rated by the Larson system tend to fall into a more narrow range. Postoperatively only six of the thirty-nine hips were rated below eighty points. The wider spread of rating in the new system made the recognition of differences between hips easier and appeared to be a more accurate representation of each patient's functional state.

The difference between the two numerical rating systems are shown clearly by reviewing the results in individual patients:

Consider C. S., a fifty-one-year-old salesman, who sustained a fracture-dislocation of the left hip. Following an open reduction and screw fixation of the acetabular fragment, the wound became infected with *Staphylococcus aureus* and drained for six months. Two years after injury, when he was admitted for arthroplasty, his preoperative status was as follows: He had only mild pain in the hip, but marked instability and considerable grating. The Trendelenburg test was positive, active abduction against gravity was impossible, and two crutches were required full time. He was fully active in his business using crutches and could walk unlimited distances. He could tie his shoe and put on his sock, climb stairs using crutches, sit comfortably in any chair, and manage his own car or public transportation. His range of motion was: fixed flexion contracture of 10 degrees, further flexion to 115 degrees, abduction to 50 degrees, internal rotation in extension to 20 degrees, external rotation in extension to 35 degrees, and adduction to 20 degrees (Figs. 3-A and 3-B).

FIG. 3-A

FIG. 3-B

Figs. 3-A and 3-B: C. S., a man, was fifty-one years old when he sustained a posterior fracture-dislocation of the left hip in an automobile accident. Postoperative sepsis developed after open reduction and internal fixation of the acetabular fracture at another hospital. A mold arthroplasty was performed two years later after the wound had been healed for eighteen months. Four years after arthroplasty he had an excellent result despite weighing 220 pounds. There had been no signs of sepsis since the arthroplasty.

Fig. 3-A: Anteroposterior roentgenogram of the left hip one year following dislocation.

Fig. 3-B: Anteroposterior roentgenogram of the left hip four years after mold arthroplasty.

In the Larson rating he would receive thirty of thirty-five points for function, losing only "negotiates stairs foot over foot" and "carries objects comparable to a suitcase." He would receive thirty of thirty-five points for freedom from pain, lose six of ten points for gait because he used two crutches, and earn ten of ten points for absence of deformity and eight of ten points for motion, or a total of eighty-two points. In short he would lose only five function points, five pain points, and only six gait points despite using two crutches full time. At the same time he would receive ten points for the absence of deformity and eight points for motion.

In the proposed system he would receive only thirty of forty-four points for pain, lose six of eleven points because of the moderate limp present due to the unstable hip even when using crutches, and lose eleven of eleven support points because of the requirement for two crutches constantly, but he would be granted eleven of eleven distance points on the basis that he could travel unlimited distances on the crutches. He would lose further points because of difficulty with stairs but receive only four points for absence of deformity and five for the free range of motion, making a total of sixty-six. The value of sixty-six, rather than eighty-two, would seem to portray more accurately the over-all status of a man with an unstable septic hip who required two crutches full time.

F.G., an eighteen-year-old boy, sustained a posterior fracture dislocation of the right hip with sciatic-nerve injury in an automobile accident. The severe injury to his left leg required a mid-thigh amputation. His right hip was reduced by closed manipulation but traumatic arthritis subsequently developed. One year later, despite acute pain in the right hip, he had flexion from a 10-degree fixed flexion contracture to 120 degrees, abduction to 5 degrees, adduction to 10 degrees, internal rotation in extension to 30 degrees, and external rotation to −5 degrees. He could tie his shoe and put on his sock but required two crutches because of hip pain and could walk only two blocks. He took Darvon for his pain, had pain at rest, and was unable to sit comfortably on a low chair or toilet. He was able to attend college, getting about by driving in a car.

In the Larson rating he received twenty-three points for function, ten for pain, four for gait, ten for absence of deformity and five for motion, or a total of fifty-four points. In the new system he received ten for pain, five for limp, five for distance walked, none for support, one for being able to climb stairs by any method, one for being able to enter public transportation, none for sitting, four for putting on shoes and socks, four for the absence of deformity and seven for motion, or a total of thirty-seven points. Again the new rating appeared to give a more accurate assessment of this patient who had marked pain and pain at rest, and who required two crutches full time.

A score of ninety to one hundred was considered an excellent result. Eighty to ninety was called good, seventy to eighty fair, and below seventy poor. In the new system the over-all results were eighteen excellent, seven good, nine fair, and five poor. Using the Larson system thirty-three were good or excellent, three were fair, and three were poor.

Of special interest was the comparison of the results of unilateral arthroplasty in the first eighteen patients in the series (done between 1945 and 1957) with those in the second nineteen patients (done between 1958 and 1966). In the first group, three required revision and a fourth had postoperative sepsis. Seven results were excellent, one was good, five were fair, and five were poor. In the second group ten patients received an excellent end-result rating, six a good, and two a fair rating. The remaining patient had a poor result. No revisions were required. The difference between eight good or excellent results in the first eighteen and sixteen good or excellent results in the next nineteen is statistically significant ($p < 0.05$).

The discrepancies between these figures and the over-all figures given previously are due to the inclusion in the over-all figures of both hips of the patient who had bilateral arthroplasty and the two ratings for the patient who changed from the poor category to the excellent category following a revision.

Although the patients under the age of forty had slightly better results than the rest, this difference was not statistically significant.

Special attention was given to any changes in hip function with time after arthroplasty. For the thirty-four hips followed for over two years, the function as determined from data recorded at one year after arthroplasty was compared with the function determined from the latest follow-up information two to fifteen years after arthroplasty. No result deteriorated from a good or excellent rating to a fair or poor category. Three patients with fair results were later rated at the poor level, while one fair result improved to excellent. All three of the patients whose rating deteriorated from fair to poor were never free from pain or able to walk without a cane postoperatively. The rating of all three declined because of increasing pain. Two patients who were rated as excellent at one year dropped to a good rating, the change being associated with a cerebral vascular accident in one and with the onset of Hodgkin's disease in the other. There was thus no significant deterioration of the good or excellent functional results of arthroplasty with time.

Of special interest were the four patients who had intra-articular sepsis of the hip following their initial open reductions. All four hips had been free of drainage for one, two, four, and seven years, respectively, prior to the insertion of the mold. None drained following the arthroplasty during follow-up periods of four, five, thirteen, and fifteen years. One patient whose result was rated good, had a pain-free hip, excellent gait, and full motion but required a cane for long walks. Two patients had excellent results (Figs. 3-A and 3-B). The fourth patient had a fair result because he had mild pain and required a cane.

Complications in this series were few. With the exception of one patient operated on in 1947, no postoperative sepsis occurred. None of the hips dislocated postoperatively. Two pulmonary emboli were recognized, but accurate data concerning the incidence of thrombophlebitis were not available. There were no deaths.

The preoperative and postoperative pain rating of the patients in this series according to the three systems are shown in Table I.

Postoperatively three patients required pain medication stronger than aspirin. One did so because of pain thought to be related to traumatic disruption of the sacro-iliac joint, one because of knee pain related to a damaged patella, and one because of hip pain.

At the follow-up examination twenty-one patients were able to elevate the opposite side of the pelvis when standing on the reconstructed hip and performing the Trendelenburg test. Of the sixteen with positive Trendelenburg tests, six were able to prevent a fall of the opposite side of the pelvis below the horizontal position but were unable to elevate it. Data were not available for two hips. The development of a negative Trendelenburg test after operation did not show a strong inverse correlation with the patients' age.

TABLE I

Comparison of Preoperative and Postoperative Pain Levels

				New System			
	None	Slight	Mild	Moderate	Marked	Bedridden	Total
Preoperatively	0	0	5	26	7	1	39
Postoperatively	12	15	8	3	1	none	39
				Larson System			
	None	Only with Fatigue	Only with Wt. Bearing	At Rest but not with Wt. Bearing	Sitting or in Bed	Continuous	Total
Preoperatively	0	3	29	3	3	1	39
Postoperatively	12	18	5	4	0	0	39
				Shepherd System			
	None	Ignores	Concessions	Disabling	Crippling	Total	
Preoperatively	0	3	28	7	1	39	
Postoperatively	12	19	7	1	0	39	

Analysis of the postoperative range of motion in the sagittal plane showed that there was no permanent flexion contracture in twenty-five hips and that in the other fourteen the maximum was 20 degrees (two hips) with an average of 5 degrees. The amount of further flexion ranged from 65 to 130 degrees, the average flexion being 105 degrees. The poorest range of motion in this plane was from 20 degrees of fixed flexion to 85 degrees of flexion.

Preoperatively twelve patients required crutches and three used two canes. At the time of follow-up examination one required two canes (the patient with bilateral hip reconstruction) and three used crutches because of the following special circumstances: One had metastatic carcinoma of the lung, was a chronic alcoholic, and spent much of her time in a mental institution. The second had received additional trauma to the reconstructed hip in a subsequent automobile accident. The third, a patient whose contralateral knee and ankle were fused, had her hip reconstructed in 1953 after it had been dislocated for ten years. The greater trochanter was transplanted distally and wired to the femur but was so osteoporotic that it fractured along the single wire suture and did not unite to the femoral shaft. This patient subsequently did not regain sufficient abductor power to walk well without crutches.

Of the nineteen patients with unilateral operations done since 1958, one used crutches (the one with metastatic carcinoma) and two used a cane full time, one because of a contralateral above-the-knee amputation, the other because of persistent hip pain. Of the remaining sixteen, ten used no support and six used a cane only for long walks.

Penetration of the cup into the acetabulum and resorption of the femoral head underneath the cup were investigated. Small degrees of penetration or resorption were difficult to assess on clinical roentgenograms but a difference in the depth of the acetabulum or relation of the cup to the femur of 6.4 millimeters or more as determined by measurements between landmarks identifiable on roentgenograms which were comparable with respect to projection as well as to rotation and position of the hip was arbitrarily established as evidence of penetration or resorption.

Comparable roentgenograms were available for thirty-five hips. Avascular necrosis of the femoral head had been diagnosed prior to arthroplasty in twelve patients on the basis of roentgenographic appearance and gross and microscopic findings. Of these twelve patients nine showed no evidence of penetration or resorption at one, one, one and one-half, two, three, four, four, eight, and fifteen years, respectively, after arthroplasty and three showed resorption of the femoral head amounting, respectively, to 6.4 millimeters at seven years, 9.6 millimeters at four years, and 1.9 centimeters at thirteen years. Two of the twenty-three patients without evidence of avascular necrosis showed shortening amounting to 1.6 centimeters at two years in one, and 1.9 centimeters at seven years in the other. In the first patient the 1.6 centimeter loss was due to resorption of the femoral head; in the

Fig. 4-A

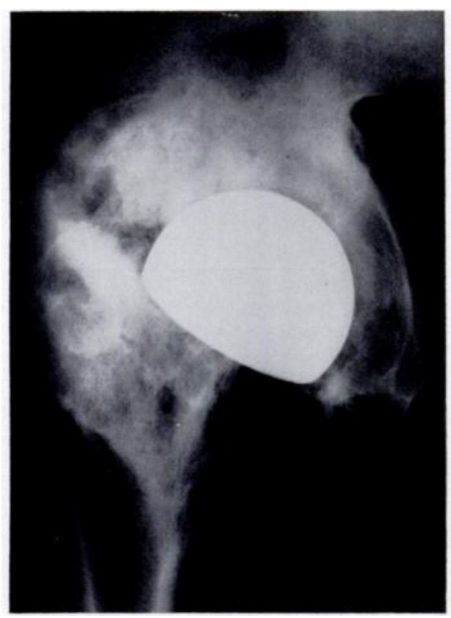

Fig. 4-B

Figs. 4-A through 4-C: B.F., a man, forty-nine years old when he was treated for traumatic arthritis of the right hip four years after an intrapelvic dislocation of the hip caused when he was crushed between two box cars. Preoperative roentgenograms showed osteophytes but no ectopic bone. Arthroplasty was performed and six months later there was severe myositis ossificans, a flexion contracture of 35 degrees and further flexion only to 55 degrees.

Revision was performed one year after the first arthroplasty. Six years later only a slight amount of ectopic bone had reformed and the hip was rated excellent. Hip motions were as follows: permanent flexion contracture of 15 degrees, further flexion to 95 degrees, abduction of 25 degrees, external rotation in extension 25 degrees, and internal rotation in extension 10 degrees.

Fig. 4-A: Frog-leg lateral roentgenogram of right hip before arthroplasty showing traumatic arthritis, osteophyte formation and no ectopic bone.

Fig. 4-B: Six months after the first arthroplasty there was severe myositis ossificans.

FIG. 4-C

FIG. 5

Fig. 4-C: Six years after revision of the arthroplasty there was only a slight amount of ectopic new bone.

Fig. 5: J. M., a man, thirty-three years old, had a central fracture-dislocation caused by a truck accident. An arthroplasty was performed nine years after the injury and six years later there was extensive ectopic bone formation. However, the result was excellent and motions of the hip were as follows: a fixed flexion contracture of 10 degrees, free flexion to 100 degrees, adduction to 35 degrees, abduction to 10 degrees, internal rotation to neutral, and external rotation to 35 degrees.

second, the 1.9-centimeter loss was the result of a loss of 1.3 centimeters of the femoral-head height and 0.6 centimeter of penetration of the cup into the acetabulum. Of these five patients, three had excellent results, one had a fair result, and one had a poor result. The poor rating was given because of hip pain and the need for a cane full time. One patient who lost 1.9 centimeters of length was fully active as a farmer, walked long distances on his farm, and went deer hunting each year without pain or support, thirteen years after his arthroplasty.

Ectopic ossification about the hip following the trauma or subsequent mold arthroplasty can compromise the end result. Myositis ossificans was present prior to mold arthroplasty in fourteen hips. In ten of these, the ectopic ossification developed after closed reduction and was small in amount as a rule. In the other four hips the myositis ossificans followed open reduction and was very extensive in two of them. After arthroplasty myositis ossificans did not reform in two hips, was less than before the operation in one, and was slightly more than existed preoperatively in one. In none of these fourteen patients was motion significantly restricted by the heterotopic bone.

Nine of the twenty-five hips which were free of myositis ossificans prior to arthroplasty had some ectopic bone following reconstruction. In seven the amount was minimum and did not restrict motion. In one instance the amount was great and restricted hip motion markedly (Figs. 4-A, 4-B, and 4-C). Following revision eighteen months later, only a small amount of ectopic bone reformed. The patient had an excellent range of motion, and the result was rated excellent in the end-result study five years later. In one other patient a large volume of new bone developed after his arthroplasty but at follow-up six years after arthroplasty he had a good range of motion and was free of pain (Fig. 5).

Considering the thirty-nine results of the initial arthroplasty only, fifteen hips were rated less than good or excellent: eight fair and seven poor. Analysis of the seven poor hips revealed that extensive ectopic bone formation caused one poor result as already noted and postoperative sepsis another. In the remaining five cases, the patients had pain in the hip on weight-bearing and in each instance the pain had been present since the patient began to walk after the operation. The femoral head of one of these five was shown at subsequent surgery to have areas of bone which were not covered by fibrocartilage. Resorption of the femoral head under the cup occurred in another, as noted previously. The cause for pain in the other three remained undetermined.

Four of the seven patients with poor results were reoperated on. One, as previously noted, had a revision for removal of ectopic bone and was rated excellent five years later (Figs. 4-A, 4-B, and 4-C). Two others had revisions. The one who had areas of the femoral head which were not covered by fibrocartilage improved

Fig. 6-A

Figs. 6-A through 6-C: Construction of the acetabulum in mold arthroplasty.

Fig. 6-A: A poor acetabulum. Note that the lateral lip is higher than the apex of the dome. This arthroplasty was done in 1948 and the patient had a fair result.

Figs. 6-B and 6-C: A good acetabulum.

Fig. 6-B: Preoperative roentgenogram shows distortion of the femoral head and acetabulum after a fracture dislocation of the hip.

Fig. 6-C: One year after arthroplasty done in 1962. Note that the lateral lip of the acetabulum is appreciably lower than the apex of the dome. The cup fits the contour of the acetabulum accurately. This patient had an excellent rating.

Fig. 6-B

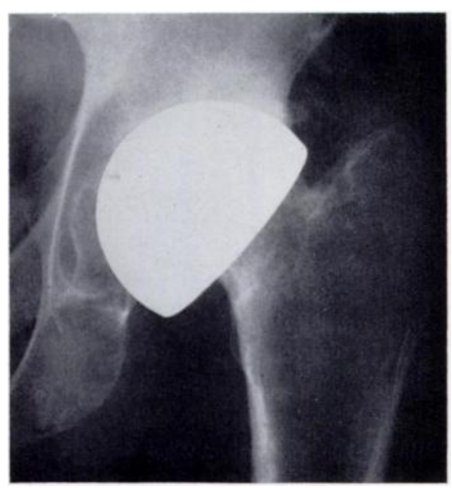

Fig. 6-C

from poor to fair and the one who had satisfactory fibrocartilage on both the socket and the femoral head did not change. The fourth patient had the cup replaced by a prosthesis at another hospital, without improvement.

The group of eight hips rated fair included the following: the patient with bilateral reconstruction for traumatic arthritis who required two canes and had mild pain in each hip, but was very active and considerably improved; the twenty-two-year-old man with the contralateral above-the-knee amputation who required pain medicine because of pain in his ipsilateral knee and used a cane; the patient whose greater trochanter did not unite to the femoral shaft, the patient who had metastatic carcinoma of the lung and the three patients who because of hip pain on weight-bearing required the use of a cane full time. One of these three was a seventy-nine-year-old woman who had had avascular necrosis of the femoral head following a bursting fracture and posterior dislocation. Her abductor power was weak, probably due to failure to transplant the greater trochanter after resecting the avascular portion of the femoral head. Full explanation of the hip pain is not available for these three patients since the hips were not re-explored. All but three of the fifteen hips with less than a good result were operated on during the first half of the series.

Discussion

In evaluating the results in this series the strict criteria used in defining the diagnosis of traumatic arthritis must be emphasized. Only fractures of the acetabulum, dislocations of the hip or both were included. (In five patients, there was a fracture of the femoral head in addition.) In order to be comparable, any series of traumatic arthritis treated by another method must be similarly defined.

The large number of automobile accidents among the causes of injury and the preponderance of men over women in this series are characteristic of trauma in contemporary society. This finding is in keeping with the reports of Brav and of Steward and Milford. The average time of seven years between trauma and arthroplasty reflects the therapeutic principle in this series of delaying reconstructive surgery until pain, limited functional capacity, or both made treatment mandatory. Only one patient in this group had arthroplasty carried out less than six months after trauma. This was done at two months because of a grossly unstable hip joint with a fracture of the femoral head and recurrent dislocation, similar to the unstable hips reported by Kelly and Lipscomb.

The statistically significant improvement in the frequency of good and excellent results in the latter half of the series is important. Four factors appear to have contributed to this improvement:

1. Use of the Aufranc concentric cup[1];
2. Improvement in surgical technique, especially in construction of the acetabulum (Figs. 6-A, 6-B, and 6-C)[7];
3. Better instruments with which to do the procedure[1];
4. Improved postoperative care[1].

Particularly gratifying were the results in the four hips which were septic after open reduction. Carrying out a major hip-joint construction without reactivating the infection is a considerable challenge. None of these patients showed any evidence of sepsis after arthroplasty.

The relief of pain (Table I) and the range of motion obtained were very satisfactory. Preliminary data indicate that the incidence of positive Trendelenburg tests can be reduced by use of the lateral approach with transplantation of the greater trochanter and the attached abductors[7].

The presence of myositis ossificans prior to the arthroplasty was not an important disadvantage and did not appear to increase the liklihood of postoperative ecotopic bone formation.

When considering the choice between arthroplasty and fusion for traumatic arthritis, a number of factors must be weighed. These include the presence of avascular necrosis of the femoral head, persistent dislocation, and disruption of the acetabulum, as well as the condition of the ipsilateral knee, contralateral hip, contralateral knee and lumbar spine, and the height of the patient [4]. Also to be considered are the prolonged immobilization in plaster and the high incidence of non-union after attempted fusion ranging from 20 per cent reported by Lipscomb and McCasling to 6 per cent as reported by Watson-Jones and Robinson in osteo-arthritis. The incidence of non-union after attempted arthrodesis for traumatic arthritis as the term is used in this study, has not been reported in any large series.

Watson-Jones stated "If the joint is destroyed by degenerative arthritis, whether it is a simple traumatic arthritis or an arthritis arising from avascular necrosis, the alternatives are to arthrodese the joint or to perform an arthroplasty. Arthrodesis is difficult, because the dead and avascular femoral head does not contribute readily to sound fusion so that fibrous rather than bony ankylosis often occurs. It is probably better in most of these cases to perform an arthroplasty." He also remarked that his results after attempted arthrodesis in traumatic dislocations which were unreduced after many months "were so bad as to dissuade most surgeons from attempting operative reduction" and fusion.

Among the twenty-five patients under the age of fifty-five in the current group one had a long-standing dislocation, one a fused knee, and another an above-the-knee amputation on the contralateral side. Two had bilateral hip disease and ten had avascular necrosis of the femoral head. In other words, only ten were primarily suitable for fusion. Of these ten, six had excellent results; one a good result, two fair results, and one a poor result. It is, therefore, concluded that mold arthroplasty is the treatment of choice for most patients who require surgery for traumatic arthritis of the hip.

Summary

An end-result analysis is presented of thirty-nine mold arthroplasties performed at the Massachusetts General Hospital between 1945 and 1965 in thirty-eight consecutive private patients for arthritis of the hip following fractures of the acetabulum or dislocations of the hip.

Of the nineteen unilateral cases in the second half of the series, sixteen were rated good or excellent. Results in the second half of the series were significantly better statistically than those in the first half of the series. Possible reasons for this improvement are discussed.

No significant deterioration occurred with the passage of time. Among the thirty-nine hips, three revisions were required. One patient had postoperative sepsis after arthroplasty. Four patients who had had intra-articular sepsis prior to arthroplasty showed no evidence of sepsis postoperatively.

Factors influencing the choice between hip fusion and hip arthroplasty in these cases are presented.

A new system for rating hip function is proposed and is compared with the systems of Larson and Shepherd.

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SECTION III

BASIC SCIENCE AND PATHOLOGY

The Tension–Stress Effect on the Genesis and Growth of Tissues

Part I. The Influence of Stability of Fixation and Soft-Tissue Preservation

GAVRIIL A. ILIZAROV, AM., M.D., PH.D.

To evaluate the optimum conditions for osteogenesis during limb lengthening and to study the changes in soft tissues undergoing elongation, a series of experiments were performed on the canine tibia. The experiments used the transfixion-wire, Ilizarov circular external skeletal fixator in configurations of differing stability of fixation in combination with a second variable, *i.e.,* preservation of the periosteum, bone marrow, and medullary blood supply. Both increased fixator stability, and maximum preservation of the periosseous and intraosseous soft tissues enhanced bone formation during limb lengthening. To assess the role that the direction of the elongation vector plays in osteogenesis, canine tibiae were widened rather than lengthened in a second series of experiments using an Ilizarov apparatus modified for lateral distraction. The new bone formed parallel to the tension vector even when perpendicular to the bone's mechanical axis. As in longitudinal lengthening, damage to the bone marrow inhibits osteogenesis occurring by the influence of a lateral tension–stress vector. In a third series of experiments, half- and full-circumference cortical defects were created in canine tibiae to study the osteogenic potential of the marrow. New bone formed rapidly, even when the marrow was separated from the surrounding periosseous soft tissues by a sheet of polyvinyl chloride, attesting to the importance of marrow element preservation during osteotomy for limb lengthening.

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Since 1951, the author has been engaged in clinical, biological, engineering, and basic science research in orthopedics and traumatology that has led to the discovery of a general biologic principle that governs the stimulation of tissue growth and regeneration during distraction.[4] Gradual traction on living tissues creates stresses that can stimulate and maintain the regeneration and active growth of certain tissue structures.[21] This principle is called the Law of Tension–Stress. Tissues subjected to slow, steady traction become metabolically activated, a phenomenon characterized by the stimulation of both proliferative and biosynthetic cellular functions. These regenerative processes depend upon the adequacy of the blood supply and the stimulating effect of weight bearing.[10,21,26]

The application of this principle has allowed control, for the first time, of both osseous healing and the shaping processes of bone and soft tissues in many situations. When

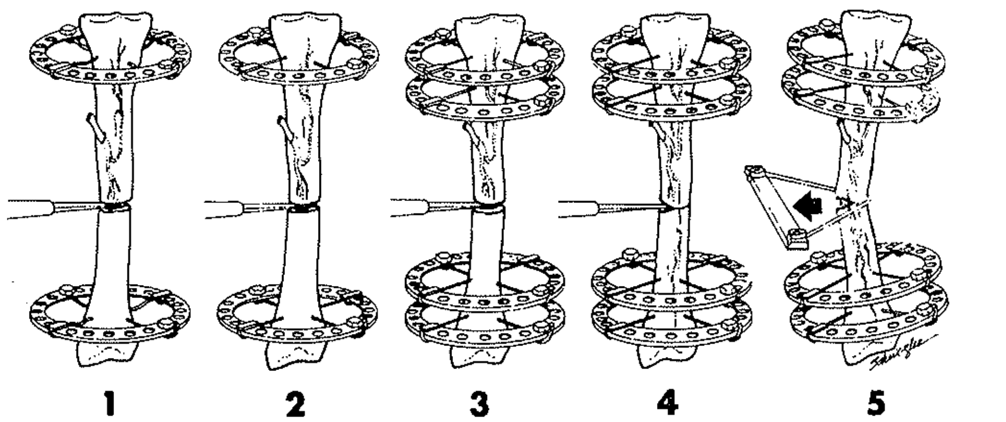


FIG. 1. The first experiment. Groups 1, 2, and 3 had an open transverse osteotomy. Group 1: Two-ring configuration with loosely attached wires. Group 2: Two-ring configuration with tensioned wires. Group 3: Four-ring configuration with tensioned wires. Group 4: Open osteotomy with transection of only one-third of the bone marrow (four-ring configuration). Group 5: Closed osteoclasis technique using a temporary curved wire with enough tension to crack the bone's cortex (four-ring configuration).

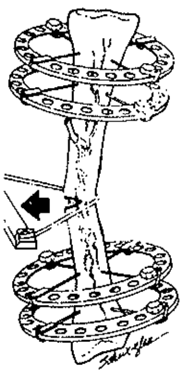
used in conjunction with the circular external fixator,[4-6] which attaches to bone fragments by tensioned wires,[30] the tension–stress effect permits the treatment of many complex injuries and diseases of the locomotor system.[6-11,20] Likewise, the application of this principle has helped in developing new methods of treating many medical problems.

This paper, and a companion paper,[12] will describe several studies designed to define the optimum mechanical and biological parameters necessary for new bone formation during limb lengthening. Clinical observation of osteogenesis during limb elongation has demonstrated that the quality and quantity of newly formed bone depend upon a number of factors: (1) the rigidity of bone fragment fixation; (2) the degree of damage (at the time of osteotomy) to the bone marrow, the periosteal soft tissues, and the nutrient artery and its branches; (3) the rate (speed) of distraction; and (4) the rhythm (frequency) of distraction. Research at the author's institution has focused on using the canine tibia to evaluate the effect of the above-mentioned factors on the quantity and quality of newly formed bone during hind-limb elongation.[13,14,18,19,21,23-25,32]

The studies described in this paper evaluate the effects that the stability of fixation and the degree of preservation of the bone marrow, nutrient vessels, and periosteal soft tissues have on osteogenesis and the surrounding soft-tissue structures during distraction. The three experiments described in this paper were designed to answer the following questions about the tension–stress effect: (1) How important to new bone formation is fixator stability and soft-tissue preservation during elongation? (2) Is the direction of distraction important to the quality of osteogenesis? (3) What is the bone marrow's contribution to bone regeneration? These animal studies have also provided an opportunity to compare the elongation of nonosseous tissues under the stimulating effect of tension–stress to the processes of natural growth.

MATERIALS AND METHODS

In the first experiment, 480 adult dogs were divided into five groups. Each animal was anesthetized with sodium thiopental after which the limb to be operated upon was shaved and prepared in the usual manner (Fig. 1). In the first three groups, an open transverse osteotomy of the tibial diaphysis, periosteum, and bone marrow was performed. These three groups differed only in the stability of



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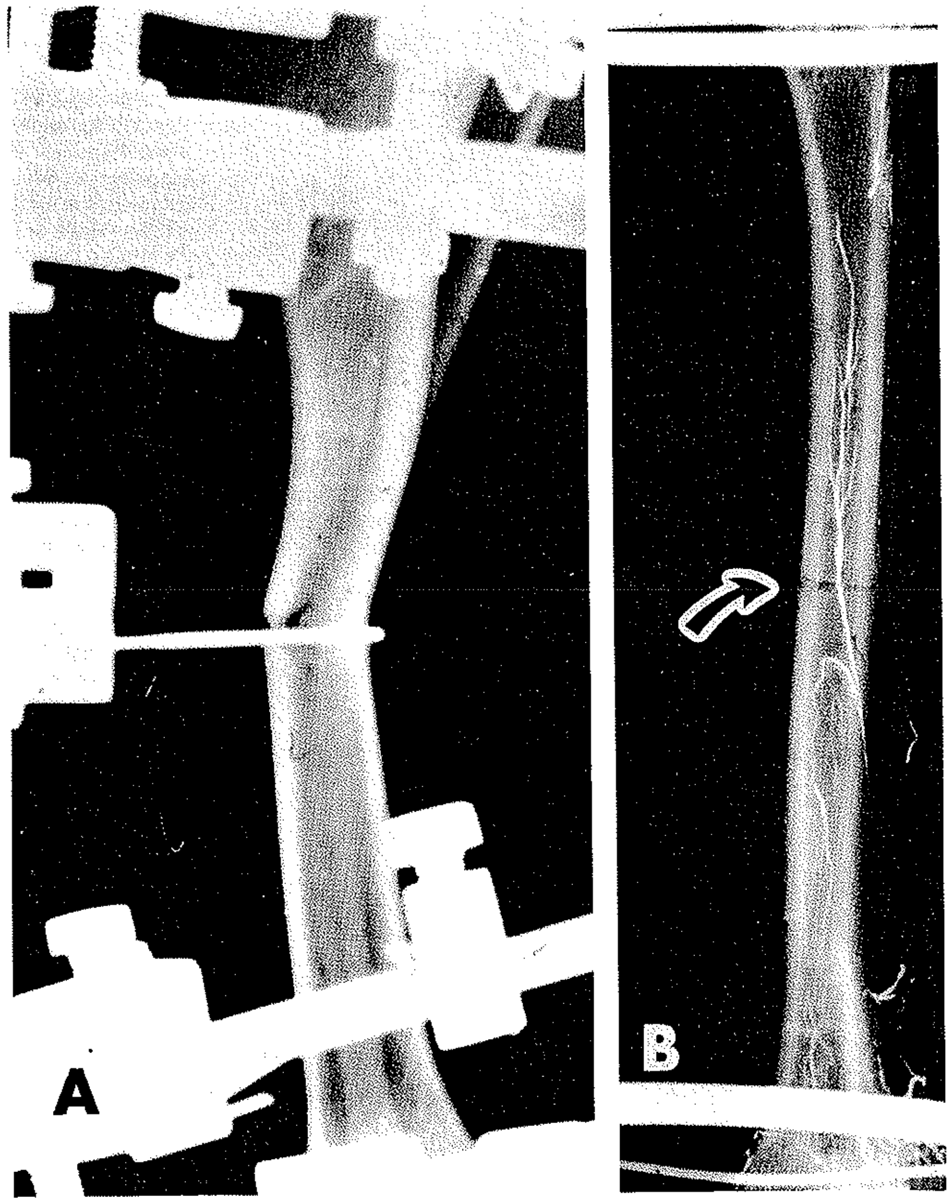


FIGS. 2A AND 2B. The technique of closed osteoclasis with a temporary tensioned wire. (A) The apparatus. (B) An angiogram after closed osteoclasis demonstrating continuity of the nutrient artery even though the bone is fractured (arrow).

bone fragment fixation within a circular external skeletal fixator. The osteotomized tibiae of the first group were placed in a fixator that permitted relatively marked mobility between the bone fragments; this mobility was accomplished by introducing only one pair of crossed Kirschner wires into each fragment. The wires were then loosely fixed to the supporting rings of a two-ring configuration fixator.

The second group differed from the first only in that the pair of crossed wires in each fragment was securely fixed with tension to the rings. This con-

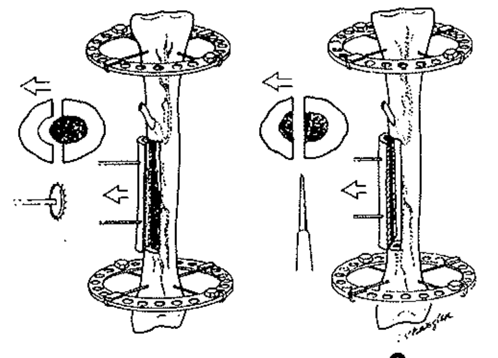


FIG. 3. The second experiment. Group 1: A rotary cutter was used to remove a cortical segment without damaging the bone marrow. Group 2: An osteotomy was used to remove the cortical segment, transversing the medullary canal.

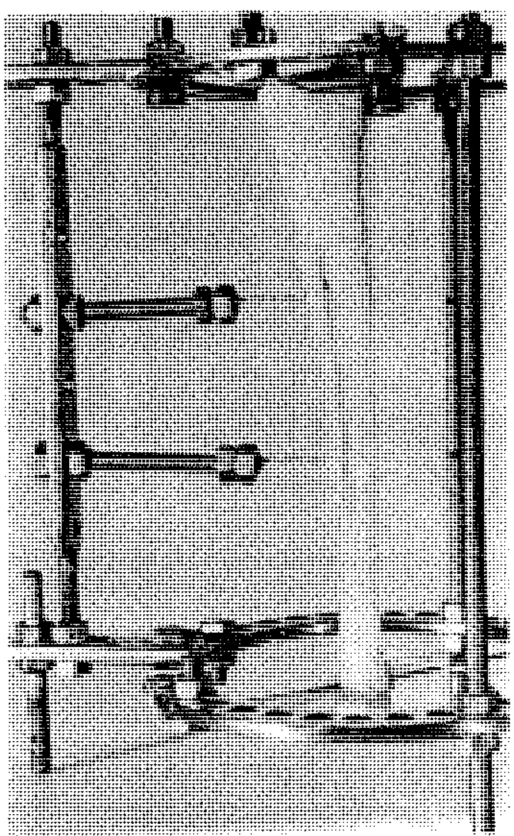


FIG. 4. The apparatus configuration used to displace the section of tibial cortex transversely.

figuration reduced the motion between the fragment ends in comparison to the first group. In the third group, still more rigid fixation of the fragments was achieved by introducing two pairs of wires into each fragment. Each pair of wires was tensioned and fixed to a separate ring, resulting in a four-ring configuration.

The fourth and fifth groups of dogs were stabilized with the same four-ring configuration used for the third group. However, Groups 4 and 5 differed from each other and from Group 3 in the degree of local damage to the bone marrow and to the intramedullary nutrient vessel branches at the level of the osteotomy. In the fourth group, the four-ring configuration was applied to the two bone fragments after an open osteotomy of the bone and periosteum with transection of only one-third of the marrow diameter. For the fifth group, the four-ring configuration was also used, but an attempt was made to maintain the maximum integrity of the periosteum, bone marrow, and nutrient vessels by performing the osteotomy with a technique of closed osteoclasis using tension curved wires to crack the cortex without traversing the marrow canal (Fig. 2).[25]

Each animal was housed in a separate cage under the supervision of a veterinarian and animal care specialists. The dogs were walked daily and fed meals prepared for them in the vivarium kitchen.

In all experimental groups, five to seven days of external fixation of the limb without distraction was followed by 28 days of distraction at a rate of 0.5 mm per day done in four equal increments (0.125 mm every six hours). In the closed osteoclasis group, distraction at 0.5 mm per day resulted in premature bone union; hence, it was necessary to distract this group of animals 1.5 mm per day in four equal increments.

Following distraction, there was a period of neutral fixation lasting from three to six weeks, after which the fixator was removed. The removal of the fixator was followed, in turn, by a period of up to six months of additional observation. Roentgenographs were obtained at weekly intervals.

Within each experimental group, animals were sacrificed immediately following the osteotomy and at seven days, 14 days, 21 days, 28 days, six weeks, two months, three months, four months, and six months after the osteotomy.

To determine the importance of the direction of traction and to further evaluate the effect of bone marrow damage on bone formation within the distraction region, a second experiment was performed using 38 dogs. These dogs were divided into two groups and a longitudinal osteotomy of the tibia was performed (Fig. 3). For both groups, a segment of the tibial cortex, comprising one-third of the diaphyseal circumference and 40% of the bone's length, was separated from the rest of the shaft. In the first group, the longitudinal tibial osteotomy was made with a rotary cutter constructed with a depth restrictor that limited penetration of the bone beyond the depth of the cortex, thereby preventing damage to the bone marrow and nutrient vessels. In the other group, the splitting of the tibia was accomplished with an osteotomy that traversed the medullary canal and sectioned the bone marrow contents.

For both groups, a two-ring circular external skeletal fixator was applied, followed by the insertion of two wires into the separated cortical fragments (Fig. 4). The external ends of the wires then were attached to screw traction devices that connected to the fixator frame. In this manner, the split cortical fragment could be gradually moved transversely. Each group was subdivided into three subgroups for lateral distraction of the cortical fragment at one of the following rates: (1) 1.0 mm per day, (2) 1.5 mm per day, or (3) 1.9 mm per day. In all animals, the distraction was accomplished in equal steps every six hours. Transverse distraction was started three days after the osteotomy in all animals. Roentgenographs were obtained weekly. The dogs were sacrificed at the same intervals as described for the five groups of dogs in the longitudinal distraction experiment.

From each dog, both the osteotomized and the contralateral (control) limbs were removed and prepared for a variety of histologic, biochemical, morphologic, and angiographic studies. Viable tissue was obtained from the distraction zone for incubation (using routine biochemical techniques) to assay lactic dehydrogenase, alkaline phosphatase, ATPase, and a variety of other substrates. Routine and special (van Gieson's, silver, and Phormasan blue) stains of longitudinal and transverse sections of the limbs were done. Likewise, radioangiographic studies were obtained by injecting some animals with radiopaque contrast material, while India ink and other substances were used for microangiographic studies. Some tissue removed from the distraction region was prepared for both transmission and scanning electron microscopy. Whole mounts, smears, and other standard techniques were used to study the hematopoietic tissues of the marrow; peripheral blood smears were obtained simultaneously for comparative analyses.

A third experiment was performed to study the osteogenic potential of bone marrow. A group of 38 adult dogs was divided into two groups (Fig. 5). In the first group, one-half of the diameter of a 30% section of tibial diaphyseal cortex was removed through an open wound while attempts were made to preserve the bone marrow. In the other group, the entire tibial cortical wall was removed (for 30% of the length of the bone) after the bone had been placed in a rigid four-ring circular external fixator. After the circular cortical defect was created, a sheet of polyvinyl chloride was placed around the bone marrow to separate it from the periosteal soft tissues.

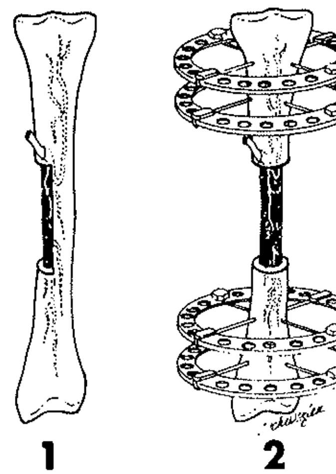


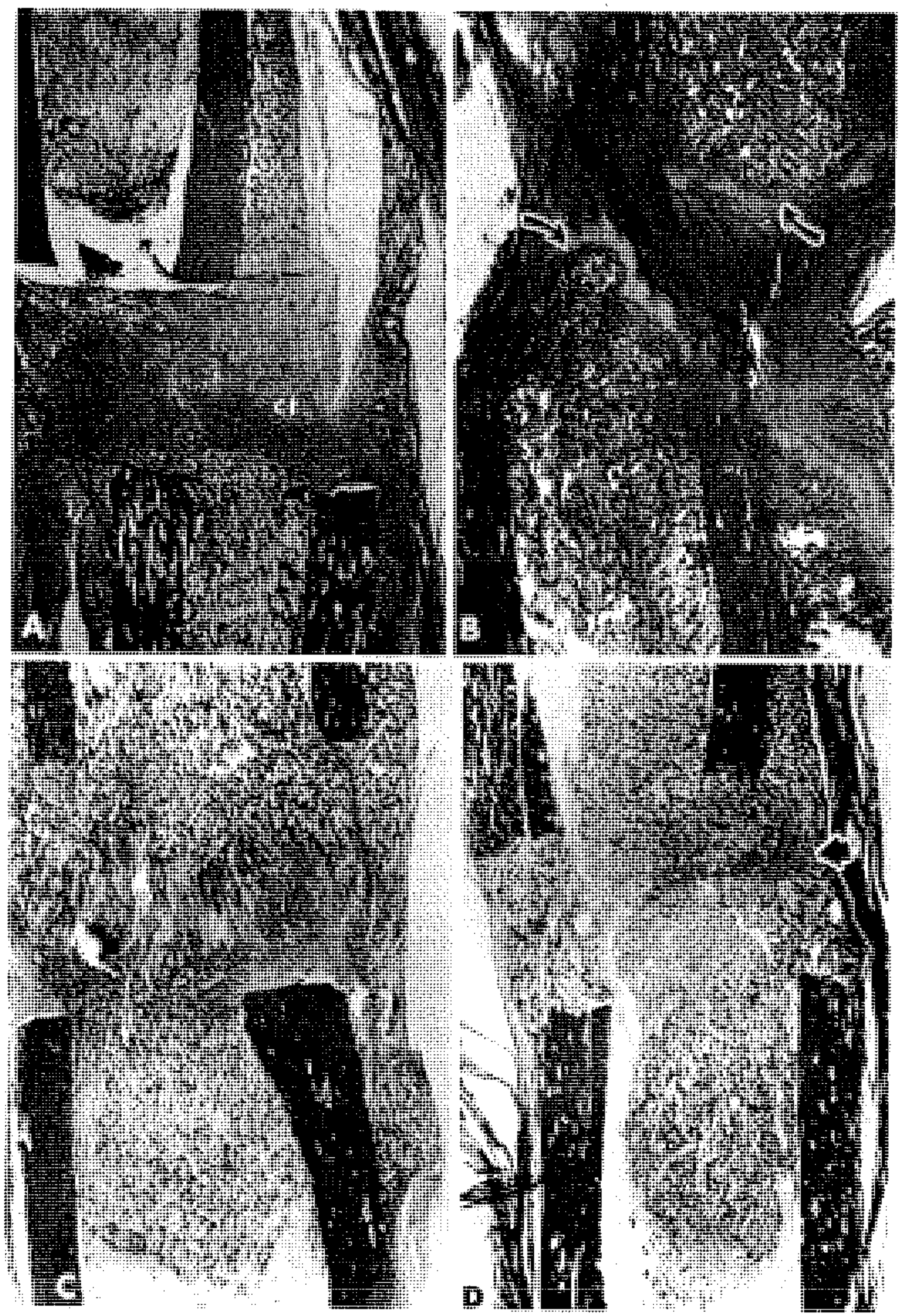
FIG. 5. The third experiment. Group 1: One-half of the tibial diameter was removed through an open wound while the bone marrow was preserved. Group 2: A section of the entire tibial cortex was removed through an open wound and the marrow was separated from the surrounding soft tissues by a polyvinyl chloride sheet. A four-ring fixator was used to stabilize the bone.

There was no distraction in this experiment although, in some of the animals with total removal of a portion of the tibial diaphysis, the marrow was deformed with lateral traction with a curved wire. The animals were sacrificed at the same intervals as described for the preceding two experiments.

RESULTS

LONGITUDINAL DISTRACTION

Among the five groups of dogs subjected to longitudinal distraction, osteogenic activity was least in the group with the most mobility between the bone ends (Group 1). By Day 14 of distraction at a rate of 0.5 mm per day (done in four equal increments of 0.125 mm every six hours), the Group 1 distraction gap was mostly filled with poorly differentiated



FIGS. 6A–6E. Animals subjected to a longitudinal distraction of 0.5 mm/day in four stages (0.125 mm every six hours) and sacrificed on Day 14. (A) Group 1. The distraction gap is filled with poorly differentiated connective tissue (CT) with a few islands of cartilage. (B) Group 2. There are small cone-shaped

E


FIG. 6 (*Continued*).

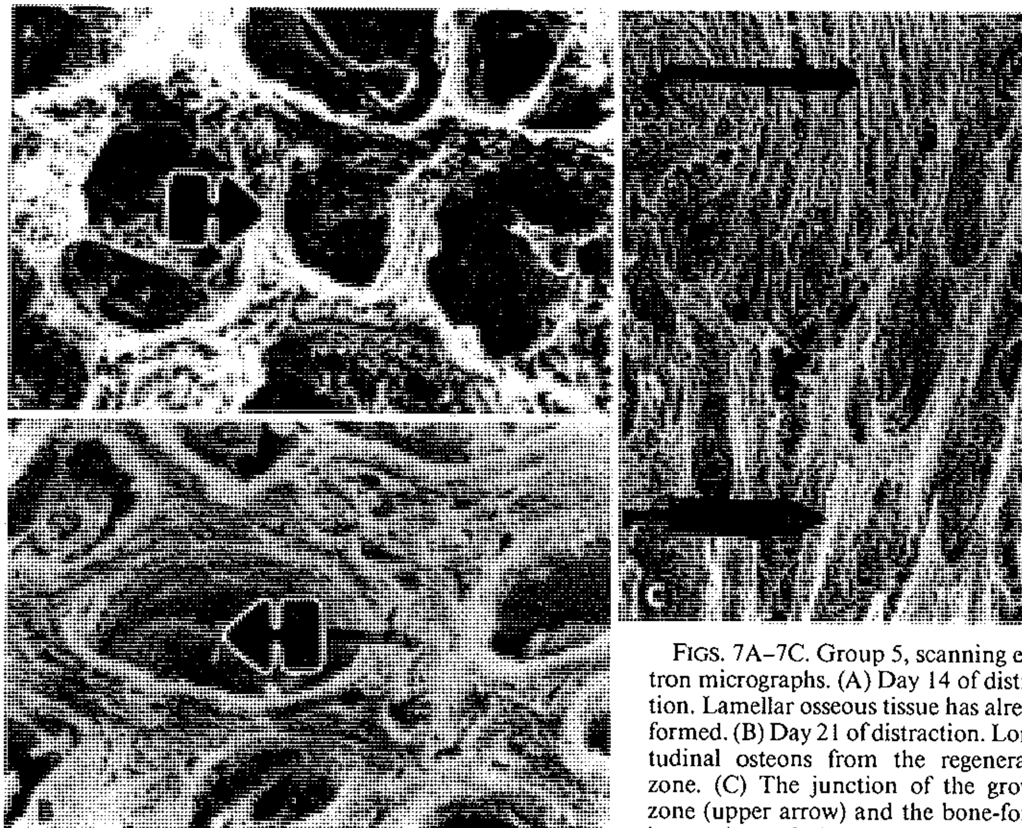
connective tissue containing large islands of cartilage (Fig. 6A). In the second group, which had somewhat less motion between the bone ends, there was, within the same time-frame, substantially more osteogenic activity in the distraction space (Fig. 6B). The upper and lower ends of the gap were filled with cone-shaped segments of regenerated osseous tissue separated by a fibrocartilaginous layer. The connective tissue and osteoid trabeculae of the middle layer did not have a definite spatial orientation.

In the third (most rigid fixation) group by Day 14 of distraction, still more osteogenic activity was noted in the space between the bone fragment ends (Fig. 6C). An even greater portion of the distraction space was filled with regenerated osseous tissue where osteoid trabeculae formed. As a result of this high level of osteogenic activity, the regenerated bone in the separation zone usually had fused to the cortex of one of the fragments. The connective tissue fibers and cells and the osseous trabeculae in the bone-forming region all had a longitudinal orientation.

In the fourth experimental group (with two-thirds preservation of the bone marrow integrity) osteogenesis proceeded more actively than in the third group. By Day 7 of distraction, nearly all of the space between the bone ends was filled with a dense network of relatively thick osseous trabeculae that penetrated into the proximal and distal bone marrow where they were knitted to the cut surfaces of the cortices over their entire thickness (Fig. 6D). In the middle of the distracted region, there was a thin osteogenic layer in which osteoid trabeculae were forming. This bone-forming layer is called the growth zone of the distraction-regenerated region, since, in some ways, it resembles an epiphyseal plate.

In the fifth experimental group, which had maximum preservation of the medullary and periosteal elements by means of a closed osteoclasis, the intense osteogenic activity overtook distraction and consolidated the bone prematurely when distracted at a rate 0.5 mm per day at a frequency of 0.125 mm every six hours (Fig. 6E). For this reason, it was necessary to distract the osteotomy site by 1.5 mm per day in four equal steps. In some animals, by Day 14 of distraction, the fracture gap con-

← segments of regenerated bone attached to each bone fragment (arrows) separated by a fibrocartilaginous layer. (C) Group 3. The distraction space contains regenerated osseous tissue with longitudinal trabeculae. (D) Group 4. Day 7. The entire distraction gap is filled with osseous tissue with a thin osteogenic growth zone (arrow) in the middle. (E) Group 5. Osteogenesis overtook distraction and consolidated the bone prematurely.

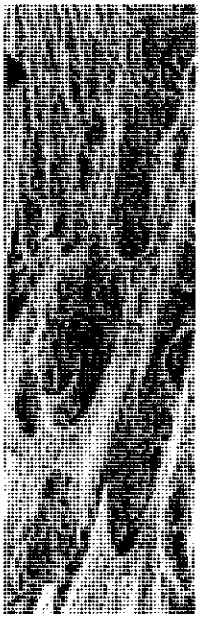


FIGS. 7A–7C. Group 5, scanning electron micrographs. (A) Day 14 of distraction. Lamellar osseous tissue has already formed. (B) Day 21 of distraction. Longitudinal osteons from the regenerated zone. (C) The junction of the growth zone (upper arrow) and the bone-forming region of the regenerated region (lower arrow). (Original magnification, ×500 in A and B, ×25 in C.)

solidated anyway, testifying to the intensity of the osteogenic process. With such a high level of osteogenesis, the orientation of the tissues within the separation zone was strictly longitudinal and, by the second week of distraction, lamellar osseous tissue was formed (Fig. 7A). By the end of the third week of distraction, osteons in the regenerated bone were already well developed (Fig. 7B). At the same time, in the central growth zone of the regenerated bone-forming layer, there were centers of active osteon formation (Fig. 7C).

The differences in osteogenic activity among the various experimental groups persisted throughout subsequent stages of distraction. Specifically, in the first experimental group, where there was marked mobility of the fragments, a tendency toward pseudarthrosis formation was observed. Thus, on Day 28 of distraction, the ends of the distracted bone fragments were sealed over with thin cone-shaped osseous plates and were separated by fibrous tissue containing much cartilage (Fig. 8A). In some cases, where the mobility between the bone ends allowed full shaft-width displacement within the fixator, osteogenesis was faint, and the gap was primarily filled with hemorrhagic cartilaginous tissue by the end of the distraction period. The network of endosteal bone trabeculae did not penetrate into the gap beyond the original marrow canal (Fig. 8B).

On the 35th and final day of distraction the second group, with somewhat less mobility of the fragments, showed formation of cones of bone 1.5–2.0 mm in height as the only osse-



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FIGS. 8A AND 8B. Day 28 of longitudinal distraction. (A) Group 1. Cone-shaped osseous plates seal over the bone ends that are separated by fibrous tissue containing islands of cartilage. (B) Group 1. With full shaft-width displacement, the gap is filled with hemorrhagic cartilaginous tissue.

ous tissue within the separation zone. The greater middle part of the gap was occupied by cartilaginous connective tissue, indicating a low level of osteogenic activity. In the third experimental group, by the end of the distraction period, almost all of the separation zone was filled with regenerated bone at a site where a bone marrow canal and a circumferential cortical plate had formed.

A very high level of osteogenic activity was observed in the fifth experimental group, the group with maximum preservation of bone marrow integrity, even though the rate of distraction was 1.5 mm per day (Fig. 9).

In animals not sacrificed during or at the end of limb elongation, distraction was followed by a variable period of neutral fixation in the apparatus without further distraction, after which the fixator was removed. In Group 5, on Day 30 of neutral fixation (Day 65 of the experiment), there was formation of a substantial osseous cortex, which was covered with periosteum, surrounding the regenerate zone (Fig. 10). Starting from the middle of the regenerate zone, the osseous trabeculae thinned out in both the proximal and distal directions, while the intertrabecular spaces had increasingly greater concentrations of fatty and hematopoietic marrow cells. Approximately the same picture was observed in Group 3 (complete marrow transection) and Group 4 (partial marrow transection). However, the described conditions were not observed in Group 4 until Day 77 of the study and not in Group 3 until Day 109 of the study. In Group 5 (closed osteoclasis), by Day 103 of the experiment, the newly formed cortex of the regenerate zone did not differ from

FIG. 9. Group 5 on Day 28 of distraction. A high level of osteogenic activity with cortex formation was observed. Note the growth zone in the center of the distraction gap.

the old bone in density and thickness; in some areas, it was even thicker. In this group, there was no definite boundary between the old and newly formed bone.

In Group 4 (two-thirds marrow preservation), the cortical plate of the regenerated area ultimately reached almost the same structure and thickness as it did in Group 5, but not until Day 139. The same results were observed in Group 3 (complete marrow transection) by Day 169.

Transverse Distraction

In the first group of dogs distracted transversely (with preservation of the bone marrow contents by using the cortical cutter), the following observations were made. In animals with the tibia widened at the rate of 1 mm per day in four steps (0.25 mm every six hours), the split was displaced from its bed by a total of 8 mm on Day 8 of distraction. Histologically, the space between the displaced fragment and the opposite cortex was filled with a finely celled network of trabeculae, most of which were oriented transversely (Fig. 11A). In the subgroup with lateral distraction at a rate of 1.5 mm per day in four steps (0.375 mm every six hours), the dis-

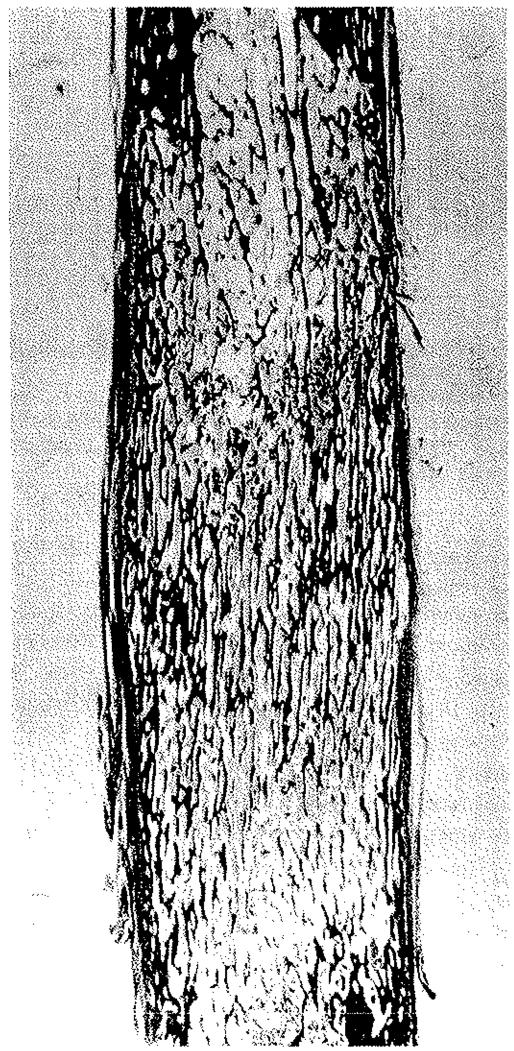

FIG. 10. Group 5, Day 30 of neutral fixation. A substantial cortex, covered with periosteum, has formed.

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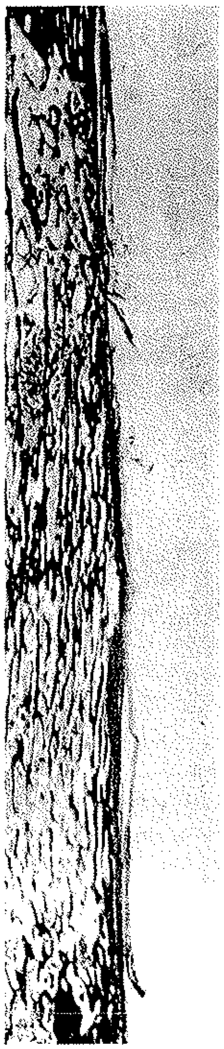

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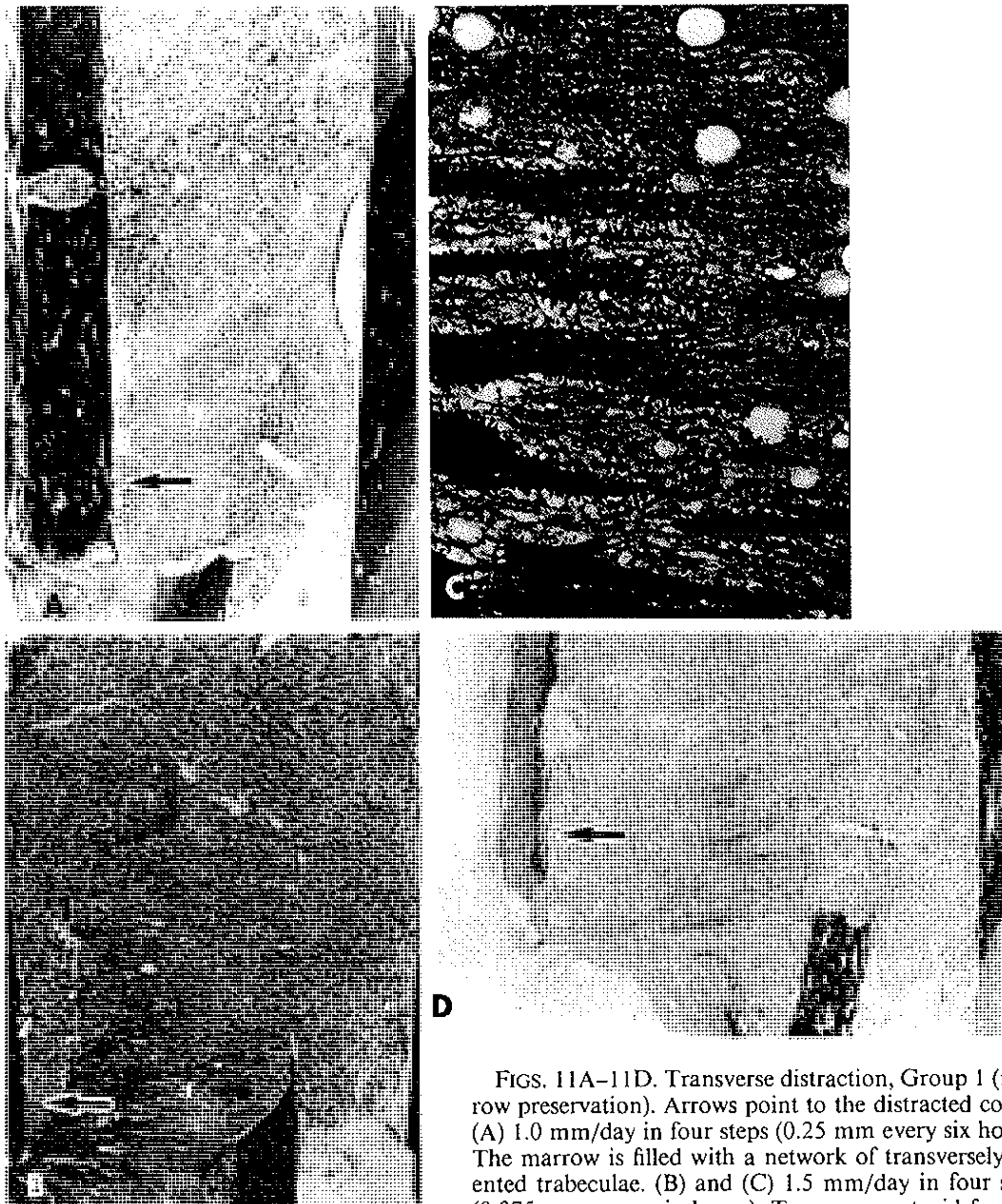
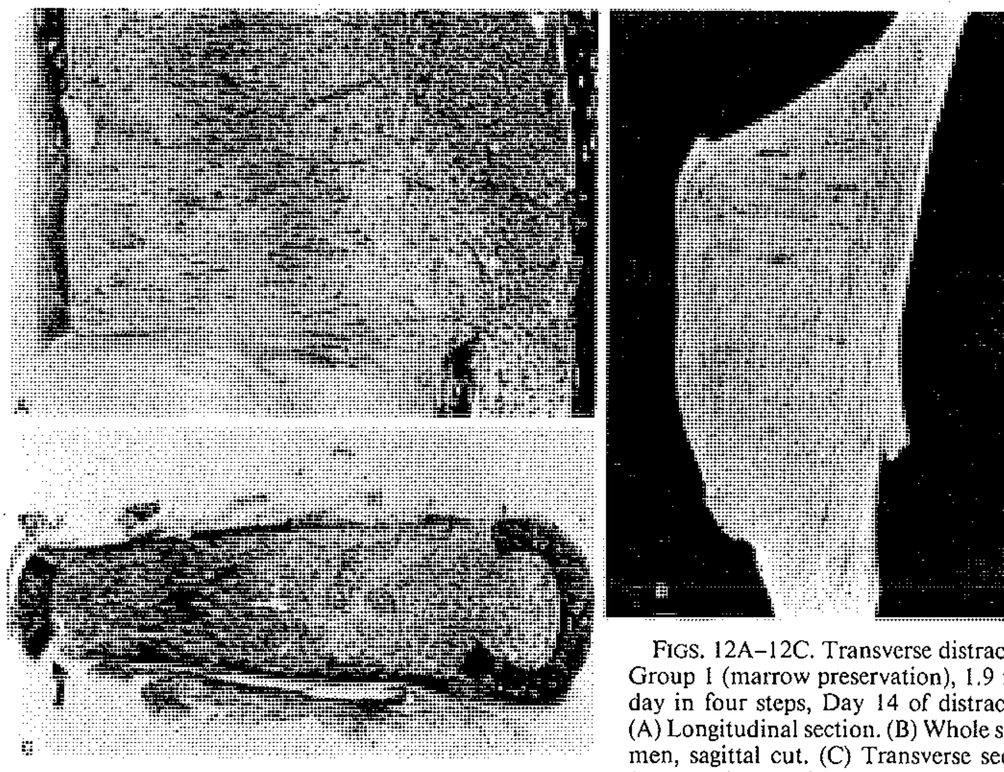


FIGS. 11A–11D. Transverse distraction, Group 1 (marrow preservation). Arrows point to the distracted cortex. (A) 1.0 mm/day in four steps (0.25 mm every six hours). The marrow is filled with a network of transversely oriented trabeculae. (B) and (C) 1.5 mm/day in four steps (0.375 mm every six hours). Transverse osteoid formed, turning into bone trabeculae at the ends of the gap. (D) Day 14 of distraction. (Original magnification, ×160 in C.)

placement of the fragment from its bed was 10–12 mm by Day 8 of distraction (Fig. 11B). In the central regions of the space formed by the displacement, there was an osteogenic layer from which transversely oriented osteoid trabeculae formed, turning into bone trabeculae toward the periphery (Fig. 11C). By Day 14 of lateral distraction in this group, the space was 20–22 mm wide and was filled with a finely celled network of osteoid and osseous



FIGS. 12A–12C. Transverse distraction, Group I (marrow preservation), 1.9 mm/day in four steps, Day 14 of distraction. (A) Longitudinal section. (B) Whole specimen, sagittal cut. (C) Transverse section (arrow points to distracted segment).

trabeculae united to the inner surfaces of both the remaining cortical bone and the split cortical plate (Fig. 11D). The structure of the regenerated tissue within the gap had a marked transverse orientation. In one dog, distracted at a rate of 1.5 mm per day, there was no lateral movement of the fragment after Day 8; all of the space between the split and its bed was filled with cancellous bone. Taking into consideration the width of the gap (11 mm), bone union had obviously occurred on Day 7 or 8 of distraction, demonstrating the rapid osteogenic process that can overtake distraction.

In the subgroup of dogs distracted 1.9 mm per day in four steps (0.475 mm every six hours), the gap was 27 mm wide on Day 14 of distraction (Fig. 12A and 12B). Some histologic studies were performed after seven additional days of neutral fixation of the distracted fragment. In this subgroup, osteogenesis was also active. The space between the split cortical fragment and the inner surface of the opposite cortex was filled with a finely celled network of bone trabeculae. Transverse sectioning through the distracted zone revealed a newly formed cortex covered by periosteum (Fig. 12C). In one dog, there was scar tissue in the region of the proximal end of the split where the bone marrow had been partially damaged while performing the osteotomy.

In the group of dogs where the cortical fragment was split off with an osteotome (damaging the marrow contents), osteogenic activity within the distraction gap was greatly reduced. The subgroup distracted at a rate of 1.5 mm per day was noted, by Day 7 of dis-

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FIGS. 13A AND 13B. Transverse distraction, Group 2 (marrow damage). (A) Day 7 of distraction, 1.5 mm/day in four steps. Necrotic tissue fills approximately one-third of the distraction gap. (B) Day 60 of the experiment. The gap is filled with fibrous tissue. An arrow points to the distracted cortex.

traction, to have necrotic tissue filling approximately one-third of the distraction gap (Fig. 13A). By Day 60 of the experiment, osteogenesis was less marked than in the corresponding animals osteotomized longitudinally without marrow damage (Fig. 13B). This deficiency in osteogenesis occurred at all rates of distraction.

ULTRASTRUCTURAL AND BIOCHEMICAL OBSERVATIONS

A growth zone is located in the middle of the regenerated region. Active osteogenesis occurred here during the entire period of elongation. The growth zone gradually ossified during neutral fixation after the elongation period.

Under the influence of tension–stress during elongation, fibroblastlike cells of the growth zone formed collagen fibers that were oriented parallel to the tension vector, upon which osteoblasts laid down osteoid tissue. This osteoid tissue gradually blended into newly formed bone trabeculae in the regions furthest away from the central growth layer (Fig. 14). This indicated that newly formed bone grew and matured distally and proximally away from the middle zone during distraction and that, moreover, a high level of osteogenic activity (resulting in morphologic and structural bone formation) occurred throughout the entire period of distraction.

The fibroblastlike cells located in the middle of the growth zone had an elongated shape and were oriented along the tension–stress vector during distraction (Fig. 15). The cells were concentrated around sinusoidal blood capillaries. At the ultrastructural level, these cells were characterized by hyperplasia of the granular endoplasmic reticulum within the cytoplasm (Fig. 16A) and the nucleoli of the nuclei (Fig. 16B), both features typical of a high level of biosynthetic activity. Surrounding the fibroblastlike cells were collagen fibrils bunching into fibers in the distal and proximal directions. These fibers also were aligned parallel to the vector of tension, whether longitudinal or transverse (Fig. 17).

With rigid fixation, active osteogenesis in

FIG. 14. Longitudinal distraction, Group 5. The middle of the distraction zone shows longitudinally oriented collagen fibers in association with fibroblastlike cells. Osteoid tissue grows and matures proximally and distally (van Gieson's, original magnification, ×25).

the distraction zone proceeded under the influence of tension–stress by the shortest, most direct route, omitting the cartilaginous phase that is characteristic of enchondral ossification.

Osteoid-producing osteoblasts were located in chains along the collagen fibers that formed the framework for the production of trabeculae. Ultrastructural studies of the osteoblasts within the regenerated region revealed an increase in both the numbers and size of their mitochondria, including the appearance of giant forms, with abundant tightly packed cristae (Fig. 18A). Furthermore, there were numerous cisterns of endoplasmic reticulum densely packed with ribosomes within the cytoplasm. These features indicate intense metabolic activity and protein synthesis. The ultrastructural elongated organelles of the osteoblasts had a distinct orientation along the tension–stress vector (Fig. 18B). This parallel orientation was also characteristic of the osteoid and the bone trabeculae as well as the osteocytes located within them.

Histochemical studies of the growth zone were performed. The high level of osteogenic activity was confirmed by the metabolic characteristics of the growth zone. Alkaline phosphatase, which is synthesized by fibroblasts and takes part in the formation of the collagen matrix and its mineralization, increased throughout distraction (Fig. 19). Pyruvic acid increased in the growth zone throughout the distraction period (Fig. 20), as did the lactic acid produced by lactic dehydrogenase (an

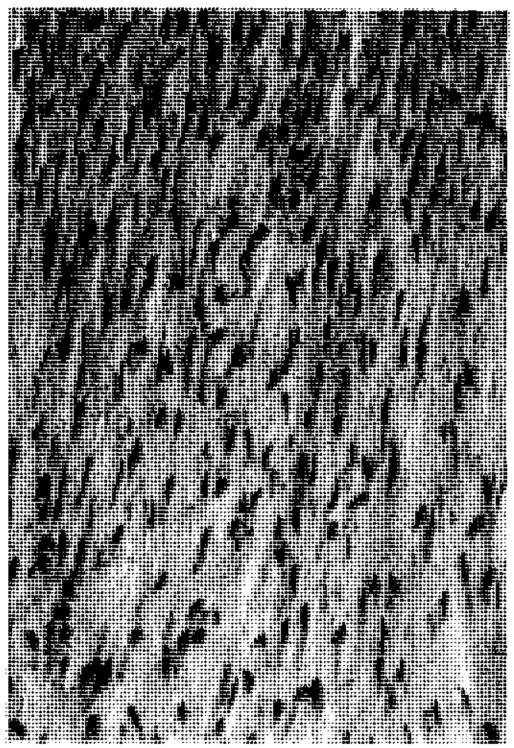

FIG. 15. Longitudinally oriented fibroblastlike cells in the middle of the growth zone, Group 5 (van Gieson's, original magnification, ×160).

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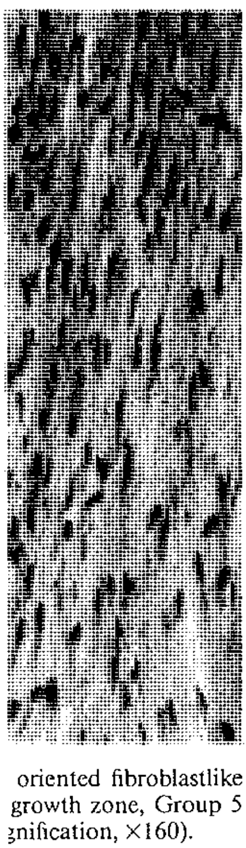

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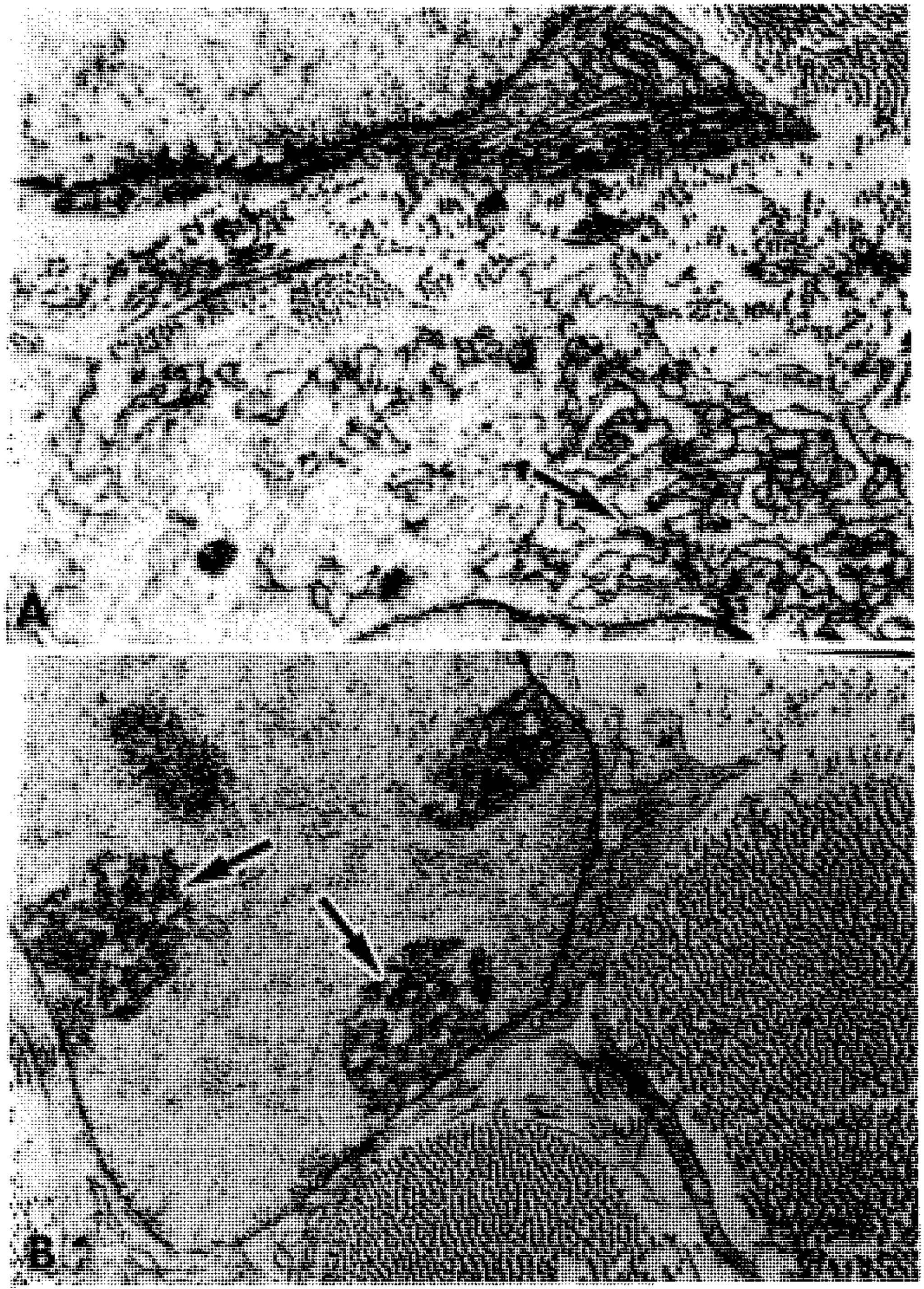

FIGS. 16A AND 16B. Ultrastructure of fibroblastlike cell in the distraction region, Group 5. (A) Hyperplasia of the granular endoplasmic reticulum (arrow). (B) Hyperplasia of nucleoli within the nucleus (arrow). (Original magnification, ×3000.)

FIG. 17. Foot stain of collagen in the distraction region, Group 5. The collagen fibers are aligned with the tension vector, forming bundles toward one bone fragment end (bottom, out of view). (Original magnification, ×25.)

oxidation-reduction enzyme that provides energy for biosynthetic processes; see Fig. 21).

New blood vessels also formed along the direction of the tension vector (Fig. 22). Under the optimum conditions of traction, blood capillaries of two types appeared by Day 7 of distraction: (1) sinusoidal capillaries characterized by a wide lumen and the presence of openings in the endothelium and (2) transport capillaries characterized by a narrow lumen and a continuous epithelium (Fig. 23A).

After Day 21 of distraction, the growth of newly formed capillaries under the influence of tension overtook the speed of distraction, as demonstrated by the appearance of lengthwise and circular folds on the inner surface of the endothelium (Fig. 23B). These newly formed vascular structures anastomosed with the soft-tissue vessels surrounding the distraction zone *via* multiple perforating vessels. This intense angiogenic activity occurred regardless of whether the distraction was longitudinal or transverse.

During elongation, under the influence of the tension–stress effect, skeletal muscle demonstrated ultrastructural changes in both the energy-supplying and protein-synthesizing systems. On Day 14 of distraction at a rate of 0.125 mm every six hours, the energy-providing mitochondria hypertrophied and displayed an enlarged volume with multiple cristae (Fig. 24A), especially in sections obtained from the ends of the muscle fibers and from the subsarcolemmal regions where actin and myosin myofilaments were being actively synthesized on the polysomes (Fig. 24B). The functional activity of the nuclei was enhanced, characterized by hypertrophy of their nucleoli and the appearance of deep karyolemmal invaginations (Fig. 24C).

Muscle growth under the influence of tension–stress occurred not only by myofibrilogenesis in preexisting muscle fibers but also by the formation of new muscle tissue, as demonstrated by the increased numbers of muscle satellite cells,[3,14] the appearance of myoblasts, and their fusion into myotubes. Within the newly formed muscle fibers, active formation of myofibrils and sarcomeres took place (Fig. 24D).

Smooth muscle tissue in the blood vessel walls also grew under the influence of the tension–stress effect. Thus, by the end of the first week of distraction at 0.125 mm every six hours, activated arterial wall smooth muscle cells were found in the subendothelial intima spaces. By Day 14 of distraction, activated smooth muscle cells were found in the middle layer of the vessel walls as well. These cells differed from contractile myocytes by the significant development of mitochondria, ribosomes, endoplasmic reticulum, and other cytoplasmic organelles. Likewise, they differed from normal arterial wall myocytes by the hypertrophy of their nuclei and by the ap-

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FIGS. 18A AND 18B. Ultrastructure of osteoblasts in the distraction region, Group 5. (A) Giant mitochondria with tightly-packed cristae (B) Elongated mitochondria (large arrow) and endoplasmic reticulum (small arrows). (Original magnification, ×3000.)

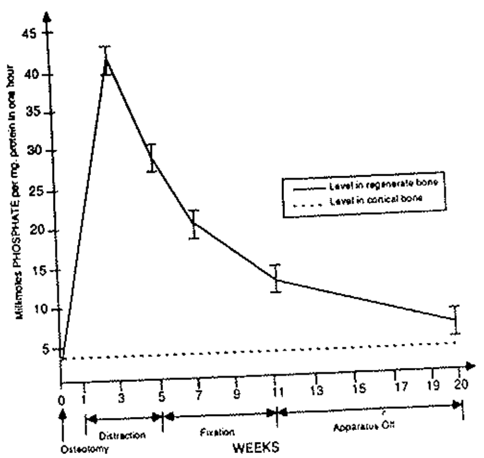

FIG. 19. Phosphate production in the regenerate zone.

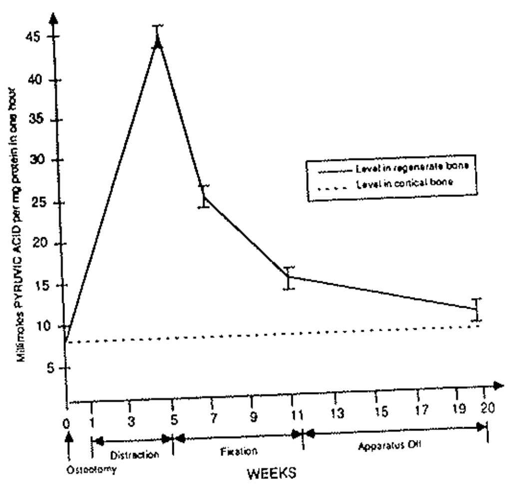

FIG. 20. Pyruvic acid production in the regenerate zone.

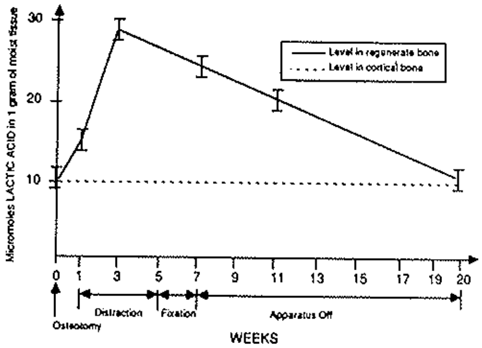

FIG. 21. Lactic acid production in the regenerated zone.

pearance of finely dispersed, functionally active euchromatin in the nuclei (Fig. 25A). This intensified smooth muscle cell biosynthetic activity and proliferation were accompanied by an increase in the extent and number of intracellular contacts between them and by the new formation of elastic structures (Fig. 25B). Furthermore, the orientation of the smooth muscle cells changed from their usual circular configuration to a longitudinal one (Fig. 25C), with cellular formation taking place near the inner elastic membrane.

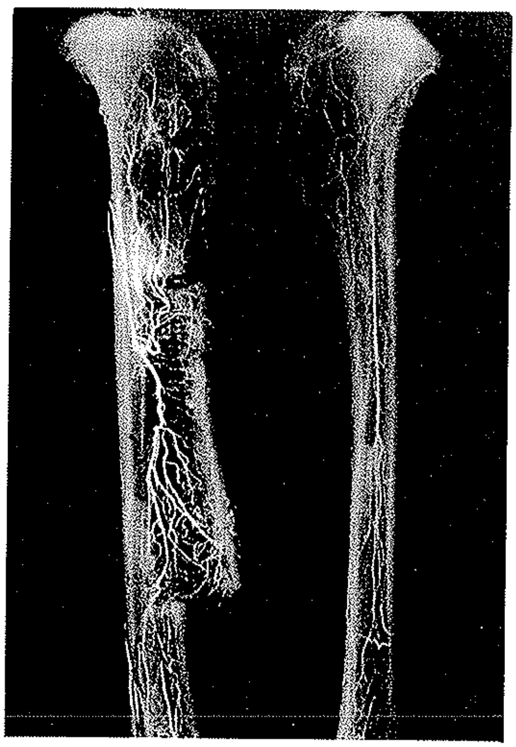

FIG. 22. Neovascularization associated with transverse distraction, revealed by contrast studies of both limbs.

These morphologic changes in the ultrastructure of arterial wall smooth muscle cells are similar to the changes described in the walls of arteries elongating during active pre- and postnatal growth.[31] Morphologic features common to elongating smooth muscle cells under the influence of either tension–stress or normal growth included (1) biosynthetic activation of smooth muscle cells and an increased number of contacts between them,[1,3] (2) new formation of elastic structures in the arterial walls,[28] and (3) longitudinal orientation of the smooth muscle cells.[29]

Alterations similar to those just described occurred in the connective tissue of fascia, tendons, and dermis as well as in the endomysium and perimysium of muscle, the adventitia of blood vessels, and the epineurium and perineurium of nerve trunks. The collagen fibers generally were oriented along the vector of tension–stress (Fig. 26A) as were fibroblast cytoplasmic organelles, including the granular endoplasmic reticula (Fig. 26B) and the mitochondria. Likewise, the number of fibroblasts increased during distraction and the contact areas between them multiplied, with dense junctions in many places. Dense intracellular junctions are characteristic of fibroblasts in developing connective tissue of embryos, fetuses, and newborn animals.

Another typical feature of the fibroblasts in the distraction region was hypertrophy of the Golgi complex (Fig. 26C), along with enlargement of the mitochondria, the cytoskeletal microfilaments, and the granular endoplasmic reticulum. Such cellular changes identified the fibroblasts as Type II collagenoblasts, cells typical of embryonic connective tissue.[27] The microfibrillar biosynthetic products within the fibroblasts were located in either large secretory vacuoles (Fig. 26D) or in the

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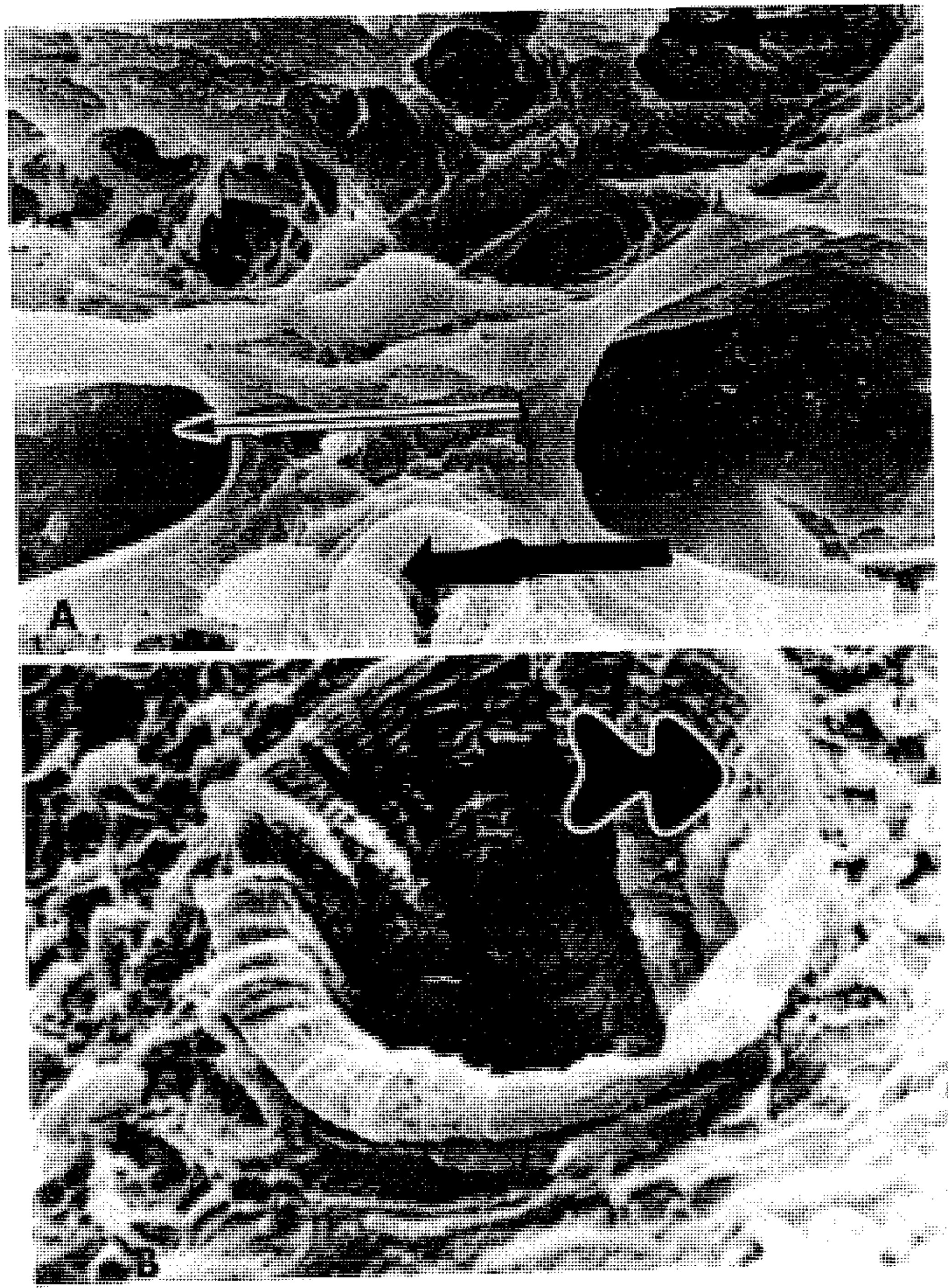
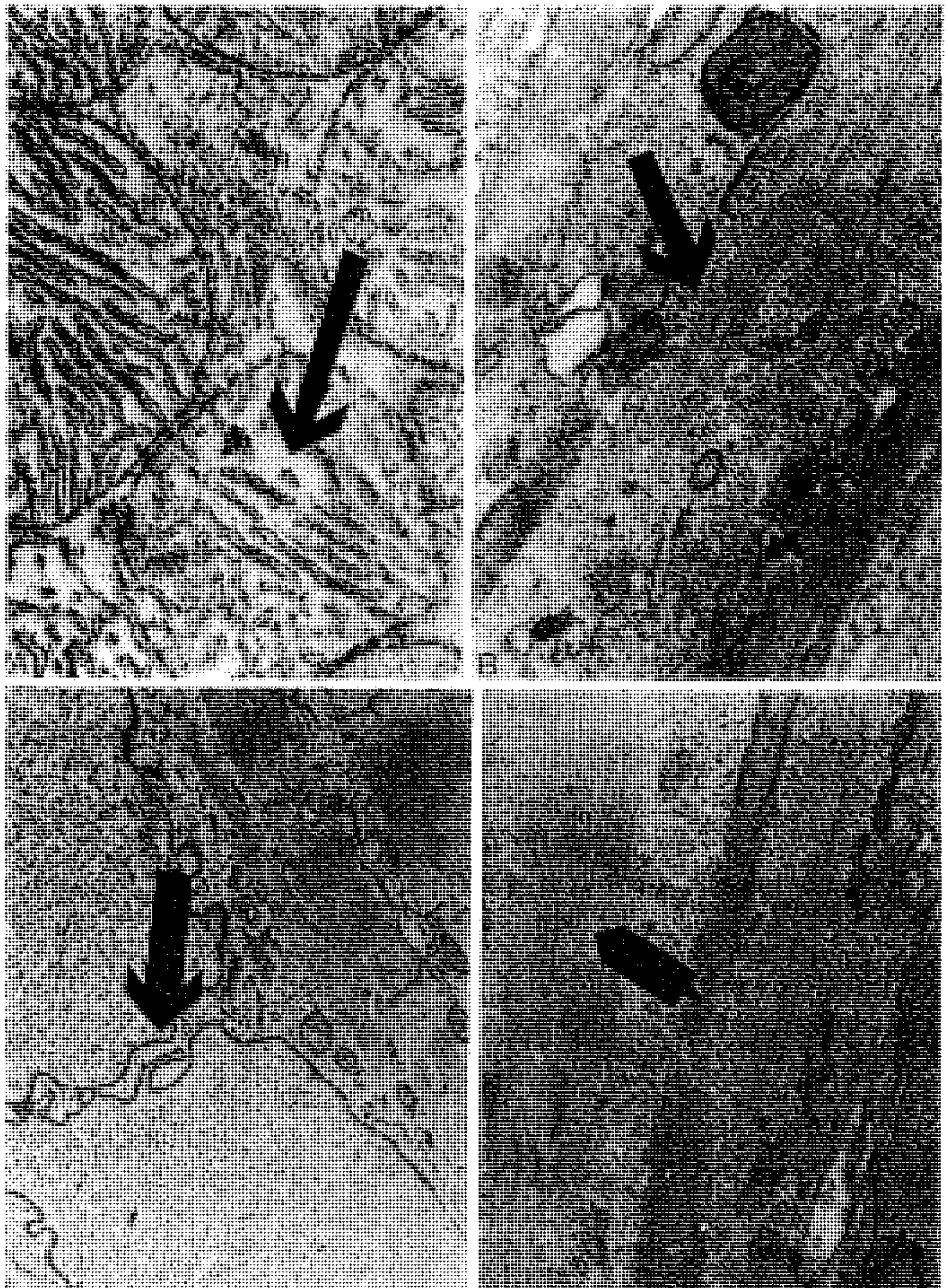
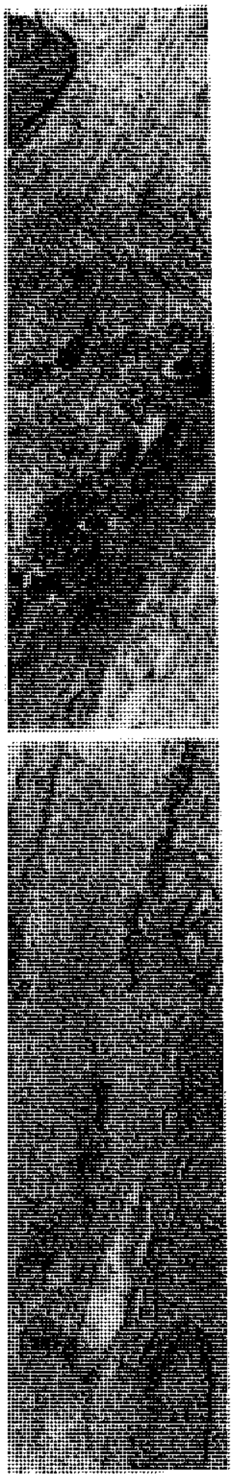


FIGS. 23A AND 23B. Capillary growth in fascia being distracted. (A) Sinusoidal capillaries (upper arrow) and transport capillaries (lower arrow). (B) Capillary endothelium with transverse and longitudinal folds (arrow) indicating that capillary growth overtook the rate of distraction. (Original magnification, ×800.)



FIGS. 24A–24D. Ultrastructure of skeletal muscle. (A) Hypertrophied mitochondria with multiple cristae (arrow). (B) Myofilament synthesization on the polysomes (arrow). (C) Karyolemmal invaginations characteristic of enhanced functional activity (arrow). (D) Active formation of myofibrils and sarcomeres (arrow). (Original magnification, ×20,000 in A; ×15,000 in B; ×8000 in C and D.)



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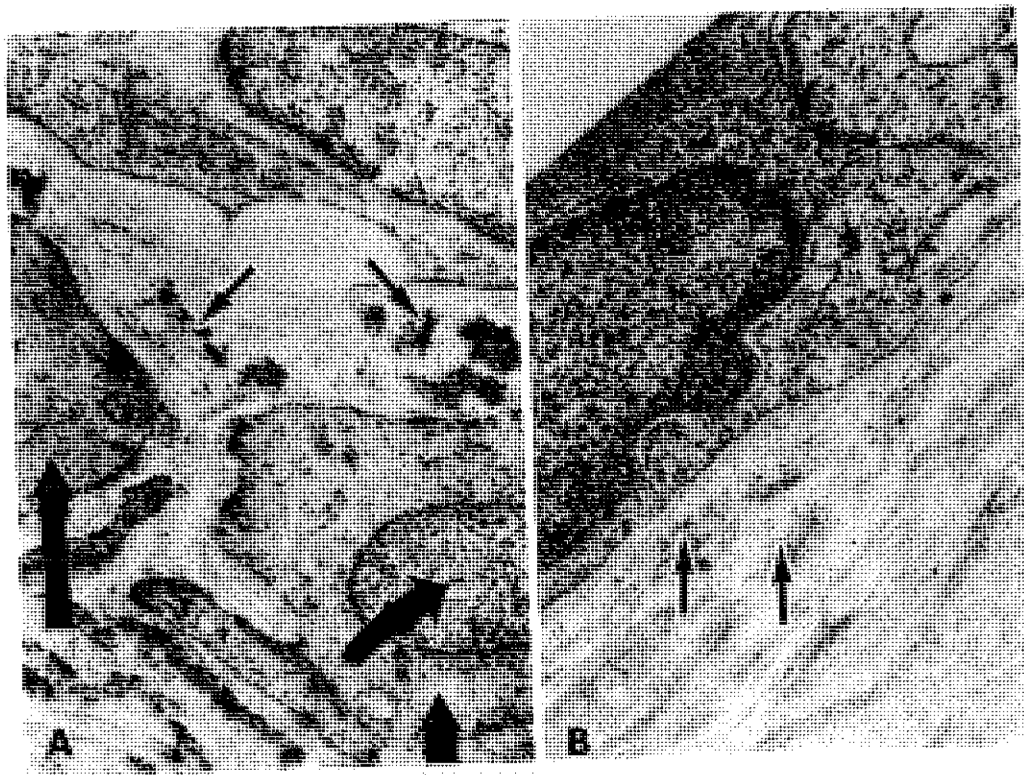
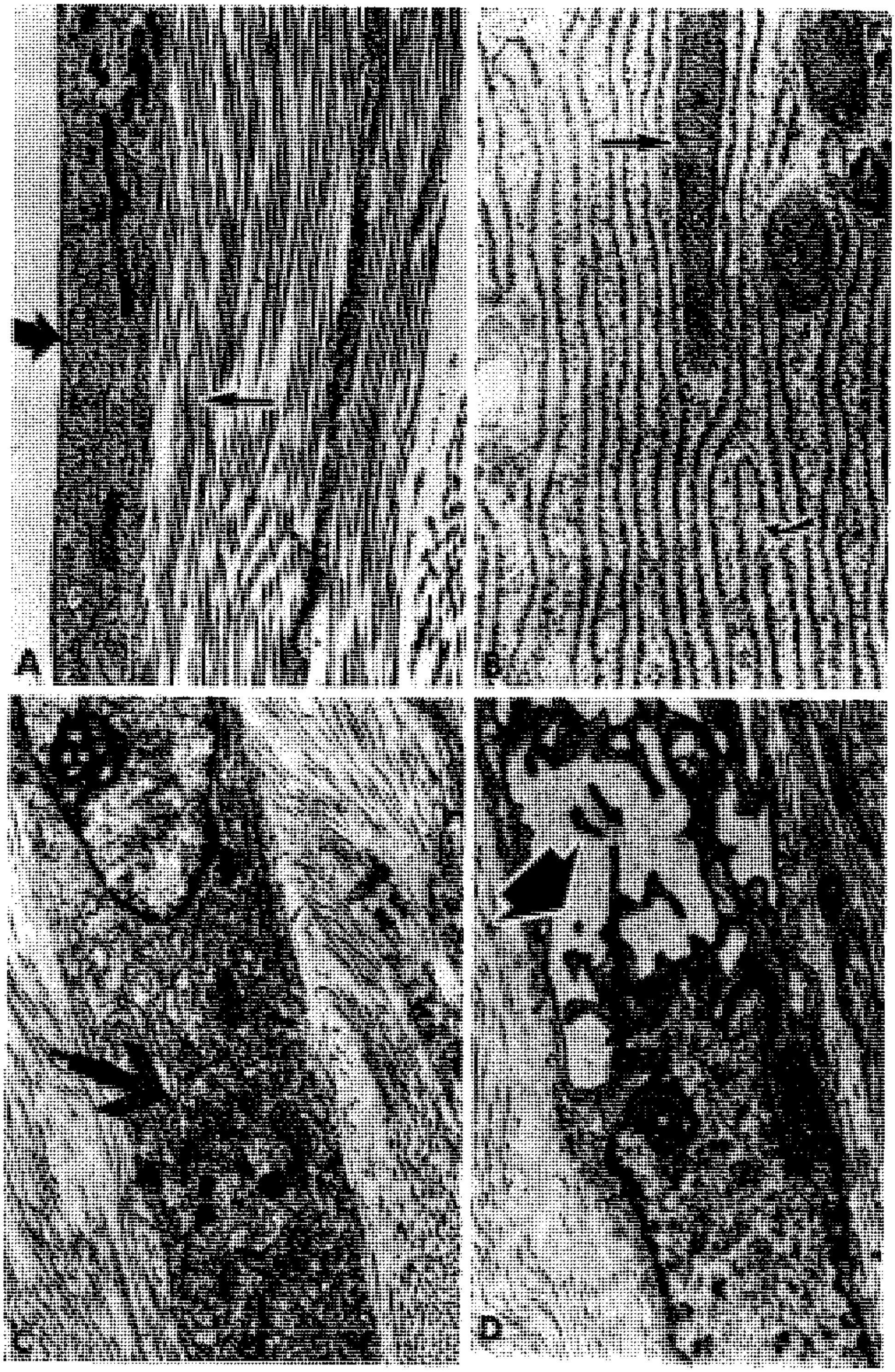
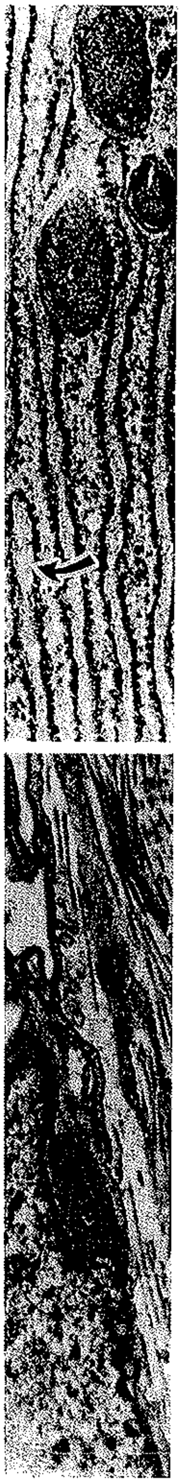


FIGS. 25A–25C. Ultrastructure of arterial wall smooth muscle cells during distraction. (A) One week of distraction. Finely dispersed functionally active euchromatin (curved arrow), elastic structures (small arrows), and activated smooth muscle cells (large straight arrows). (B) Formation of elastic structures (arrows). (C) Longitudinal orientation of arterial wall smooth muscle cells. (Original magnification, ×15,000 in A; ×8600 in B; ×500 in C.)



FIGS. 26A–26D. Ultrastructure of connective tissue with longitudinal traction. (A) Longitudinal orientation of collagen fibers (small arrow) and fibroblast (large arrow) along the tension–stress vector. (B) Longitudinal orientation of granular endoplasmic reticulum (lower arrow) and mitochondria (upper arrow). (C) Hypertrophy of Golgi complex within fibroblast (arrow). (D) Microfibrillar biosynthetic products within large secretory vacuoles (arrow). (Original magnification, ×22,200 in A and B; ×12,000 in C; ×22,000 in D.)



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cisternae of the granular endoplasmic reticulum. The microfibrils were, in some sections, being excreted directly into the pericellular space, apparently bypassing the Golgi complex, thus indicating intense secretion of collagen and elastic fiber precursors. Moreover, the orientation of the fibroblasts parallel to the tension vector predetermined the position of the newly forming collagen fibers; this, in turn, directed the orientation of the new microcirculatory blood vessels within the connective tissue.

As with normal limb growth, tissues elongated under the influence of the tension–stress effect were accompanied by the development and growth of nerves innervating them. By Day 7 of distraction, the elongated axons were partially surrounded by the cytoplasmic processes of Schwann cells (Fig. 27A). Eventually, these processes grew to completely envelop an axon and join one another (Fig. 27B). By Day 21 of distraction, the Schwann cells (1) had lengthened, (2) had spiraled around an axon (Fig. 27C), and (3) had formed a myelinic membrane (Fig. 27D). These changes are well known to embryologists studying the electron microscopic features of embryonic peripheral nerve formation, yet they appear as the result of the tension–stress effect in adult animals during limb elongation.

The cellular elements of the skin also showed signs of activation as a result of tension–stress, mainly in the basal cell layer of the epidermis. By Day 21 of distraction, the basal cells had acquired a highly cylindrical shape, with their long hyperchromatic nuclei oriented toward the long cellular axis, perpendicular to the basement membrane (Fig. 28A). Many mitotic figures were noted in the cells of the basal layer. As a result of this proliferative activity, the number of basal cell layers (and consequently the thickness of the skin) increased considerably—up to ten layers (compared to three to five layers in the control limbs; Fig. 28B). Moreover, the thickened basal cells appeared in four distinct subdivisions: growth, granular, squamous, and corneous zones. These changes are considered typical of skin with marked proliferation of the epidermal basal cells.

The skin appendages also were activated by tension–stress. By Day 21 of distraction, the number of hair follicles increased considerably, along with their associated sebaceous and sweat glands (Fig. 28C). Moreover, the glands, especially the sebaceous glands, hypertrophied. The hair roots were close to one another within the dermis, rather than being isolated structures, and were parallel to the surface. During further elongation, the number of hair follicles per cross-section area continued to increase (Fig. 28D). Hairs within the follicles of the distracted limb were of greater diameter than those of the control limb.

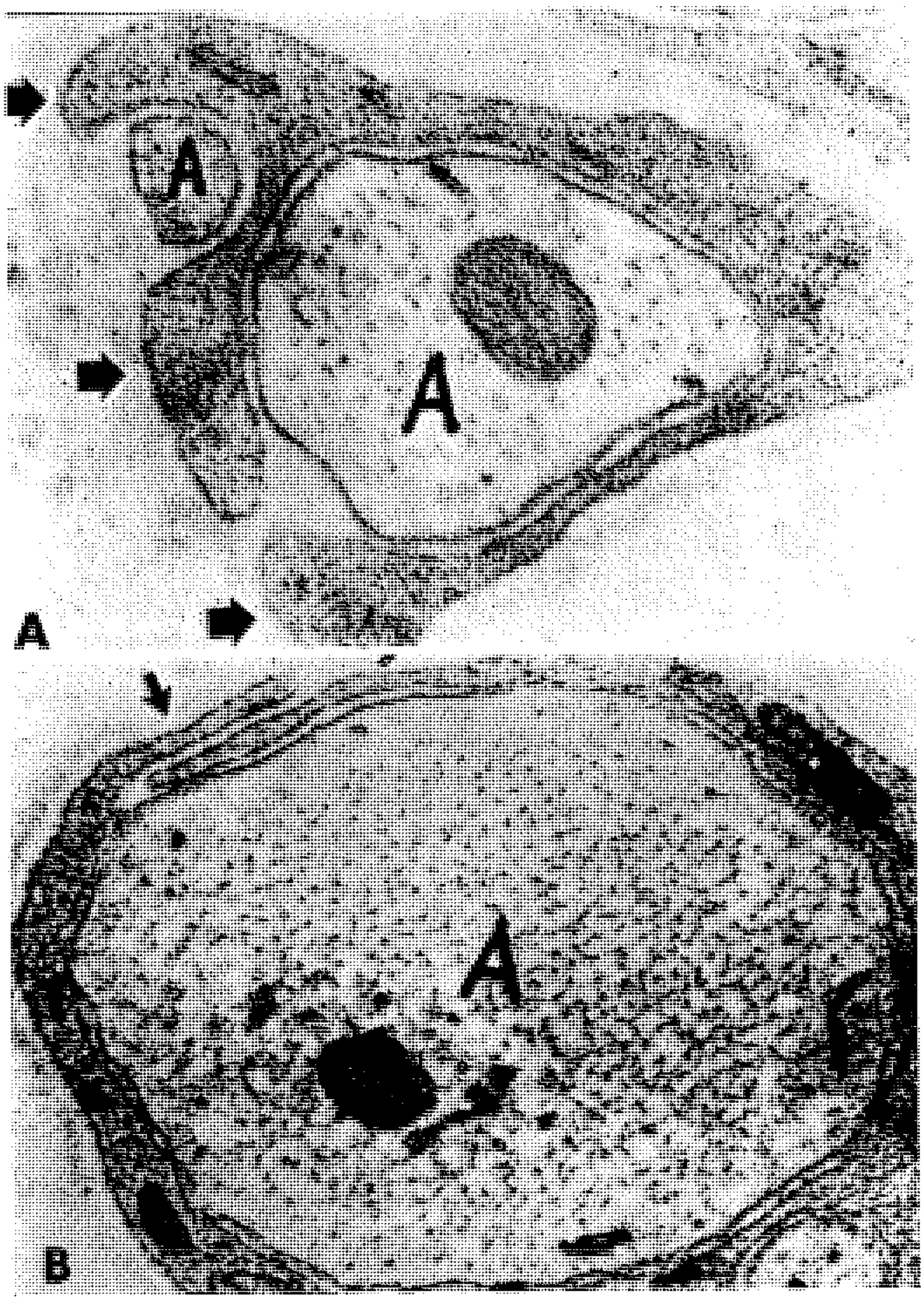
Cortical Defect

In the study involving half-circular and full-circular defects, the animals with a half-circular cortical defect showed a complete substitution within 21 days by new cancellous bone that spread far beyond the limits of the original bone marrow canal (Fig. 29A). In the animals with a complete cortical diaphyseal defect with intact marrow and uninterrupted nutrient vessels (Fig. 29B), the defect was filled with relatively dense regenerated bone by Day 21 of the experiment (Figs. 29C and 29D). In a few animals where the bone marrow blood supply was damaged inadvertently, osteogenesis was less pronounced, and there was no sign of bone union.

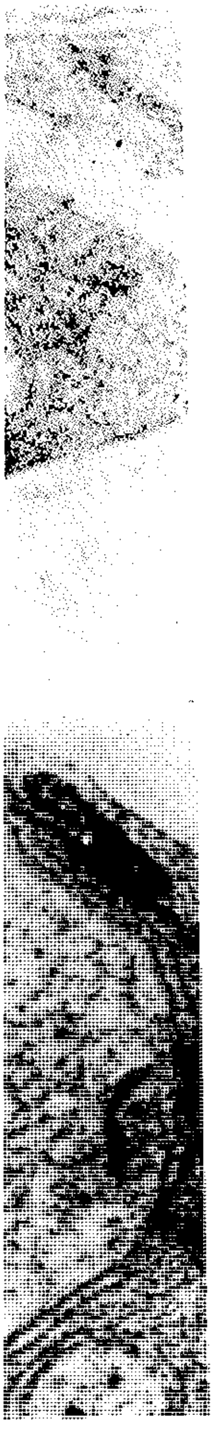
DISCUSSION

The studies described above, along with others performed in Kurgan[11,13,14,18,19,22–24] and elsewhere,[2,29,30,32] demonstrated that the level of osteogenic activity within the distraction zone depends upon (1) the degree of stability and (2) the amount of damage to the bone marrow, periosteum, and nutrient vessels occurring at the time of osteotomy.

The type of tissue filling a distraction space after osteotomy depended, to a considerable



FIGS. 27A–27D. Ultrastructure of the sequential changes of elongating nerves. (A) Axons, A, partially surrounded by Schwann cells (arrows). (B) Envelopment of axons, A, by Schwann cell (arrow). (C, next page) Spiral envelopment of axon, A, by Schwann cell (arrows). (D, next page) The formation of a myelinic membrane (arrows) around an axon, A. (Original magnification, ×3000.)



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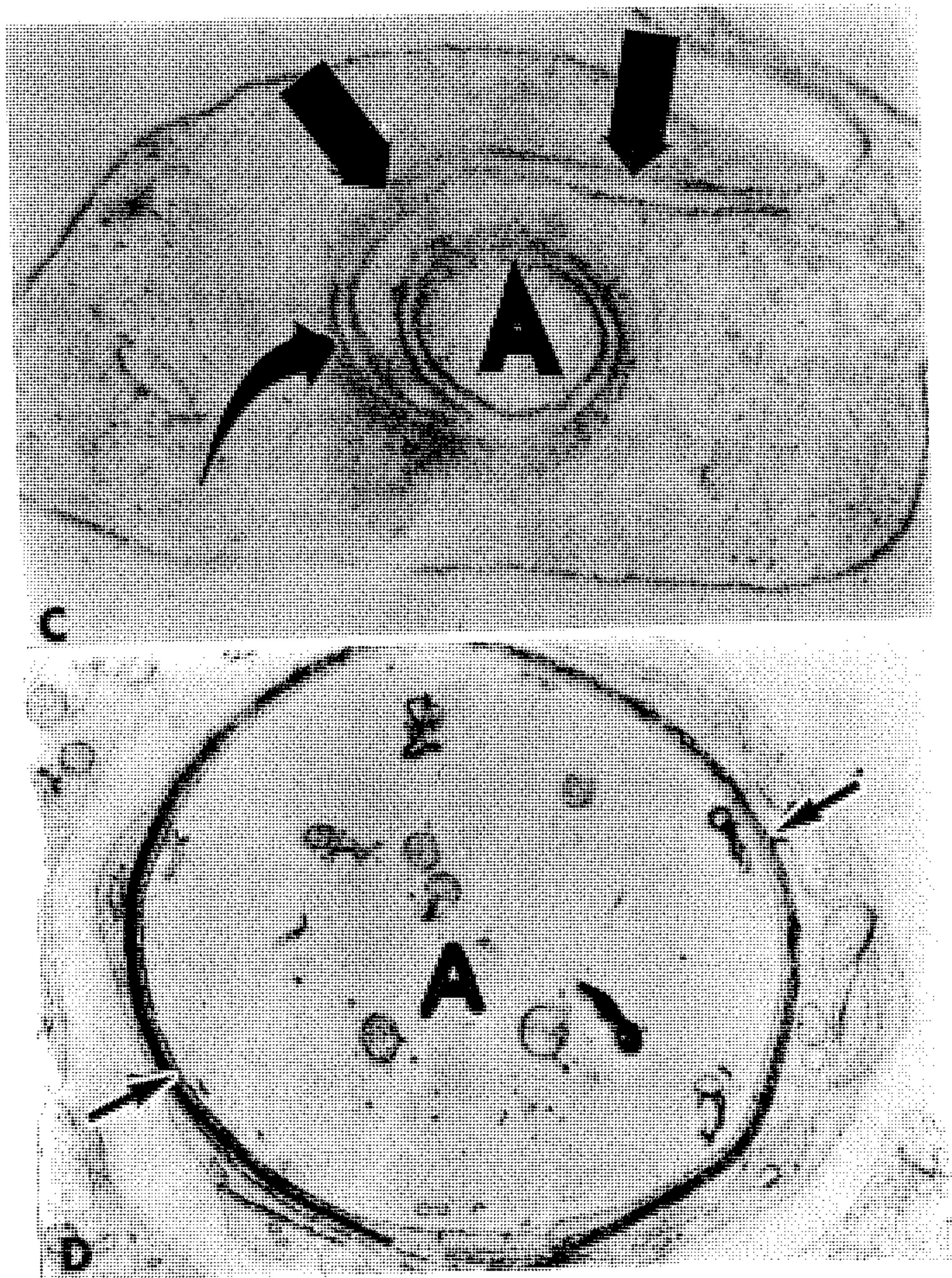
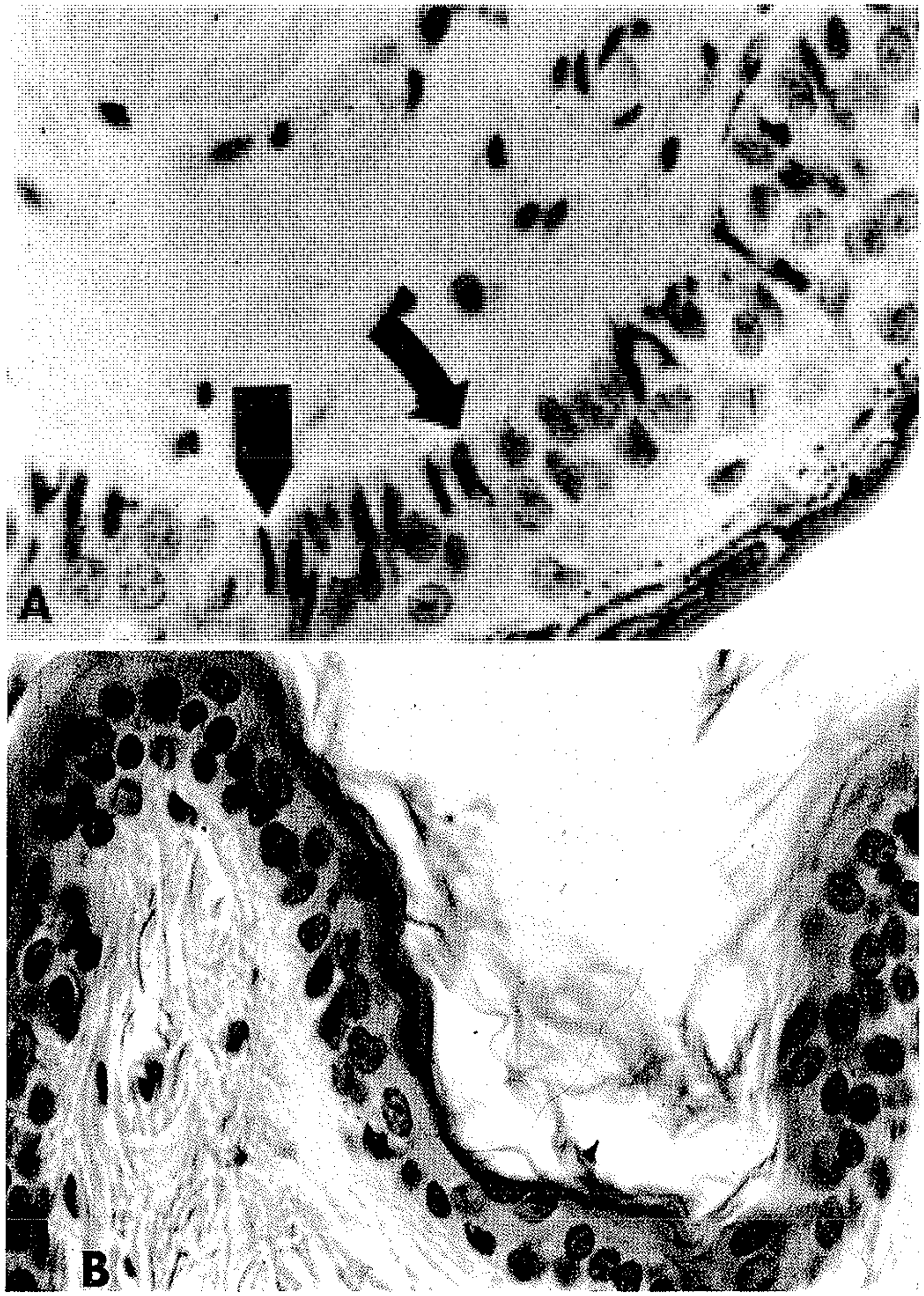
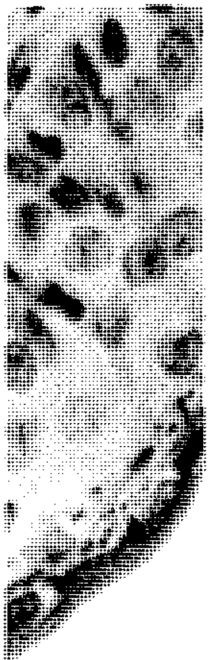




FIGS. 28A–28D. Skin changes during elongation. (A) Elongation of the basal cell nuclei (arrows), a sign of hyperplasia. (B) Appearance of the control limb without basal cell hyperplasia. (C, next page) Hyperplasia of sebaceous and sweat glands. (D, next page) Hyperplasia of hair follicles. (Hematoxylin and eosin in A and B, van Gieson's in C and D; original magnification, ×250 in A and B, ×160 in C and D.)



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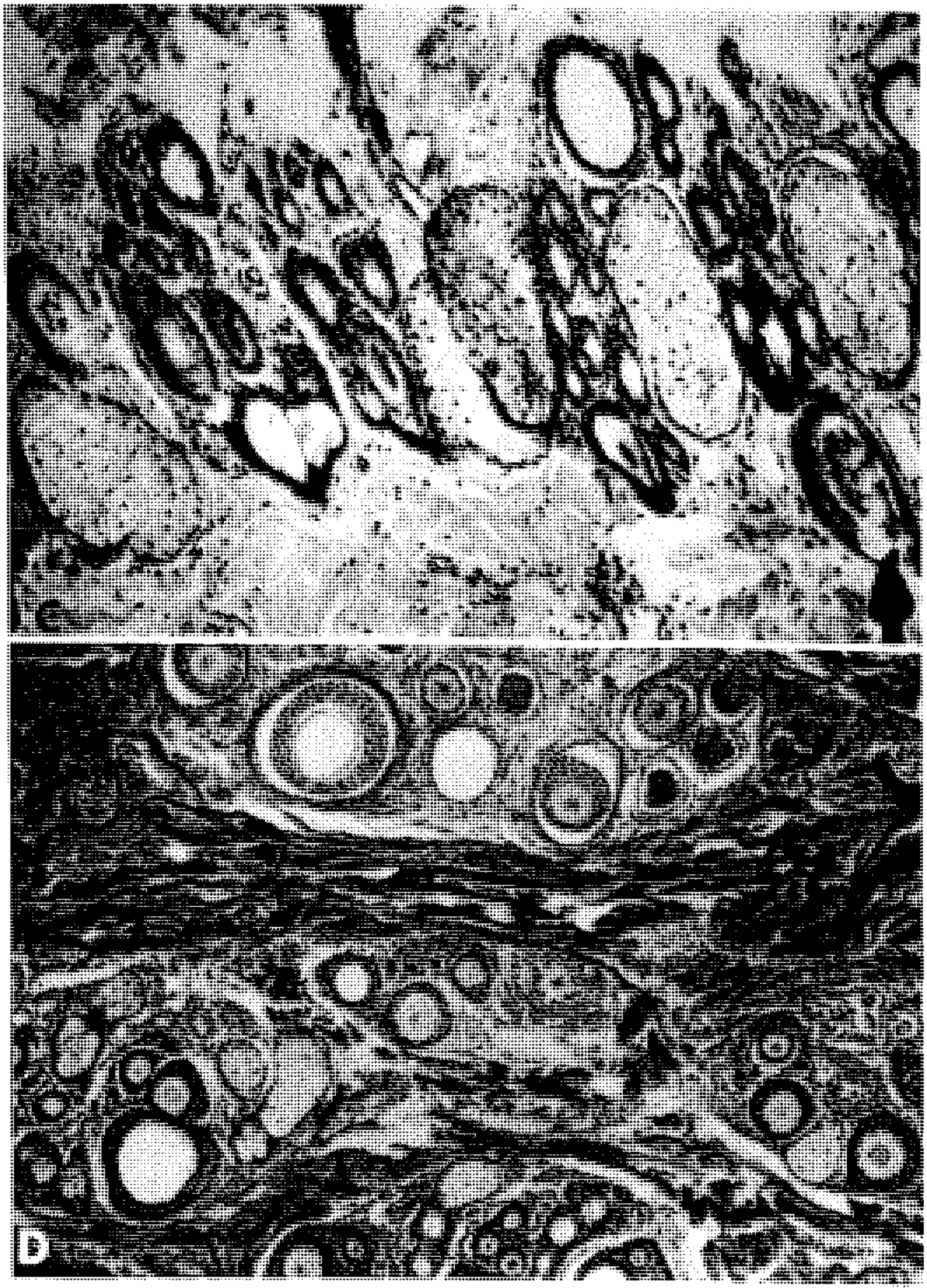
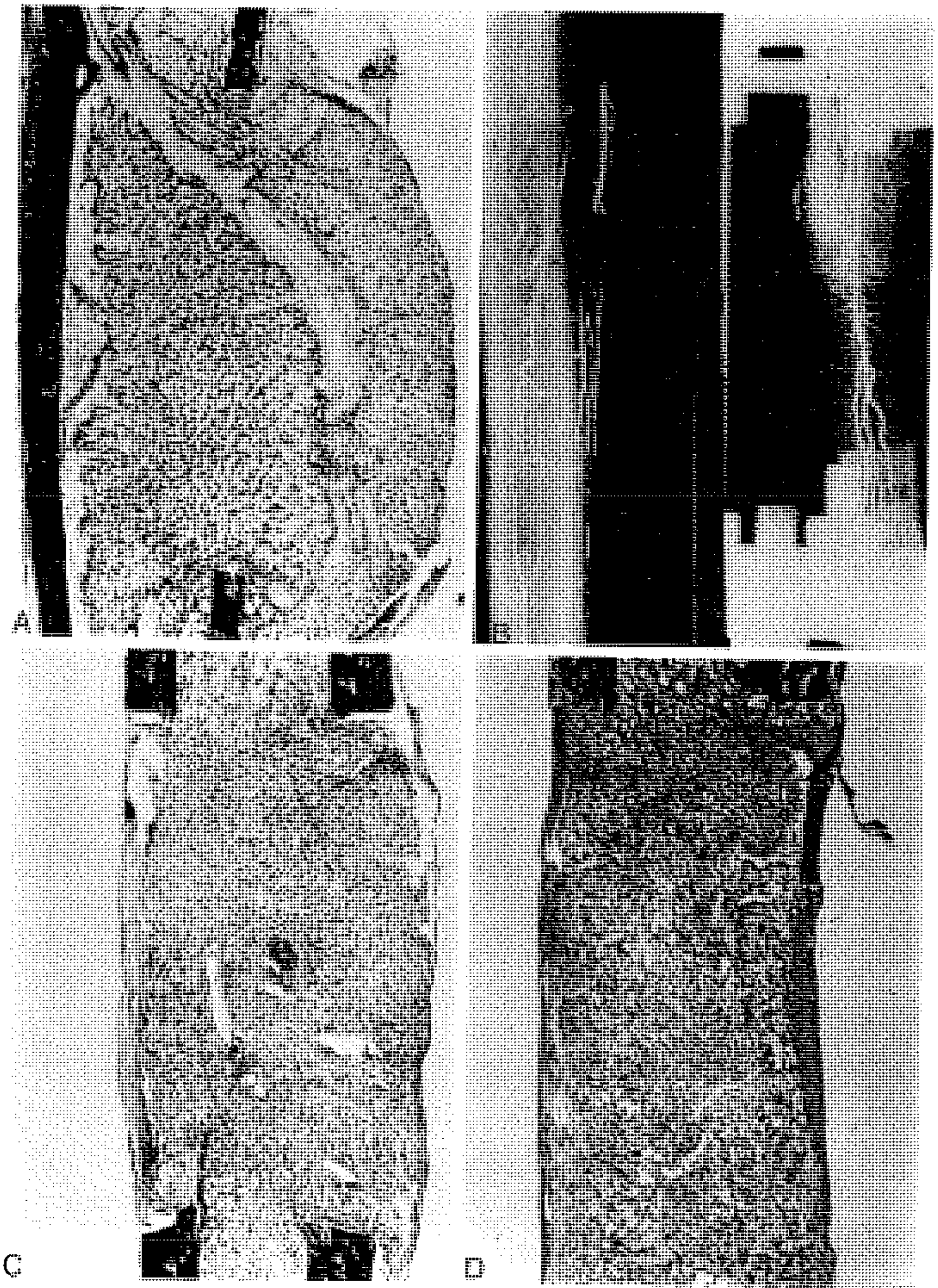
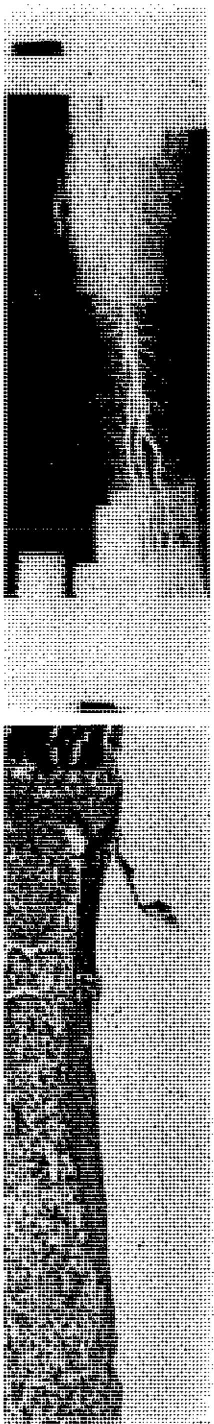


FIG. 28 (*Continued*).



FIGS. 29A–29D. Partial cortical defect experiment. (A) Day 21. The new cancellous bone has spread beyond the limits of the original marrow canal. (B) An angiogram of the control limb (left) and the limb with a full-circular cortical defect (right) demonstrating continuity of the medullary blood supply. (C) and (D) Regeneration of bone by intact marrow, Day 21, full-circular defect group.



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extent, upon the degree of stability of fixation. Minimally restrained motion led to fibrous tissue formation with focal hemorrhagic areas and a few islands of cartilage but not to bone formation. Somewhat more stability led to cartilage tissue formation that might eventually result in a pseudarthrosis. The maximum stability of fixation used in these experiments led, however, to direct osteogenesis within the distraction zone.[26] These studies also demonstrate that, within a stable fixator configuration, the greater the preservation of the soft tissue, marrow elements, and blood supply at the level of the osteotomy site, the more rapid the bone formation.

In some ways, the regenerated bone that develops within the distraction zone under the appropriate conditions of stability and preservation of the blood supply resembles an epiphyseal growth plate with its orientation of trabeculae parallel to the direction of elongation. Histologically, there are parallel columns of osteoid that turn into lamellar bone extending in both directions from a central layer. The central growth zone contains elongated fibroblastlike cells that rapidly produce collagen fibrils to serve as a matrix for osteoid formation. The growth zone may be 2–4 mm wide, but, under the best condition of stability and blood supply preservation, the growth zone is almost nonexistent.[22]

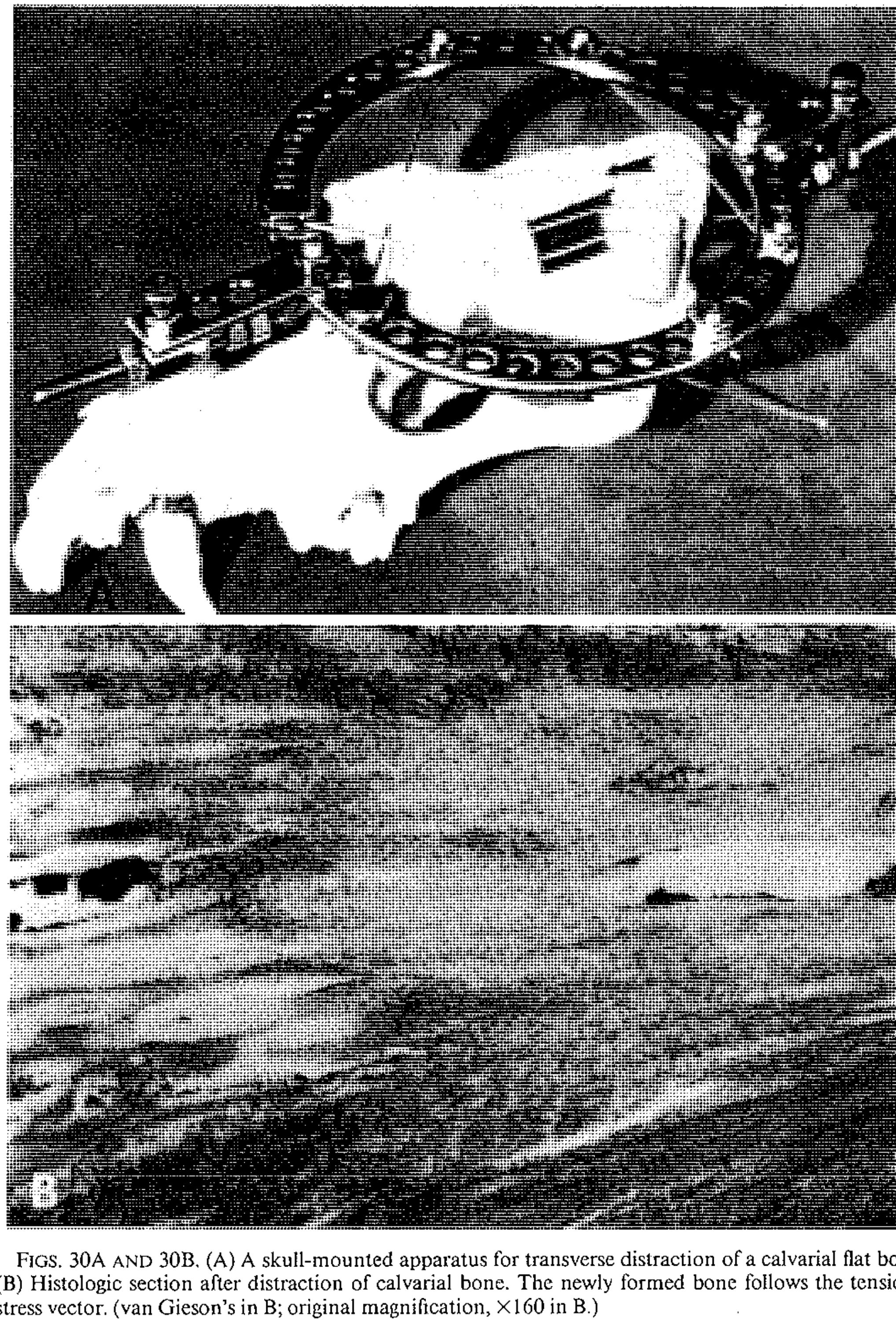
Unlike the epiphyseal growth plate, the regenerated bone created under optimal conditions by the tension–stress effect develops without the formation of an intermediate cartilaginous layer. In this respect, regenerated bone formation resembles the intramembranous bone development of normal growth. Thus, osteogenesis under the influence of the tension–stress effect shares some features of both enchondral and intramembranous ossification, yet is neither.

The tension–stress effect has been shown to stimulate osteogenesis in the flat bones of the canine calvarium where a skull-mounted apparatus (Fig. 30) was used to provide traction on an osteotomized flat bone segment. Vertebral bodies also can be lengthened in puppies by the technique of traction epiphysiolysis–growth plate distraction using the fixator (Fig. 31).[2]

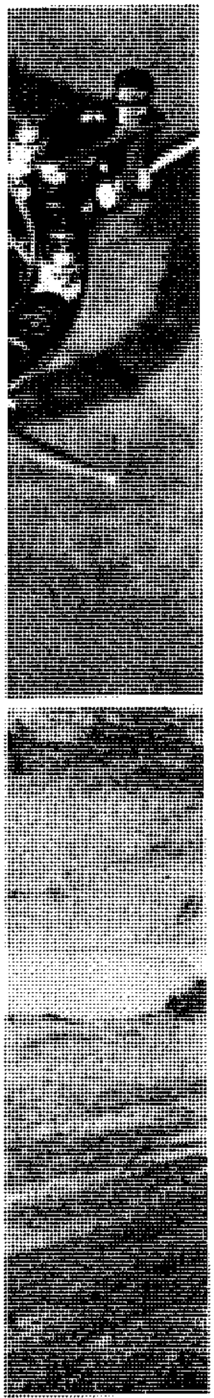
At the ultrastructural level, cells within the distraction zone shared features seen in the cells of embryonic, fetal, and neonatal limb development and growth. Proliferation and hypertrophy of mitochondria, endoplasmic reticula, nucleoli, the Golgi complex, and other structures were observed in many types of tissues. Cellular lengthening along the tension vector was accompanied by elongation of many cytoplasmic organelles as well.

The importance of preserving both the endosteal and periosteal blood supplies at the time of osteotomy has long been recognized.[9] This has led to the development of surgical techniques that ensure the maximum preservation of the bone's blood supply when performing an osteotomy for either limb lengthening, correction of a deformity, or the treatment of a musculoskeletal problem. With this technique, an osteotomy is performed with a narrow osteotome through a small skin incision in such a manner as to break the bone's cortex without either damaging the periosteal soft tissues or transecting the medullary canal contents. This technique is called either a corticotomy or a compactotomy, depending upon the level of the bone osteotomized. Obviously, the cortex on the opposite side of the limb from the skin incision cannot be osteotomized directly without crossing the marrow canal; for this reason, the far cortex is cracked by closed osteoclasis after the osteotome cuts the cortex around the bone in each direction.

On occasion, an opportunity arises to confirm the importance of preservation of the bone marrow and blood supply during limb elongation in a clinical setting. At the author's institution, achondroplastic dwarfs are made taller by simultaneous elongation of both lower extremities.[15] In such cases, identical frame configurations may be applied to both legs (or both arms). Occasionally, there is inadvertent damage to the bone marrow and blood supply (caused by the osteotome)



FIGS. 30A AND 30B. (A) A skull-mounted apparatus for transverse distraction of a calvarial flat bone. (B) Histologic section after distraction of calvarial bone. The newly formed bone follows the tension-stress vector. (van Gieson's in B; original magnification, ×160 in B.)



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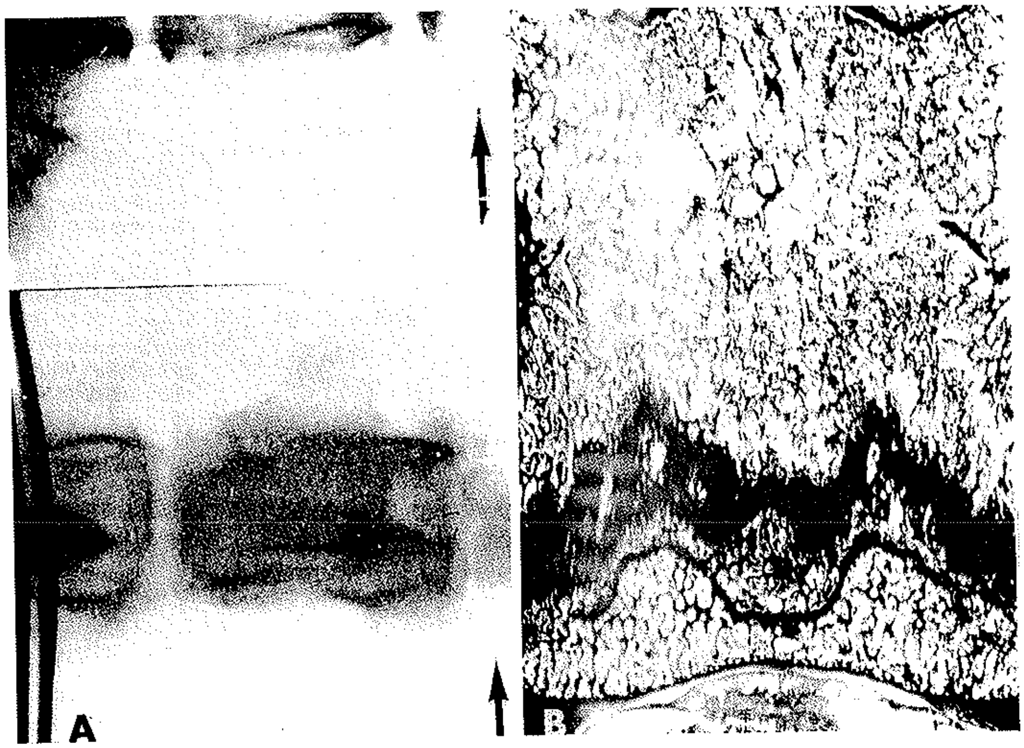

FIGS. 31A AND 31B. Vertebral body elongation by traction epiphysiolysis. (A) Roentgenogram of elongated vertebral body at the completion of distraction. (B) Whole-mount preparation showing the elongated vertebral body and distraction of the growth plate (dark region).

on one side but not on the other. In other instances there may be greater bone displacement at the level of osteotomy on one side than the other. In either of these cases, the side with greater preservation of blood supply (or less displacement at the time of osteotomy and fixation) invariably demonstrates more rapid consolidation.

Clinical studies of fractures managed in the circular external skeletal fixator reaffirm the importance of the medullary blood supply in fracture healing. In a large population of patients with closed transverse or short oblique long-bone fractures with various degrees of displacement, radionuclide bone scans were obtained shortly after injury.[32] Radioisotope uptake was greatest where there was least fracture site displacement and least in cases with full shaft-width displacement. With anatomic reposition of the fragments using the circular external fixator of the author's design, bone union was slowest in patients with fully displaced fractures and most rapid in fractures that were nondisplaced.

It is evident from the experiments involving transverse distraction of a cortical segment that the orientation of bone trabeculae (and, indeed, the entire osteogenic process) parallels the vector of tension–stress. The clinical application of this principle includes the possibility of widening a bone for cosmetic or functional reasons.[13] For example, a limb thinned by poliomyelitis can be made to appear more normal by widening the tibia posteriorly, thereby creating a more attractive calf contour. Such a correction can be accomplished either at the same time as a longitudinal lengthening or later. Likewise, when treating certain forms of congenital pseudarthrosis of the tibia, bone widening helps prevent refracture after reconstruction.[16] A full-length tibial diaphyseal defect can be filled in by longitudinal splitting of the fibula followed by medial traction of the split fragment to create a greatly widened fibula and a tibiofibular synostosis.[17]

The intense angiogenesis that takes place under appropriate conditions within the regenerate zone has a remarkable clinical application. The newly formed blood vessels can serve as an interosseous bypass graft in cases of vascular insufficiency caused by local occlusive diseases such as thromboangiitis obliterans or Buerger's disease. The technique involves a longitudinal splitting of the bone, usually the tibia, at the level of an angiographically confirmed occlusion. A simple frame is applied (since the limb remains stable), and the apparatus is modified to permit transverse displacement of the split fragment in accordance with the principles of tension–stress. The preliminary clinical results are gratifying, with angiographically and plethysmographically confirmed improvement in peripheral circulation accompanied by a lessening of the signs and symptoms of ischemia.

Active growth of the skin and its appendages under the influence of tension–stress permits the treatment of large cutaneous defects, scars, and trophic ulcers without the need for cutaneous transplantation. Likewise, gradual distraction can be used to create redundant skin between the digits in cases of syndactyly, allowing subsequent surgical separation without the need for skin grafting.

The clinical observations described briefly in this paper confirm the experimental findings that the stability of fixation and the preservation of the marrow and blood supply are critical factors in the formation of new bone under the influence of the tension–stress effect. The proper application of the Law of Tension–Stress will permit unique solutions to many medical and surgical problems.

ACKNOWLEDGMENTS

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SECTION III

BASIC SCIENCE AND PATHOLOGY

The Tension–Stress Effect on the Genesis and Growth of Tissues:

Part II. The Influence of the Rate and Frequency of Distraction

GAVRIIL A. ILIZAROV, A.M., M.D., PH.D.*

To assess the influence of both the rate and the frequency of distraction on osteogenesis during limb elongation, a canine tibia was used with various combinations of distraction rates (0.5 mm, 1.0 mm, or 2.0 mm per day) and distraction frequencies (one step per day, four steps per day, 60 steps per day). The distractions were performed after both open osteotomy and closed osteoclasis. Histomorphic and biochemical studies were conducted on the elongated osseous tissue, fascia, skeletal muscle, smooth muscle, blood vessels, nerves, and skin. It was determined that distraction at a rate of 0.5 mm per day often led to premature consolidation of the lengthening bone, while a distraction rate of 2.0 mm per day often resulted in undesirable changes within elongating tissues. A distraction rate of 1.0 mm per day led to the best results. It was also observed that the greater the distraction frequency, the better the outcome. With optimum preservation of periosseous tissues, bone marrow, and blood supply at the time of osteotomy, stability of external fixation, and 1.0 mm per day of distraction in four steps, osteogenesis within the distraction gap of an elongating bone takes place by the formation of a physislike structure, in which new bone forms in parallel columns extending in both directions from a central growth zone. The growth plate that forms under the influence of tension–stress has features of both physeal and intramembranous ossification, yet is neither; instead, the distraction regenerated bone is unique, providing numerous applications in clinical traumatology, orthopedics, and other medical disciplines.

The factors that influence the quality and quantity of bone produced during limb elongation have been investigated.[7] The quality of osteogenesis depends on the stability of the external fixation being used for distraction and the degree of preservation of the periosteal and marrow tissues and the nutrient blood vessels at the level of the osteotomy.[15,30] Different daily rates of distraction and frequencies of distraction may have an effect on both bone and soft tissues under the influence of tension–stress. Therefore, an extensive study on how the rate and frequency of distraction affect bone formation during limb elongation was undertaken.

METHODS AND MATERIALS

Using the previously described canine tibia model,[15] 120 dogs were divided into two groups. In one group, the tibia was osteotomized with total transection of the marrow through an open surgical exposure, while in the other group, the osteot-

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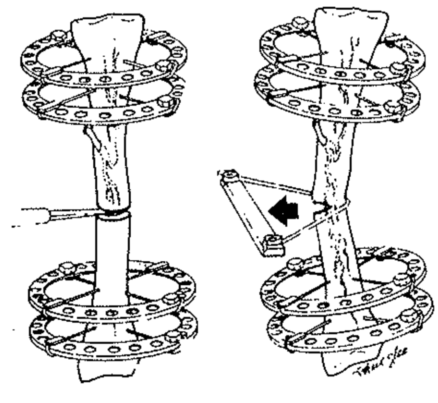

FIG. 1. Diagram of the experimental osteotomy technique. Group 1: open osteotomy. Group 2: closed osteoclasis with a temporary tensioned wire.

omy was performed with a closed osteoclasis technique using tensioned curved wires attached to an external fixator.[34] In both groups, a stable four-ring circular external skeletal fixator was connected to the bone fragments with tensioned wires (Fig. 1).

Each group was further divided into six subgroups. The first subgroup of each group consisted of dogs whose limbs were distracted at a rate of 1 mm per day done in one step every 24 hours. The second subgroup consisted of animals distracted at a rate of 1 mm per day, but the frequency of distraction was four steps per day (0.25 mm every six hours). A third subgroup of dogs was also lengthened 1 mm per day, but the dogs were placed in a fixator incorporating a mechanical autodistractor that lengthened the limb 0.017 mm every 24 minutes (a total of 60 times per day). A fourth subgroup of dogs was distracted at a rate of

TABLE 1. Distraction Rates and Frequencies

Rate (mm)	*No. Steps*	*Frequency*
1.0	1	1.0000 mm/24 hours
1.0	4	0.2500 mm/6 hours
1.0	60	0.0170 mm/24 minutes
0.5	4	0.1250 mm/6 hours
0.5	60	0.0085 mm/24 minutes
2.0	4	0.5000 mm/6 hours

0.5 mm per day at a frequency of four times per day (0.125 mm every six hours), while a fifth subgroup of dogs, also distracted a total of 0.5 mm per day, was placed on the autodistractor, resulting in a frequency of 0.0085 mm every 24 minutes, 60 times a day. The final subgroup of dogs in each group was lengthened at a rate of 2 mm per day with a frequency of 0.5 mm every six hours (four times per day; Table 1).

In all dogs, after osteotomy or osteoclasis, five to seven days of neutral fixation were followed by 28 days of steady distraction, followed by a further period of neutral fixation for six weeks. The tibiae of each dog were roentgenographed weekly. One dog of each subgroup was killed immediately following osteotomy and additional dogs were killed at seven days, 14 days, 21 days, 28 days, six weeks, two months, three months, four months, and six months after the osteotomy. Their tibiae were studied histologically and biochemically. The tissues were stained with both routine staining materials and special stains, including van Gieson's and silver stains. Biochemical studies of the tissue of the distraction zone consisted of assays for oxidative–reductive enzymes including succinyl dehydrogenase, alkaline phosphatase, and ATPase. Histochemical studies were also carried out on the soft tissues of the distraction zone. Tissue was obtained from both the distraction zone and the surrounding soft tissues for studies with both transmission and scanning electron microscopes. The tissues were prepared, mounted, and stained in the usual manner for these studies.

RESULTS

With a distraction rate of 0.5 mm per day and a frequency of 0.125 mm every six hours, three-fourths of the animals undergoing closed osteoclasis had premature union of the bone, indicating that osteogenesis overtook elongation. Judging by the width of the distracted space, union occurred by Day 10 of distraction (Fig. 2). Following open osteotomy, when the limb was lengthened at the same rate and frequency of 0.125 mm every six hours, bone union did not take place, although a relatively high degree of osteogenic activity occurred (Fig. 3A).

When an open osteotomy was followed by limb lengthening with the autodistractor at a rate of 0.5 mm per day in 60 steps (0.085 mm every 24 minutes), the entire space between the original bone ends was filled with rela-

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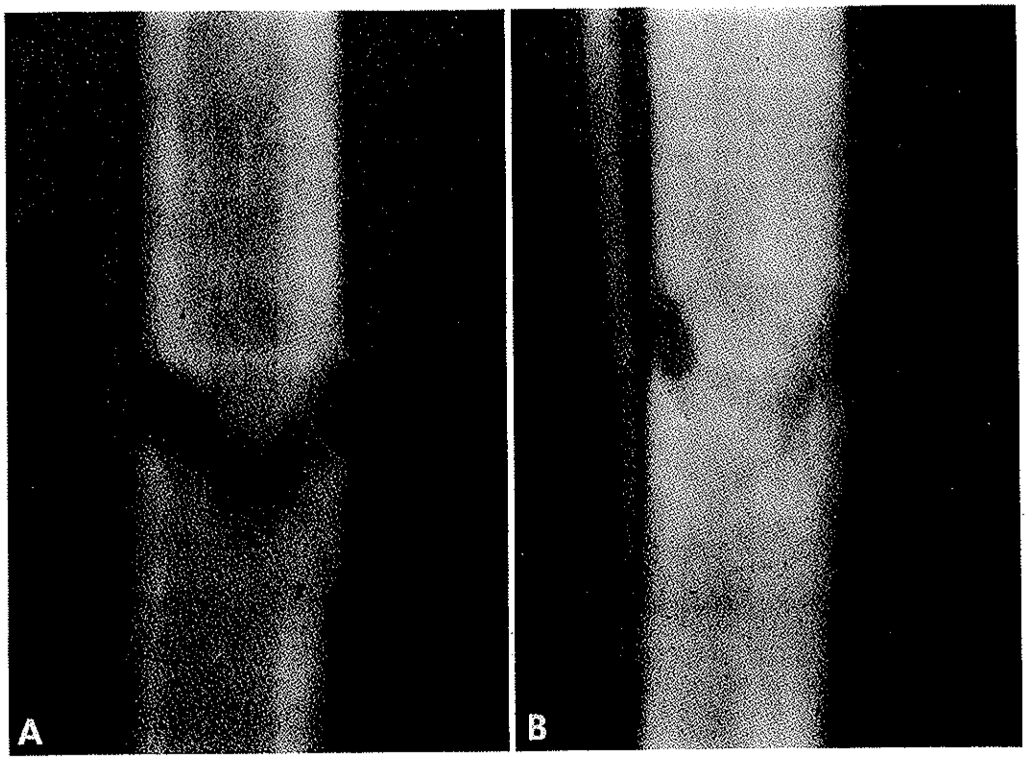


FIGS. 2A AND 2B. Closed osteoclasis, distracted 0.5 mm/day in four steps (0.125 mm every six hours). (A) Day 7 of distraction. (B) Day 14 of distraction. In this animal, premature consolidation occurred on Day 10.

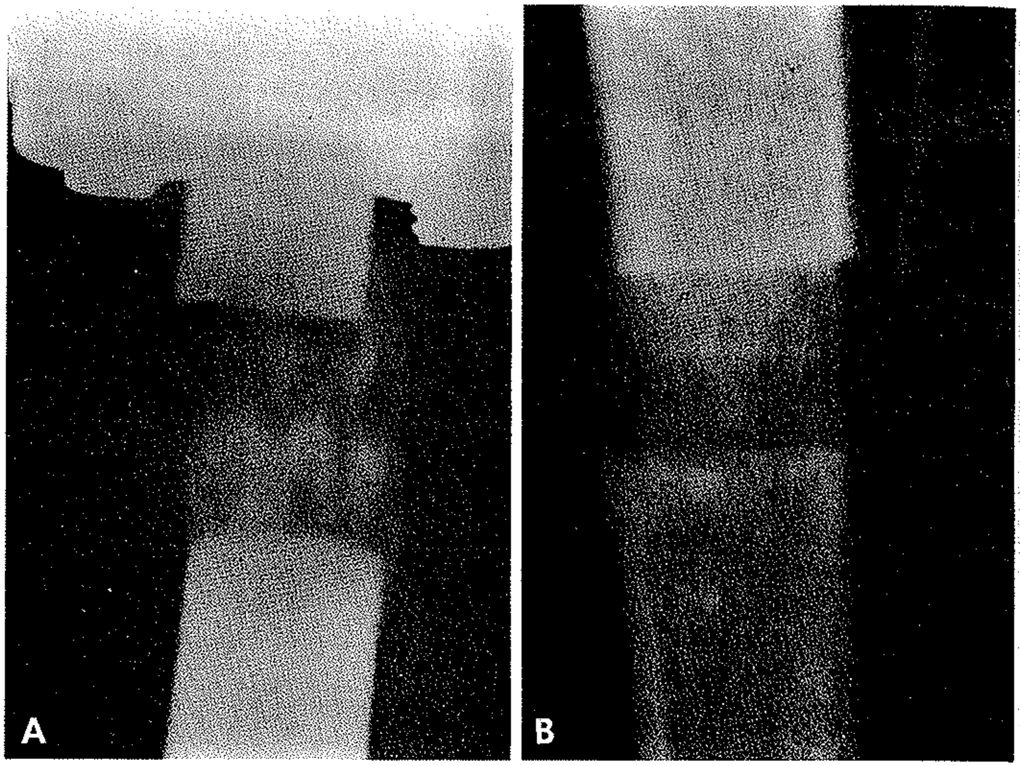
tively dense regenerated bone that consolidated by Day 23 of distraction (Fig. 3B).

A rate of distraction of 1 mm per day done in only one step every 24 hours was detrimental to osteogenic activity, even in animals where the closed osteoclasis technique was used. Thus, by Day 28 of distraction following closed osteoclasis, the space between the bone ends was partially filled with regenerated bone of very low density (Fig. 4A). At the same rate (1 mm per day) but with a frequency of 0.25 mm every six hours following closed osteoclasis, most of the distraction space was filled with relatively dense bone with a central growth zone 2–4 mm in height (Fig. 4B).

When the autodistractor was used at a distraction rate of 1 mm per day, osteogenesis proceeded even more actively and the growth zone could barely be observed (Fig. 4C).

The pronounced difference in osteogenic activity occurring after closed osteoclasis with the same 1 mm per day distraction rate but at different frequencies was revealed even more clearly on Day 60 of observation after five days of initial stabilization, one month of elongation, and one month of postelongation fixation. With the autodistractor (0.017 mm every 24 minutes), the bone in the distraction zone clearly demonstrated the formation of a cortex that was almost identical to the original bone in both thickness and density (Fig. 5A).

With a 1 mm daily distraction rate at 0.25 mm every six hours, the cortex of the regenerate zone was far less evident on Day 60 of the study (Fig. 5B). On the other hand, at a rate of 1 mm in one step every 24 hours, the distraction gap had not yet filled with new bone at this point (Fig. 5C). Indeed, it took 180



FIGS. 3A AND 3B. Open osteotomy, distraction 0.5 mm/day, Day 28 of distraction. (A) One step per day. (B) Sixty steps per day in the autodistractor.

days for the dogs in this group to reach the level of osteogenesis observed at Day 60 in the autodistractor group.

In some animals distracted at a rate of 1 mm per day in the autodistractor, osteogenesis overtook distraction, leading to premature ossification by Day 21 of distraction. Further distraction resulted in a traction fracture at the junction of the regenerated bone and the original diaphyseal bone (Fig. 5D).

Among animals distracted at the fastest rate (2 mm per day in four doses), those dogs with the closed osteoclasis demonstrated only a moderate level of osteogenic activity by Day 28 of distraction (Fig. 6A), while in those animals that had an open osteotomy, a large portion of the regenerate zone was filled with dense fibrous connective tissue with virtually no osteogenic activity (Fig. 6B). The tendency of the distraction zone to fill with fibrous tissue rather than bone was also observed on Day 28 in the open osteotomy (Fig. 6C) animals distracted at a rate and frequency of 1 mm once a day.

Histochemical studies of the tissue within the distraction zone confirmed the effect of both rate and frequency on the quantity and quality of osteogenesis during limb elongation. Succinyl dehydrogenase activity, which reflects the level of aerobic metabolism (a measure of osteogenic activity), was measured as part of the experiment. The intensity of the reaction was judged by the amount of Phormasan blue within the cellular cytoplasm of the regenerate zone. The more stain in each cell and the more area occupied by cells containing Phormasan blue, the higher the level of aerobic metabolism.

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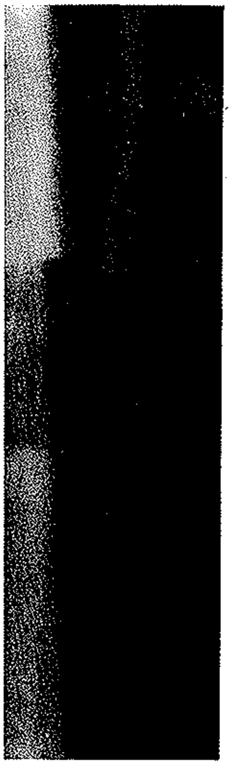

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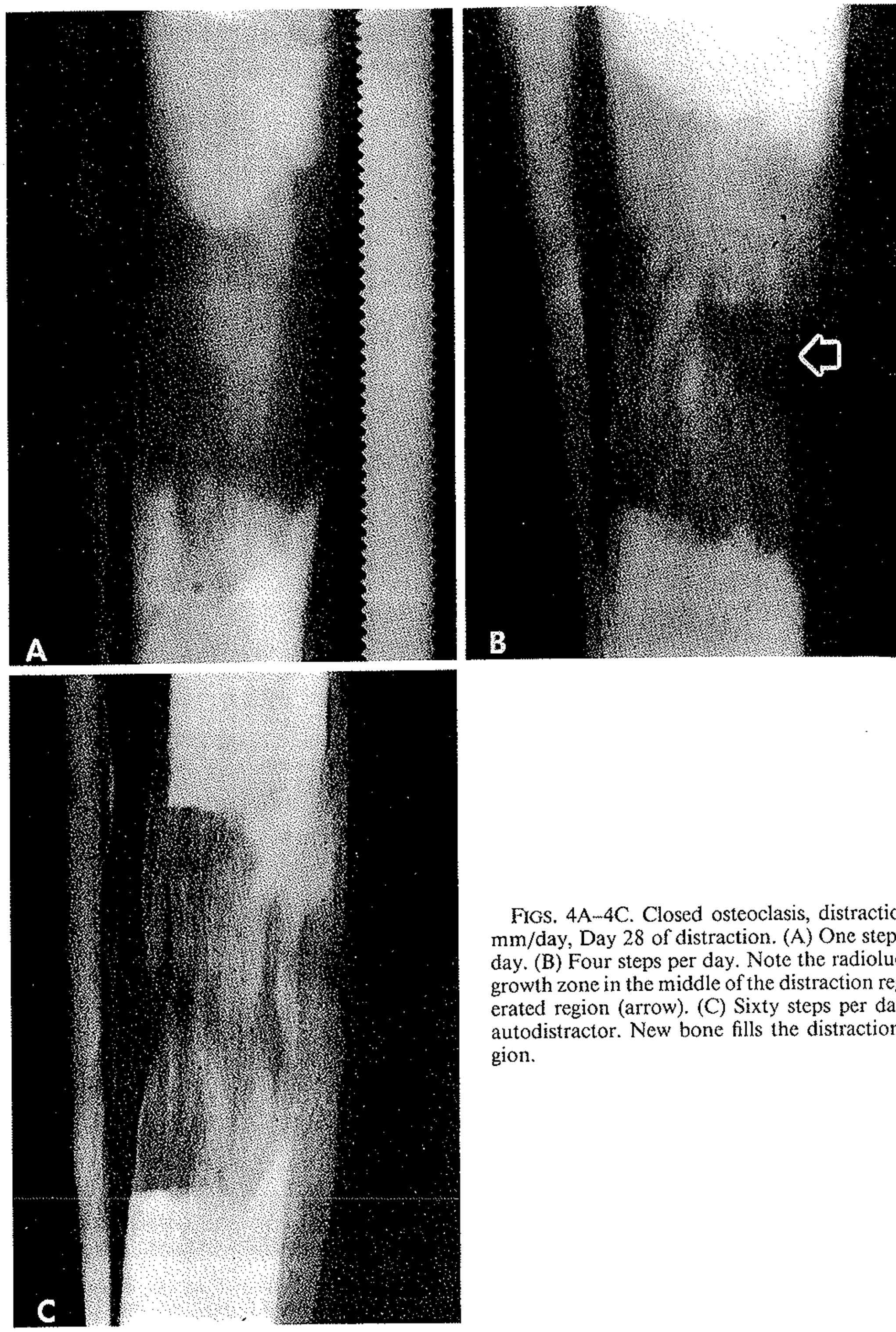
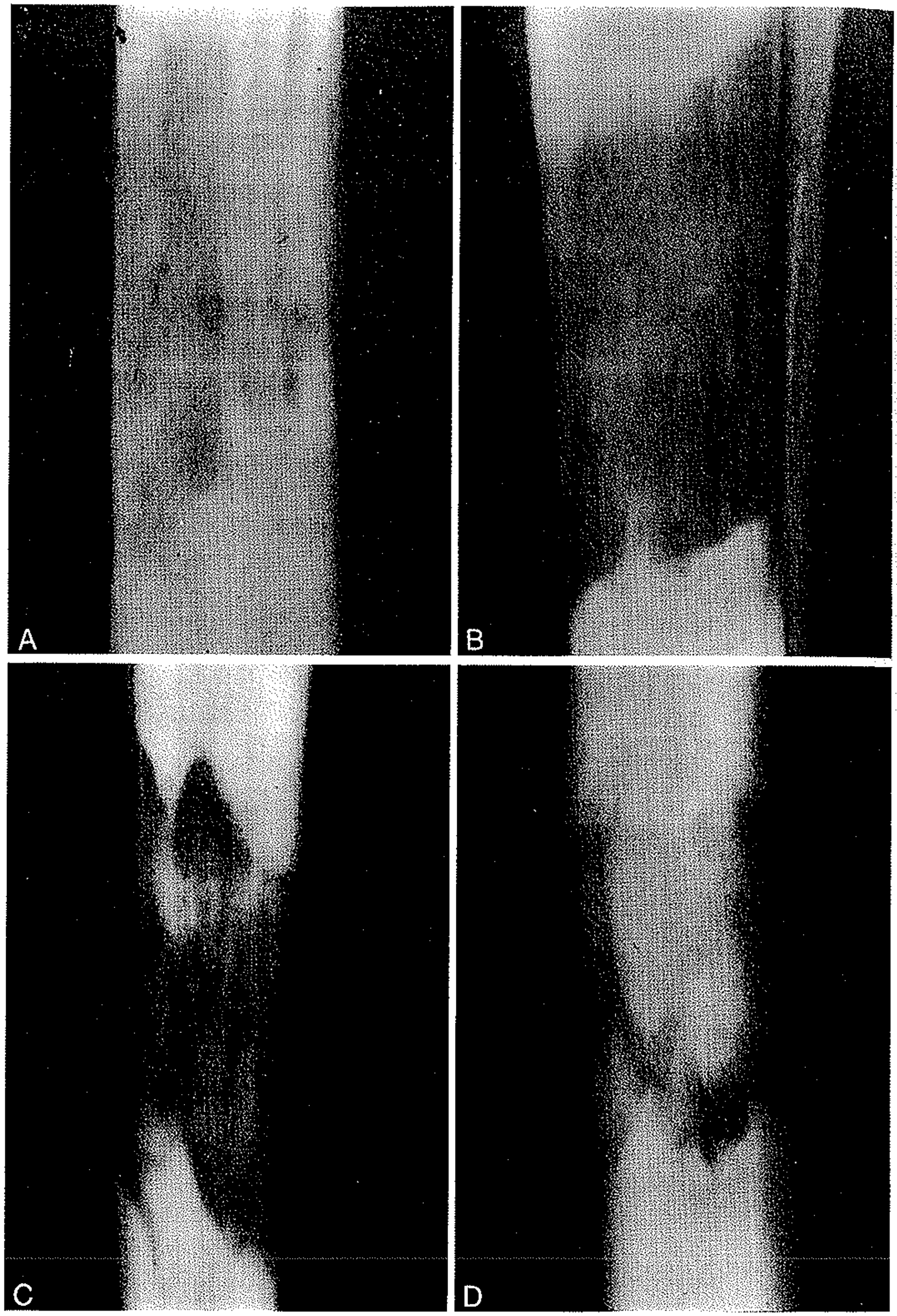
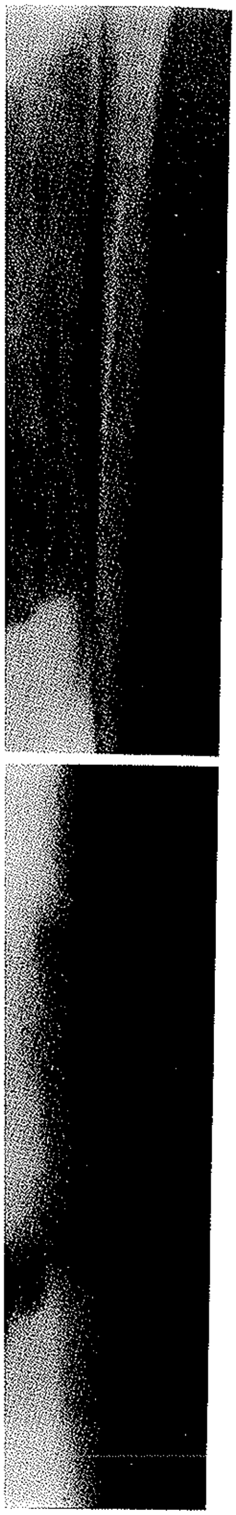


FIGS. 4A–4C. Closed osteoclasis, distraction 1 mm/day, Day 28 of distraction. (A) One step per day. (B) Four steps per day. Note the radiolucent growth zone in the middle of the distraction regenerated region (arrow). (C) Sixty steps per day in autodistractor. New bone fills the distraction region.



FIGS. 5A–5D. Closed osteoclasis, distraction 1 mm/day, Day 60 of the experiment. (A) Sixty steps per day. Note the formation of a cortex. (B) Four steps per day. (C) One step every 24 hours. The osteogenesis is of poor quality. (D) Sixty steps per day. In this animal, premature consolidation led to a traction fracture between the regenerated bone and the original cortex.



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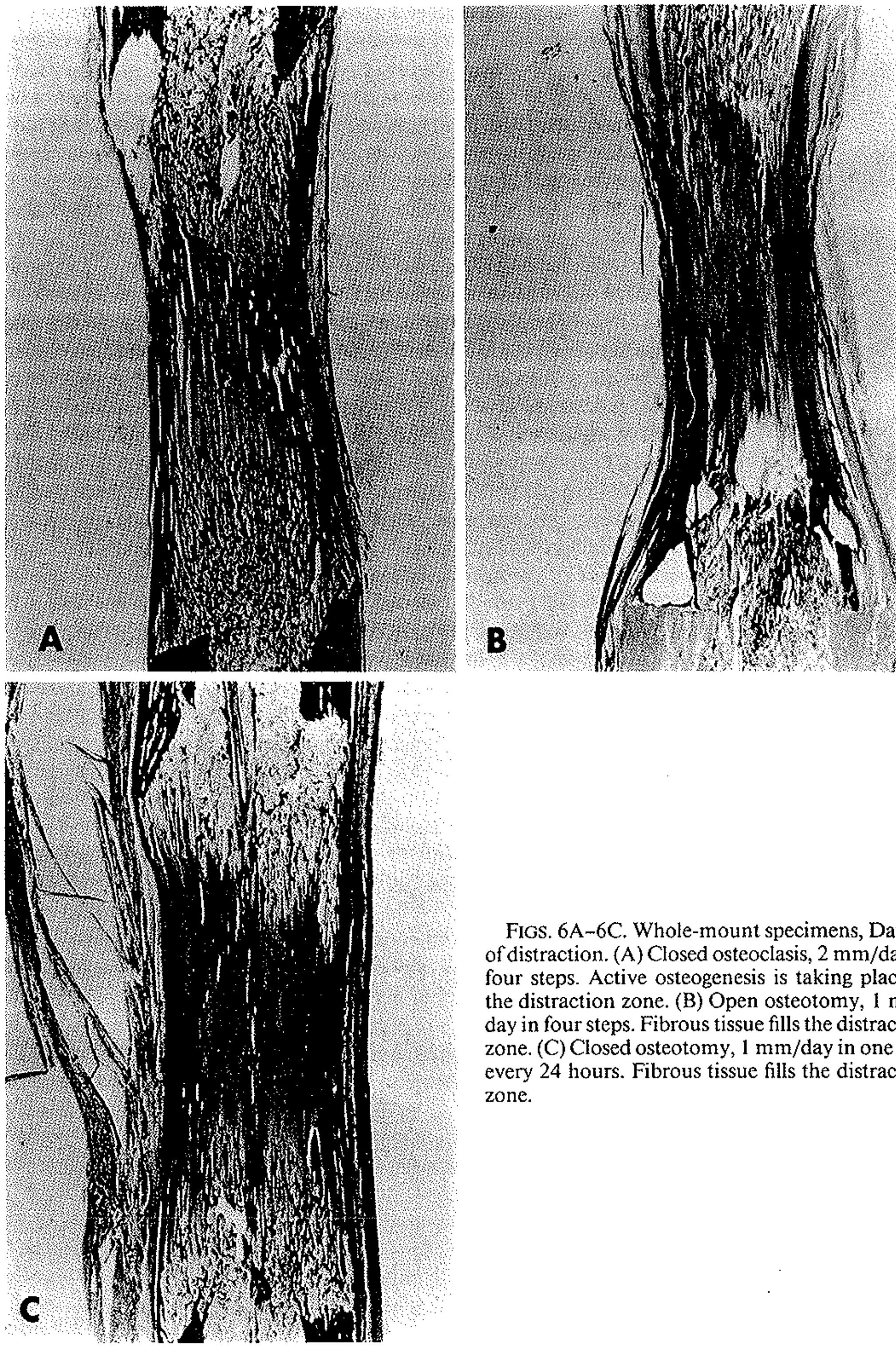

FIGS. 6A–6C. Whole-mount specimens, Day 28 of distraction. (A) Closed osteoclasis, 2 mm/day in four steps. Active osteogenesis is taking place in the distraction zone. (B) Open osteotomy, 1 mm/day in four steps. Fibrous tissue fills the distraction zone. (C) Closed osteotomy, 1 mm/day in one step every 24 hours. Fibrous tissue fills the distraction zone.

and the closed osteoclasis groups where the distraction was performed at a rate of 1 mm in one step every 24 hours had slight cellular staining with Phormasan blue, indicating a low level of succinyl dehydrogenase activity and, consequently, a low level of osteogenesis within the stratum (Fig. 7A). At a rate of 1 mm per day and a frequency of 0.25 mm every six hours, the precipitation of Phormasan blue was considerably higher. Moreover, the intensity of staining increased from the middle of the regenerate zone toward both ends (Fig. 7B). An even greater level of staining was observed in the animals distracted 1 mm per day at 0.017 mm every 24 minutes in the autodistractor (Fig. 7C). The intensity of staining was reduced at the rate of 2 mm per day at 0.5 mm every six hours (Fig. 7D).

Histochemical studies assessing the levels of alkaline phosphatase activity demonstrated similar findings. Alkaline phosphatase participates in the mineralization of osteoid. At a 1 mm daily rate of distraction achieved in one step, there were low levels of activity of this enzyme within the regenerate zone. At a rate of 1 mm per day in four steps, activity was present, but was unevenly distributed, increasing from the middle part of the regenerated tissue toward both ends. With the autodistractor at a rate of 1 mm per day, a high level of alkaline phosphatase activity was observed through the entire distraction zone, indicating a rapid course of osteogenesis throughout this region.

In both groups of dogs distracted 2 mm per day in four steps, the level of phosphatase was lower than that observed at a rate of 1 mm per day in four steps, but higher than the phosphatase levels noted at a rate of 1 mm of distraction performed in one step every 24 hours.

Similar observations were made during the course of histochemical studies of ATPase activity in the regenerate zone. ATPase reflects the rate of osteoblastic formation of the primary bone matrix. The intensity of the reaction was judged by the saturation of staining of the cells and the local density of stained cells in a region. Investigations into the level of ATPase activity demonstrated a distribution across various animals similar to that noted with succinyl dehydrogenase.

At a distraction rate of 1 mm per day in one step, slight ATPase activity was observed in a few scattered areas of the distraction zone, suggesting an overall low level of osteogenic activity at this rate and frequency of distraction. A higher level was observed at a distraction rate of 1 mm per day in four steps. In this subset of animals, the highest level of activity was noted in the middle part of the regenerate zone, decreasing toward both ends.

With a distraction rate of 1 mm per day with the autodistractor, high levels of both alkaline phosphatase and ATPase activity were observed along the entire length of the distraction zone, indicating a rapid course of osteogenesis in all areas. When the distraction proceeded at 2 mm per day in four steps, the phosphatase activity was lower than that occurring at a rate of 1 mm per day in four steps, but higher than at 1 mm per day in one step every 24 hours.

Thus, the studies of osteogenesis under various conditions of elongation demonstrated both a quantitative and qualitative dependence on the rate and frequency of distraction. Osteogenesis occurs more rapidly as the frequency of distraction increases. Histologic evaluation of the paraosseous soft tissues demonstrated similar variations with different rates and frequencies of limb distraction. The changes due to distraction were independent of the type of osteotomy.

The fascia in its natural state has a wavy appearance when studied with the light microscope (Fig. 8A). Distraction at a rate of 1 mm in one step every 24 hours caused the fascial collagen fibers to lose their normal wavy structure by Day 14 of distraction and to stain unevenly with silver due to pronounced swelling and focal homogenization (Fig. 8B). When distracted at a rate of 1 mm in four steps there was, by Day 14, slight swelling in some of the fibers and less waviness than in the fibers of the undistracted control limb

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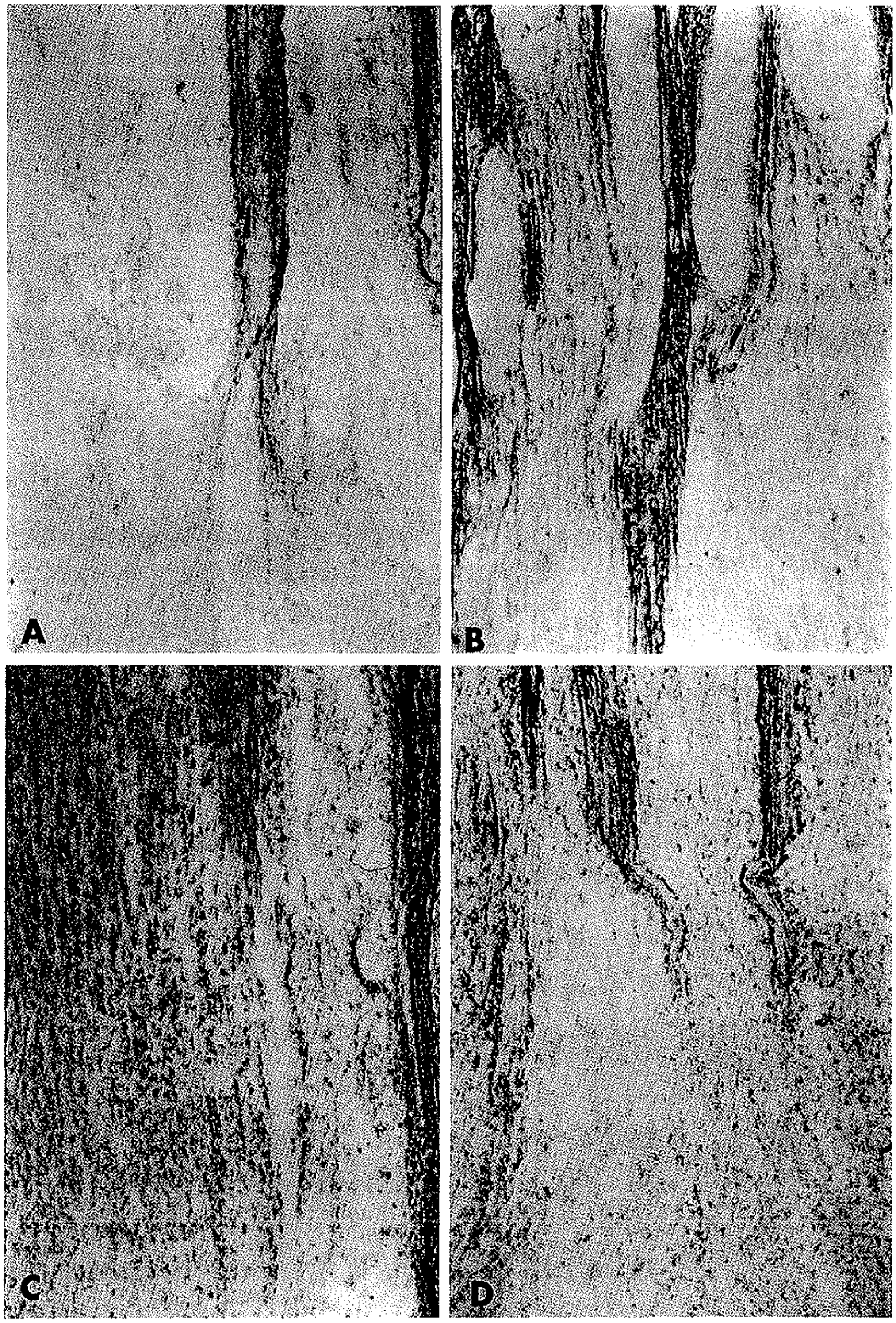
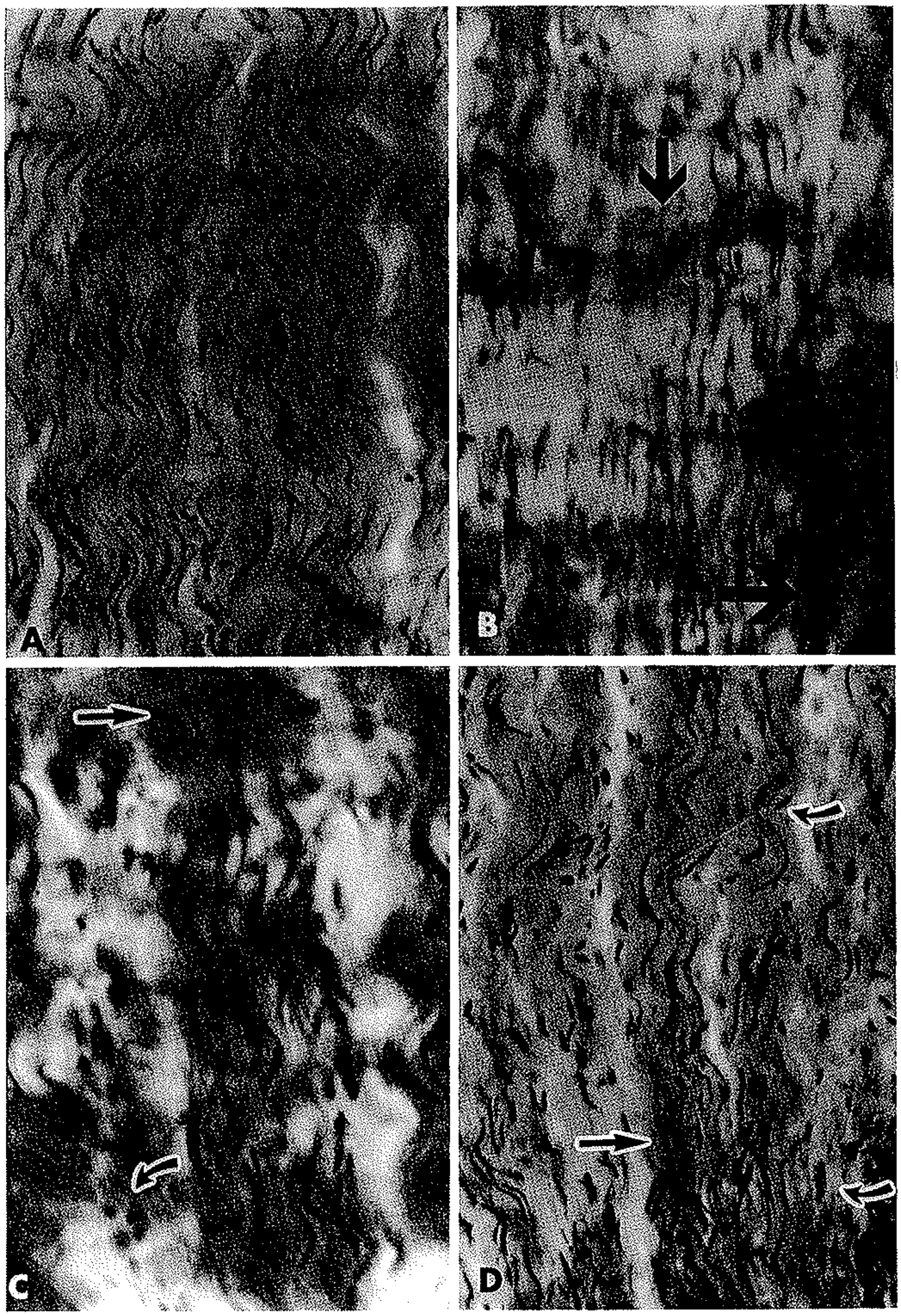
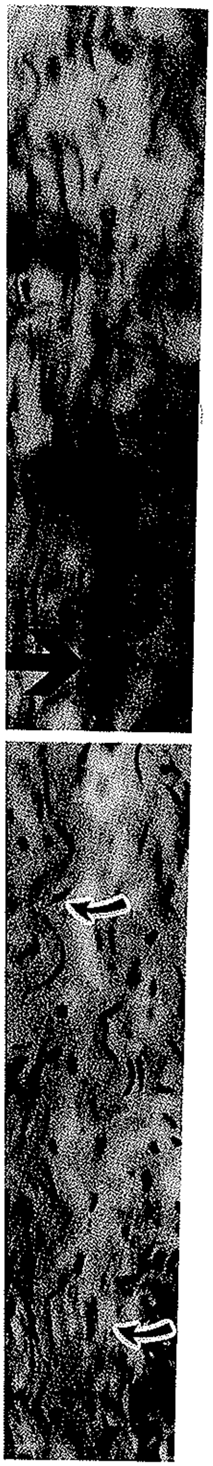


FIGS. 7A–7D. Phormasan blue stain measures the histochemical levels of oxidative–reductive enzymes, a measure of direct osteogenesis. (A) 1 mm/day in one step every 24 hours. (B) 1 mm/day in four steps. (C) 1 mm/day in 60 steps. (D) 2 mm/day in four steps. (Original magnification, ×160.)



FIGS. 8A–8D. The fascia, Day 14 of distraction. (A) Control limb; note the wavy nature of normal fascia. (B) 1 mm in one step every 24 hours. Note the uneven staining (upper arrow) and focal homogenization (lower arrow). (C) 1 mm/day in four steps. Note the fiber swelling (upper arrow) and accumulations of fibroblastlike cells (curved arrow). (D) 1 mm/day in 60 steps in the autodistractor. The wavy fascial structure is almost normal. New fibroblasts (curved arrows) and minimal fibrous swelling (straight arrow) are noted. (Stain, silver; original magnification, ×250.)



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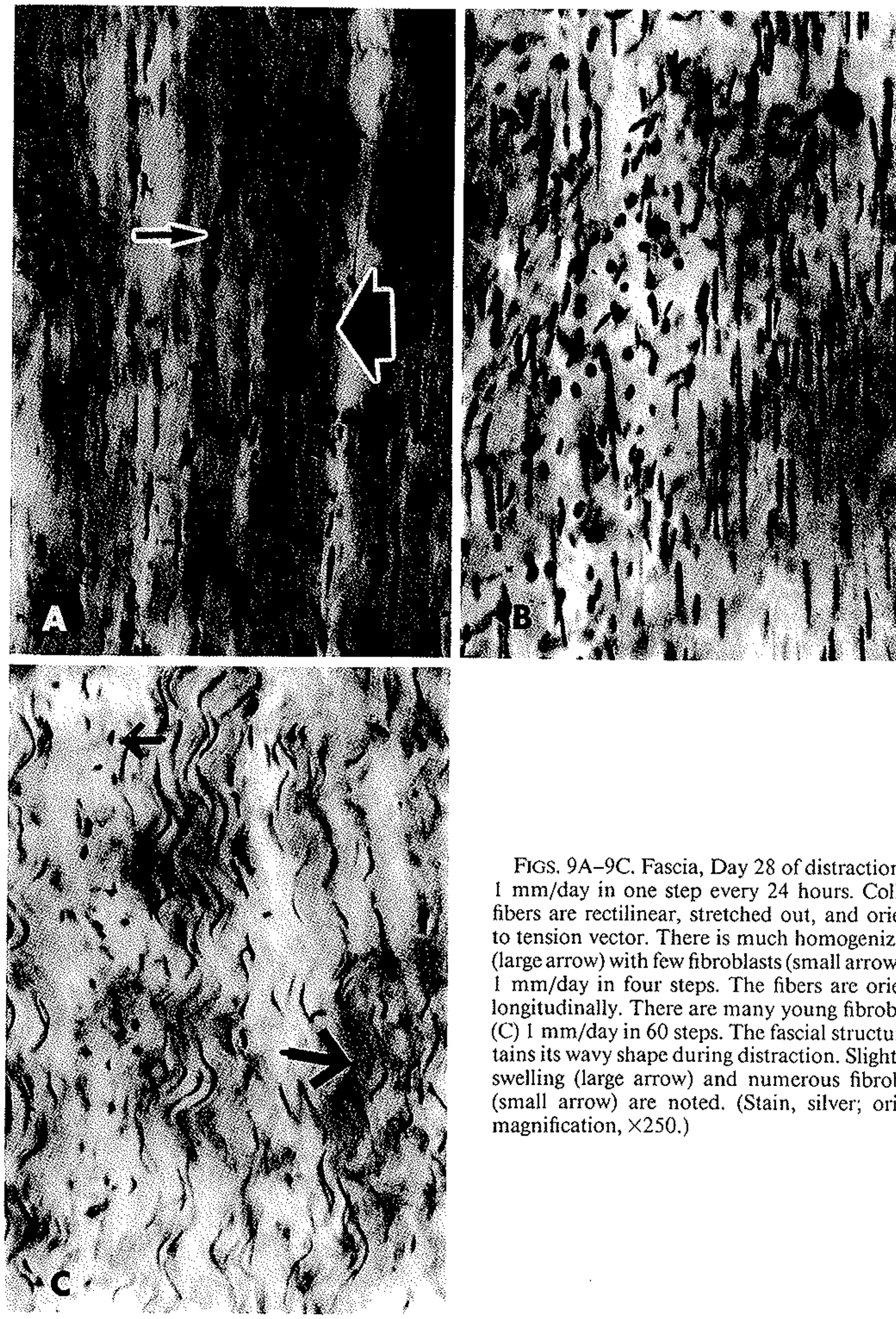
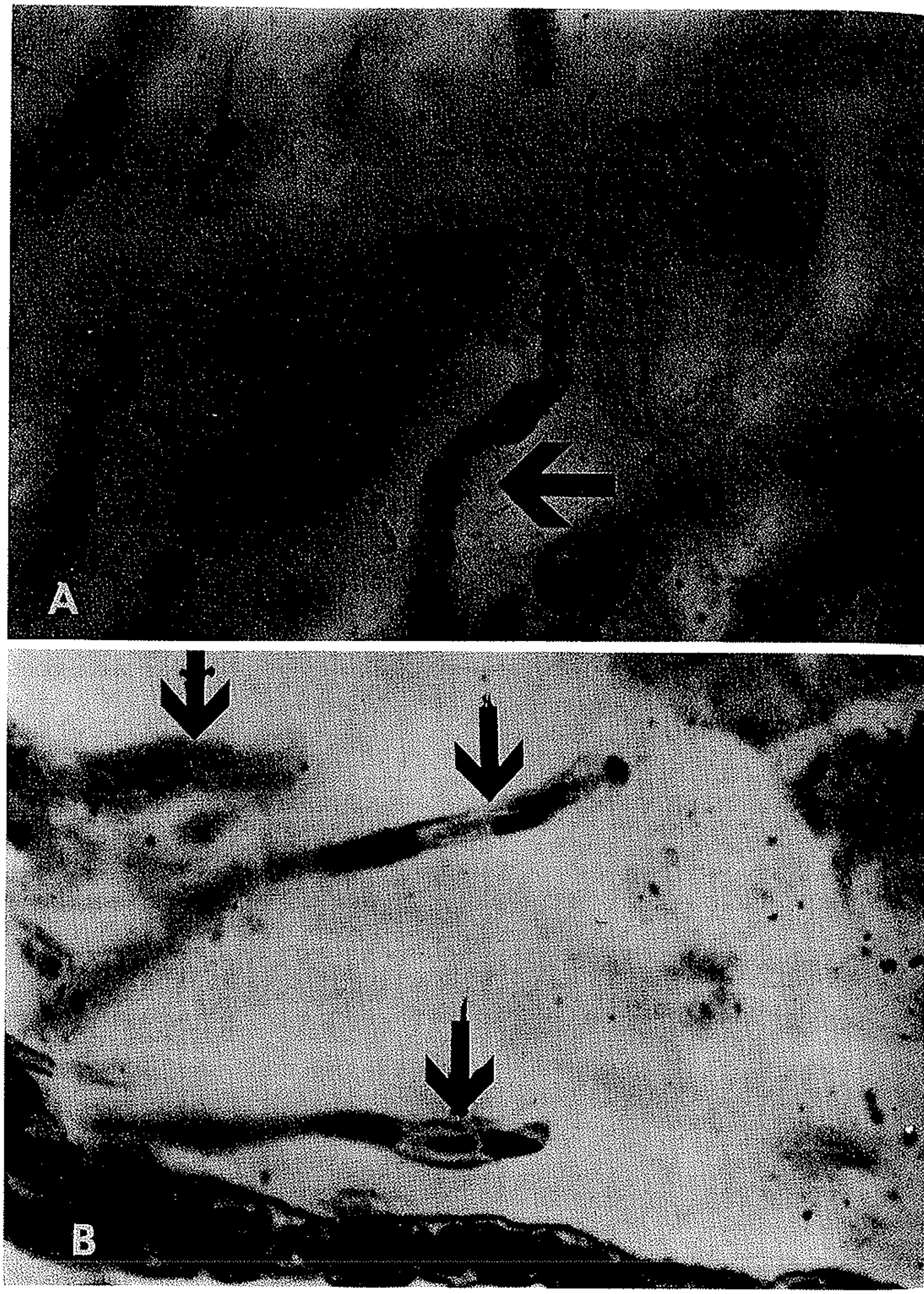
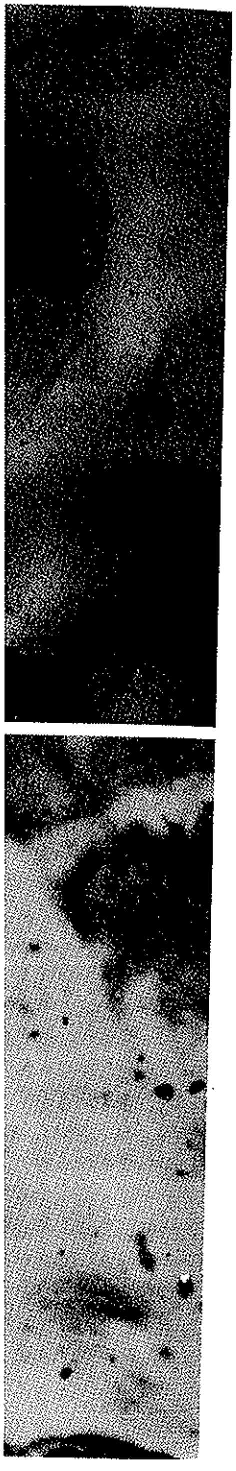


FIGS. 9A–9C. Fascia, Day 28 of distraction. (A) 1 mm/day in one step every 24 hours. Collagen fibers are rectilinear, stretched out, and oriented to tension vector. There is much homogenization (large arrow) with few fibroblasts (small arrow). (B) 1 mm/day in four steps. The fibers are oriented longitudinally. There are many young fibroblasts. (C) 1 mm/day in 60 steps. The fascial structure retains its wavy shape during distraction. Slight fiber swelling (large arrow) and numerous fibroblasts (small arrow) are noted. (Stain, silver; original magnification, ×250.)



FIGS. 10A–10C. Capillaries within fascia, 1 mm/day distraction, Day 28 of distraction. (A) 1 mm/day in one step. Minimal new capillary formation. (B) 1 mm/day in four steps. New capillary formation with terminal directional cells at their blind ends. (C) 1 mm/day in 60 steps. Numerous new capillaries form an anastomosing capillary network. (Original magnification, ×500.)



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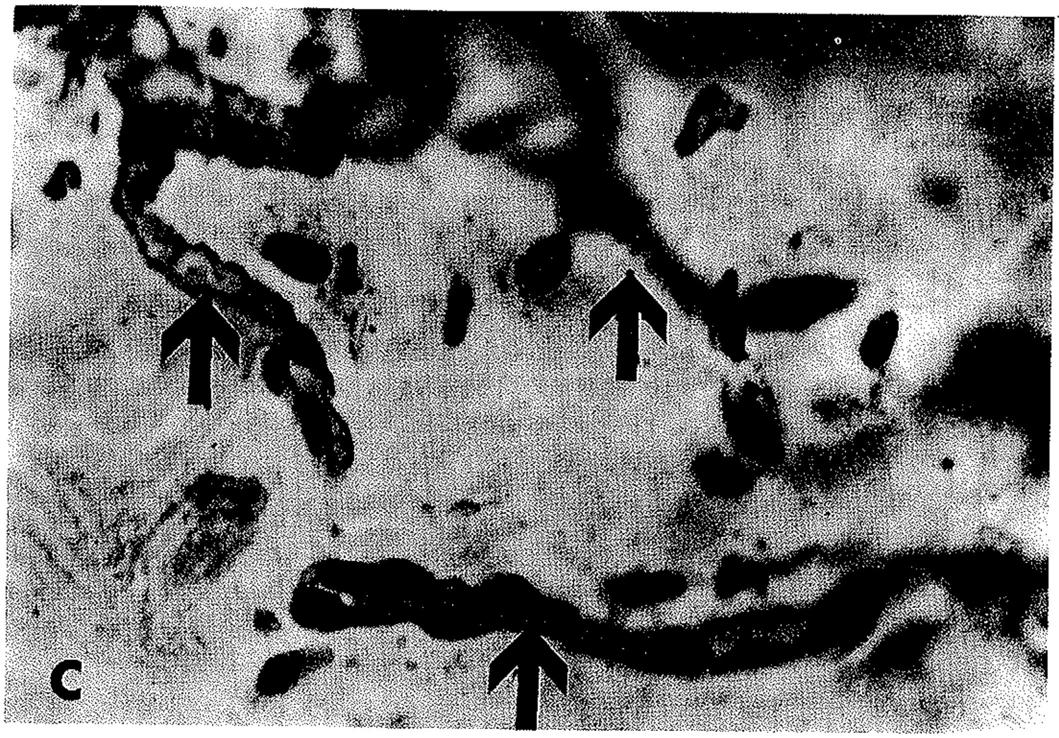


FIG. 10 (*Continued*).

(Fig. 8C). Along the periphery of the second-order bundles, small accumulations of undifferentiated fibroblastlike cells appeared, indicating a stimulation of tissue growth. Fiber homogenization, a sign of damage, was observed in only a few small areas.

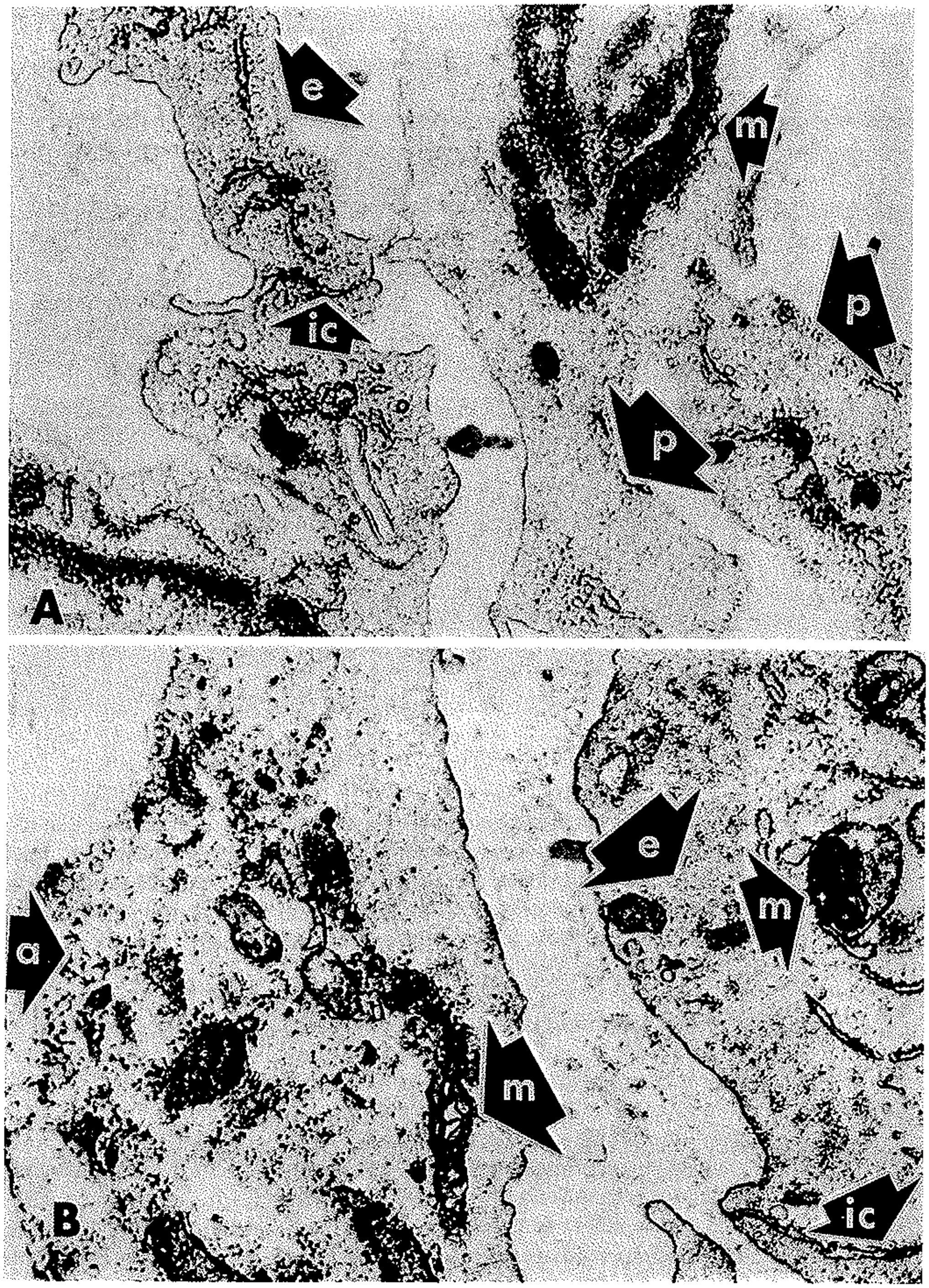
In animals distracted 1 mm per day in the autodistractor, the fascial structures appeared almost normal, maintaining their wavy appearance when studied at Day 14 of distraction (Fig. 8D). There was greater accumulation of undifferentiated fibroblastlike cells than in the previously described specimens, indicating activation of fibrillogenesis. There was less swelling of the fibers, a sign of damage, than in animals distracted at the same rate but with fewer steps.

By the end of distraction on Day 28 at a rate of 1 mm once a day, the collagen fibers had a rectilinear shape and were oriented along the vector of distraction (Fig. 9A). The boundaries of the fibrillar bundles were not well-visualized due to swelling and focal homogenization. A few groups of fibroblasts were seen in the sections, indicating a relatively low level of growth activity.

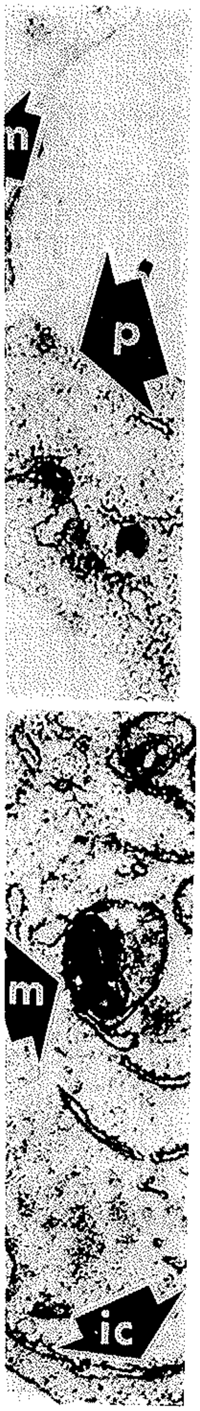
At a distraction rate of 1 mm per day in four steps (after 28 days of distraction), the collagen fibers had lost their wavy appearance and were dense with some evidence of swelling. Young fibroblasts accumulated along the periphery of the bundles, testifying to the active formation of new tissue structures (Fig. 9B).

In the autodistractor, with a distraction of 1 mm per day, the fascial tissue, by the end of elongation (28 days), appeared similar to that of the undistracted control limbs. Swelling of the fibers was minimal and the tissue maintained its wavy appearance (Fig. 9C). There were accumulations of numerous young fibroblasts along the edges of the bundles, indicating a high level of histogenic activity.[33]

Capillaries within the fascia demonstrated



FIGS. 11A–11D. Arterioles, Day 28 of distraction. (A) 1 mm/day in one step. Distrophic changes are noted, including structural mitochondrial damage (m), micropinocytic cells (p), and endotheliocytes (e) with short intracellular contacts (ic). (B) 1 mm/day in four steps. Less mitochondrial damage (m) is observed. Activated smooth muscle cells (a) indicate tissue growth. There are increased intracellular contacts (ic). (C) 1 mm/day in 60 steps. The activated smooth muscle cells (a) have hypertrophied. The structure



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of contractile myocytes (cm) have been preserved and the cytoplasmic volume of the endotheliocytes (e) has grown, as have the intracellular contacts (ic) between them. (D) 2 mm/day in four steps. Cellular damage is indicated by the presence of cytoplasmic excrescences (small curved arrows). (Original magnification, ×15,000 in A–C, ×20,000 in D.)

a similar dependency on the frequency of distraction. Lengthening of the limb 1 mm in one step resulted in the formation of a small number of newly formed capillaries within the fascia (Fig. 10A). A daily distraction of 1 mm in four steps resulted in the production of more capillaries that had terminal directional cells on their blind ends. These capillaries had not yet formed a common capillary network (Fig. 10B). With the autodistractor (1.0 mm per day), there were numerous newly formed capillaries growing deeply into the distraction zone from all directions and close enough to each other to anastomose (Fig. 10C).[42]

The arterioles of the paraosseous tissues were damaged at a distraction rate and frequency of 1.0 mm once every 24 hours. Thus by Day 28 of distraction, electron micrographs of the arteriolar endotheliocytes revealed disturbances of inner mitochondrial structures and an abundance of micropinocytic cells forming short straight intracellular contacts (Fig. 11A). These changes indicate extensive dilation of the arterioles.[26,27] Such dystrophic changes were less pronounced on Day 28 of distraction when the frequency of elongation was 0.25 mm every six hours (Fig. 11B). At this frequency, the inner structure of some mitochondria was only slightly disturbed; however, at the same time, there was a marked increase in those biosynthetic cellular activities that parallel the growth of tissue structures under the influence of the tension-stress effect. The appearance of activated smooth muscle cells within the arteriolar walls, for example, indicates tissue growth.[2,6,19,45] At 0.25 mm of distraction every six hours, there was also an increase in the volume of cytoplasm enriched with organelles and an increase in the length of the intracellular contacts, both characteristics of actively growing blood vessels.

With the autodistractor and a tissue elongation rate of 0.017 mm every 24 minutes, the signs of active arteriolar tissue growth were even more pronounced, characterized by marked hypertrophy of the organelles within the cytoplasm of vascular smooth muscle cells and combined with preservation of the normal structures of the contractile myocytes. There was an increase in the cytoplasmic volume of the endotheliocytes and in the length and complexity of the intracellular contacts between them (Fig. 11C).

When the limb was distracted at the rapid rate of 2 mm per day in four steps, cellular biosynthetic activity of the arterioles decreased and signs of a negative cellular reaction appeared, characterized by the presence of numerous cytoplasmic excrescences (Fig. 11D).

Nerve tissue also demonstrated reactive changes dependent on the distraction rate and frequency of a limb undergoing elongation. When distracted at a rate of 1 mm once every 24 hours, nerve fibers exhibited an uneven diameter of axons and the formation of irregular accumulations of cytoplasm (Fig. 12A). These pathologic changes were less pronounced at a rate of 2 mm a day in four steps (Fig. 12B). With limb lengthening of 1 mm per day in four steps (Fig. 12C), the axons appeared only minimally changed when compared to the control limb, whereas with the autodistractor functioning at a rate of 0.017 mm every 24 minutes, the nerve fibers had a normal structure (Fig. 12D). Moreover, newly formed nerve fibers were seen at various stages of differentiation when the speed of distraction was 0.25 mm every six hours or slower. Schwann cells surrounded whole groups of axons when the rate of distraction was either 0.25 mm every six hours or 0.017 mm every 24 minutes. Indeed, the histologic picture seen when the autodistractor was used for limb lengthening had features typical of developing fetal nerve trunks (Figs. 13A and 13B).

DISCUSSION

These studies clearly demonstrated that both the rate and frequency of distraction are important to osteogenesis under the influence of the tension-stress effect. When the f vascular smooth d with preservation of the contractile increase in the cy- ndotheliocytes and ity of the intracellu- (Fig. 11C).

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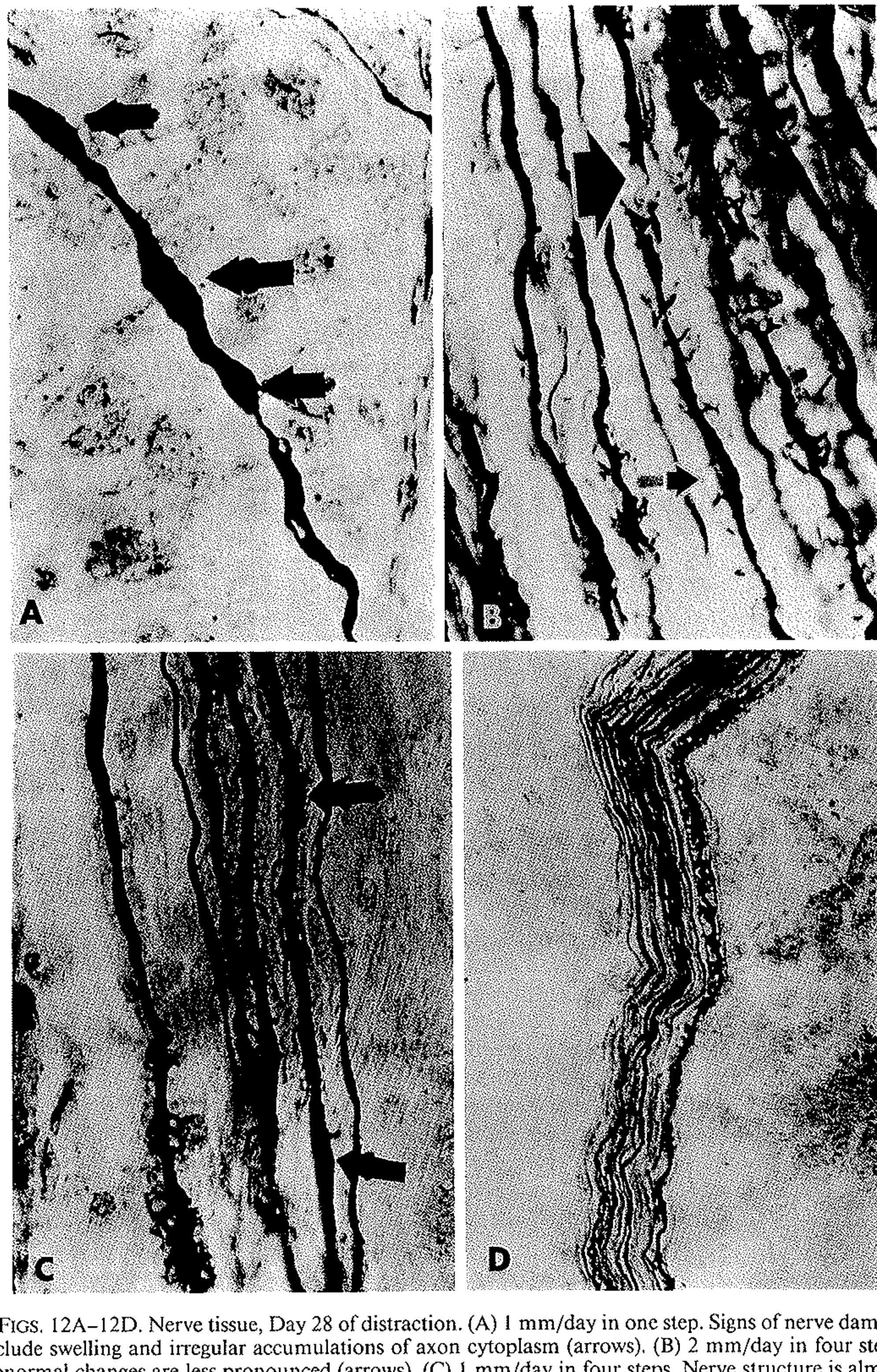
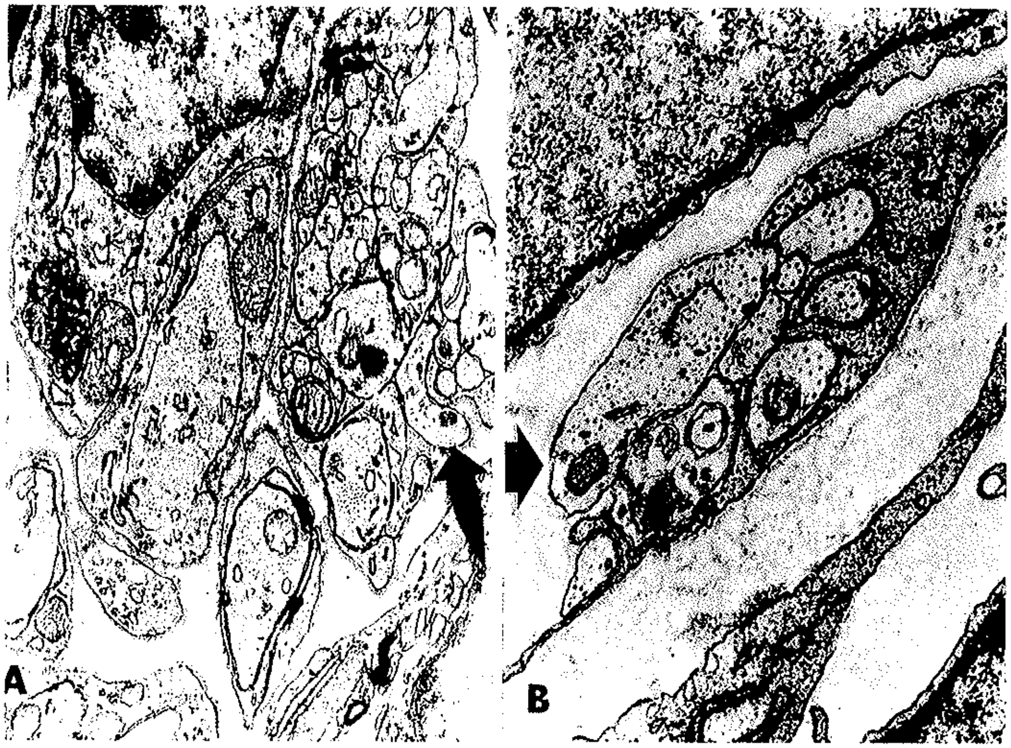


FIGS. 12A–12D. Nerve tissue, Day 28 of distraction. (A) 1 mm/day in one step. Signs of nerve damage include swelling and irregular accumulations of axon cytoplasm (arrows). (B) 2 mm/day in four steps. Abnormal changes are less pronounced (arrows). (C) 1 mm/day in four steps. Nerve structure is almost normal. (D) 1 mm/day in 60 steps. The nerve structure appears normal. (Stain, silver; original magnification, ×500.)



FIGS. 13A AND 13B. The relationship between lemmocytes and axons. (A) Nerve fiber from developing limb of fetal dog. (B) Nerve fiber from limb elongated 1 mm/day in the autodistractor. (Original magnification, ×12,000.)

limb is daily lengthened 0.5 mm at a frequency of 0.125 mm every six hours, osteogenesis overtook the speed of distraction causing premature consolidation, especially when the closed osteoclasis technique was used. A rapid distraction rate of 2 mm per day at a frequency of 0.5 mm every six hours, in contrast, not only retarded osteogenesis but also caused detrimental changes in the soft tissues surrounding the site of distraction. Elongation by 1 mm per day in four equal increments (0.25 mm every six hours) led to more favorable results than either a slower or faster rate.

These experiments also demonstrated that, at a given rate of distraction, a greater frequency of distraction provided a better outcome. With a distraction rate of 1 mm per day, the autodistractor proved superior to a distraction frequency of four times per day that in turn was better than once per day. The elongation of fascia illustrated the point. Normal fascia, in its resting state, has a wavy appearance with distinct collagen bundles. At a distraction rate of 1 mm per day in one step every 24 hours, the fascia became stretched in appearance and many areas of homogenization, indicating structural damage, were noted. At 1 mm per day in four steps, the stretched appearance persisted, but there was far less evidence of homogenization. At 1 mm per day in 60 steps, the fascia retained its wavy appearance despite histologic evidence of growth, *i.e.*, fibroblast proliferation and ultramicroscopic evidence of collagen production.[33,39,40] Changes in other tissues mirrored these findings.[35]

In summary, when the autodistractor was used for limb lengthening, the proliferative, metabolic, and biosynthetic changes in cellu-

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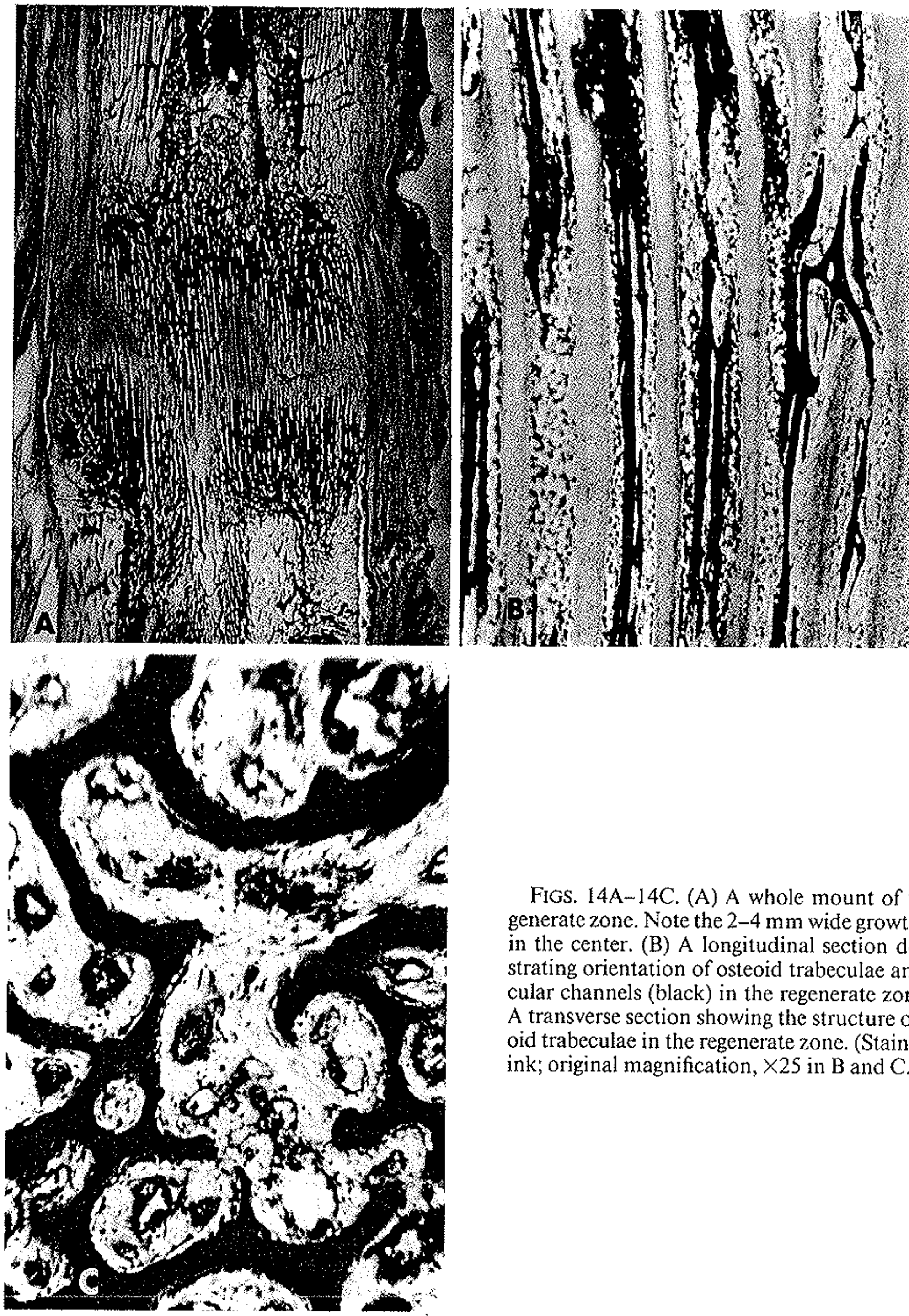
lar activity in many tissue elements took on features characteristic of histogenesis during embryonic, fetal, and postnatal limb growth. This experimental research on the influence of the tension–stress effect on tissues has led to the recognition of the importance of stability, soft-tissue and marrow preservation,[15] as well as the rate and frequency of distraction during limb lengthening. When the optimum circumstances are combined with the proper application of the external fixator, a special type of growth plate is created within the elongated bone. At the same time, the perosseous soft tissues undergo histologic and functional adaptive changes that recreate the conditions of normal growth (Fig. 14).[35]

During elongation, a temporary decline in the hematopoietic function of the marrow in the distraction zone was observed. During the fixation period following distraction, the hematopoietic cell population within the maturing regenerated bone gradually returned to normal. This observation led to the hypothesis that there is a common genetic community of hematopoietic and osteogenic stromal stem cells that is stimulated by the tension–stress effect. Since blood loss also stimulates hematopoiesis, the possibility that stimulation of the hematopoetic stem cells by blood loss might lead to enhanced osteogenesis was investigated.

In studies reported elsewhere using a 5 mm rabbit fibular defect as a model,[31] one-half the animals were bled to obtain a volume of blood equal to 1% of their body weight. One hour after bleeding, a 5 mm defect was created in the fibulae of these animals and an identical defect was made in a group of rabbits that were not bled. More rapid osteogenic activity occurred in the group that was bled compared to the control group. Specifically, in the experimental group, there was a full substitution of the fibular defect with regenerated bone by Day 21 of the experiment, while in the control group full roentgenographic substitution was not observed until Day 35 of the experiment. Radioimmunoassays of these two groups focused on the dynamics of cyclic adenosine-3,5-monophosphate in the blood plasma of the experimental and control groups. The increase in adenosine monophosphate plasma concentration was accompanied by the simultaneous activation of both osteogenic and erythropoietic elements of the bone marrow. Thus, the preliminary stimulation of the hematopoietic bone marrow elements under the conditions of the experiment appears to have a favorable effect on bone regeneration, which suggest that the same stromal stem cells may be precursors for both hematopoietic and osteogenic cells.[32]

The circular external skeletal fixator designed by the author, when properly applied, stabilizes the bone fragments in all planes, but allows enough axial micromotion to stimulate osteogenesis.[44] Furthermore, the use of thin wires to secure the bone fragments to the rings minimizes damage to the soft tissues, periosteum, and marrow blood supply. The modular nature of the apparatus allows displacement of the rings with respect to each other in three planes at once, thereby permitting the simultaneous correction of angulation, rotation, and shortening. A clinical model of the autodistractor used in these experiments has resulted in rapid consolidation of the regenerated bone for a variety of orthopedic conditions.

The ability to safely and predictably lengthen bone by gradual distraction has lead to the development of the technique of compression–distraction osteosynthesis,[11,28,50] a strategy for overcoming segmental bone defects whether due to a congenital anomaly, resection for tumor, traumatic bone loss, or as a consequence of debridement of osteomyelitic and nonviable osseous tissue. With this method, the limb length is maintained, or limb shortening is gradually overcome, in the circular external fixation apparatus while, at the same time, a corticotomy is performed through healthy bone some distance away from the skeletal defect. Components of the apparatus are attached with wires to the segment of bone between the corticotomy and the defect. Thereafter, steady traction is applied to the intercalary bone segment, simultaneously elongating the corticotomy region



FIGS. 14A–14C. (A) A whole mount of the regenerate zone. Note the 2–4 mm wide growth zone in the center. (B) A longitudinal section demonstrating orientation of osteoid trabeculae and vascular channels (black) in the regenerate zone. (C) A transverse section showing the structure of osteoid trabeculae in the regenerate zone. (Stain, india ink; original magnification, ×25 in B and C.)

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<25 in B and C.)

while closing and compressing the original skeletal defect. New bone formation within the distraction zone forms according to the tension–stress effect and the defect is eliminated without the need for bone grafting.

The biological principle of the tension–stress effect, when combined with the circular external fixator, provides a surgeon with the possibility of treating numerous types of injuries and orthopedic diseases including: (1) the percutaneous treatment of all closed metaphyseal and diaphyseal fractures as well as many epiphyseal fractures[7,8,14,41]; (2) the repair of extensive defects of bone, nerve, vessel, and soft tissues without the need for grafting in one operative stage[11–13]; (3) bone thickening for cosmetic and functional reasons[16]; (4) the percutaneous one-stage treatment of congenital or traumatic pseudarthroses[3,24,46,49,50]; (5) limb lengthening or growth retardation by distraction epiphysiolysis or other methods[1,4,5,17,18,22,23,35]; (6) the correction of long-bone and joint deformities, including resistant and relapsed club feet[20,47,51]; (7) the percutaneous elimination of joint contractures; (8) the treatment of various arthroses by osteotomy[21] and repositioning of the articular surfaces; (9) percutaneous joint arthrodesis[9,10,36]; (10) elongating arthrodesis—a method of fusing major joints without concomitant limb shortening[36]; (11) the filling of solitary bone cysts and other such lesions; (12) the treatment of septic nonunion by the favorable effect on infected bone of stimulating bone healing[25,28]; (13) the filling of osteomyelitic cavities by the gradual collapsing of one cavity wall[29]; (14) the lengthening of amputation stumps; (15) management of hypoplasia of the mandible and similar conditions; (16) the ability to overcome certain occlusive vascular diseases without bypass grafting; and (17) the correction of achondroplastic and other forms of dwarfism.[23,37,38,43,48]

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Displaced Proximal Humeral Fractures: PART I. CLASSIFICATION AND EVALUATION

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Displaced Proximal Humeral Fractures

Part I. Classification and Evaluation*

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Most proximal humeral fractures respond satisfactorily to simple conservative treatment. It is only the occasional displaced fracture or fracture-dislocation that demands special treatment and judgment; yet existing classifications are inadequate to identify these lesions. Failure to portray the specific fracture under consideration has led to confusion in the literature and difficulty in establishing guidelines for treatment. This paper describes a classification that has been found not only adequate for sorting lesions for analysis of results but also helpful in correlating the roentgen appearance and type of fresh fractures.

Material and Method

A study was made of the anatomy of 300 displaced proximal humeral fractures and fracture-dislocations, selected at random from those treated by closed reduction under anesthesia or surgery at the New York Orthopaedic Hospital–Columbia-Presbyterian Medical Center between the years 1953 and 1967. The ages of the patients ranged from twenty-two years to eighty-nine years and averaged 55.6 years. Treatment consisted in closed reduction under anesthesia in 162, open reduction in seventy-five, with removal of the humeral head on five occasions [8], and prosthetic replacement [15,16,17] in sixty-three patients. Roentgenograms of the fracture made before treatment were studied and the precise relationships of the major segments were charted. Operative findings and photographs of those treated surgically were correlated with the roentgen appearance. As distinct anatomical categories became evident, the classification was evolved.

Deficiencies in Existing Classifications

Traditional classifications according to the level of the fracture [2,11] are of little assistance in depicting the type of displaced fracture because two levels were frequently involved (Fig. 1). As Codman observed, fractures at the humeral neck separate one, two, or three of the four major segments from the rest: the segments are the head, the lesser tuberosity, the greater tuberosity, and the shaft. Fracture of both tuberosities produces a lesion that can be termed either an *anatomical-neck fracture* or a *surgical-neck fracture* because both levels are implicated. This leads to

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inconsistencies in the literature, as is shown by variations in the reported incidence of each level of fracture as interpreted by different observers [6,19,23]. Furthermore, a classification based merely upon the level of the fracture permits a non-displaced lesion to be grouped with a serious displacement.

Classification according to the mechanism of the injury [5,22] also fails to portray

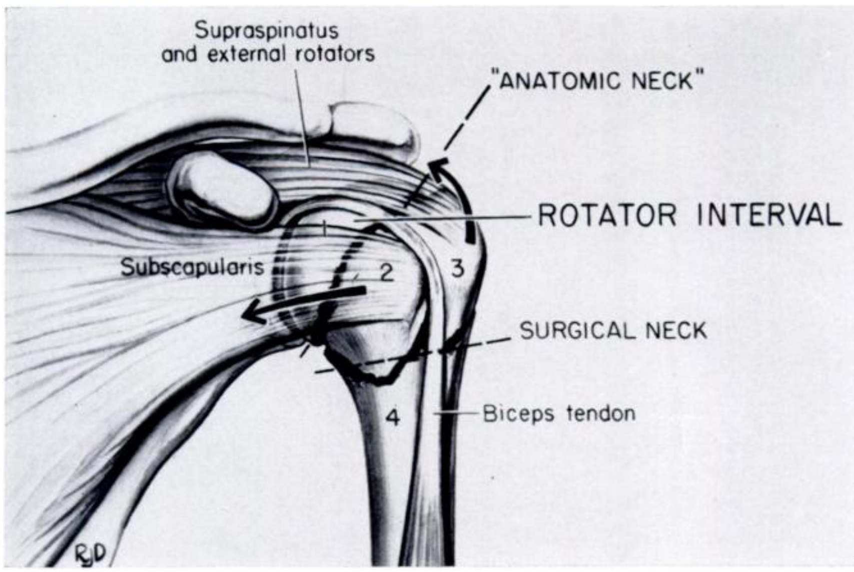


FIG. 1

Drawing illustrating the rotator interval, a ligamentous area between the tendons of the supraspinatus and subscapularis, and the four major fragments of proximal humeral fractures: (1) head, (2) lesser tuberosity, (3) greater tuberosity, and (4) shaft. Retraction of both tuberosities tears the rotator interval and involves both the surgical-neck and anatomical-neck levels.

FIG. 2-A

FIG. 2-B

Figs. 2-A and 2-B: Anteroposterior roentgenograms of a malunited fracture depicting the fallacy of the terms *abduction fracture* and *adduction fracture*.
Fig. 2-A: With the humerus internally rotated the head appears to be in valgus position, the adduction fracture.
Fig. 2-B: With the same humerus externally rotated the head appears to be in varus position, the abduction fracture.
The apex of the angle is, as in this case, usually directed anteriorly and not in the scapular or coronal planes.

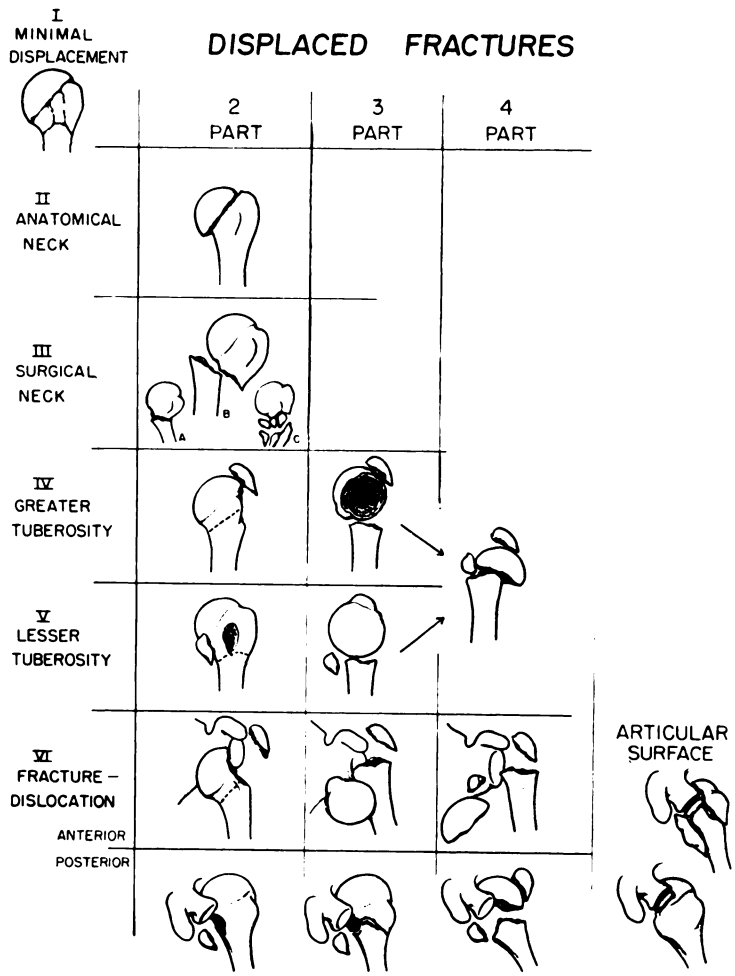


FIG. 3

The anatomical classification. Each of the four major segments shown in Fig. 1 is considered. Group I includes all proximal humeral fractures, regardless of the number of lines of cleavage, in which no segment is displaced more than 1.0 centimeter or angulated more than 45 degrees. Group II, the anatomical-neck fracture, is a displacement of the head segment, with or without hairline tuberosity components. Group III, the surgical-neck fracture, is a displacement of the shaft segment with the rotator cuff intact. Group IV, the greater tuberosity displacement, occurs as a two-part and, with an unimpacted surgical-neck fracture, as a three-part lesion. Group V, the lesser tuberosity, occurs as a two-part and, with an unimpacted surgical-neck fracture, as a three-part lesion. Groups IV and V blend as the four-part fracture in which both tuberosities are displaced Group VI, the fracture-dislocation, implies damage outside the joint space, anteriorly and posteriorly, and segment distribution is important in estimating the circulation of the head. The articular surface fractures, in which portions of the head are dislocated, are the impression fracture and the head-splitting fracture.

the type of lesion. The terms *abduction fracture* and *adduction fracture* are misleading because the apex of angulation usually is directed anteriorly, occasionally in some other plane, but rarely in the coronal or scapular planes. Anterior angulation can produce the roentgen appearance of either the abduction fracture or the adduction fracture, depending on the position of rotation of the humerus (Figs. 2-A and 2-B).

It also is confusing to find that opinions differ [1,6,9,10,20] as to what constitutes a fracture-dislocation. The glenohumeral-joint capsule is large enough to contain two humeral heads and when there is muscle atony or when one of the tuberosities is detached, the articular surface of the humerus can easily be subluxated or rotated out of the glenoid cavity. This has led to such terms as *fracture-subluxation* [7,21], *rotary*

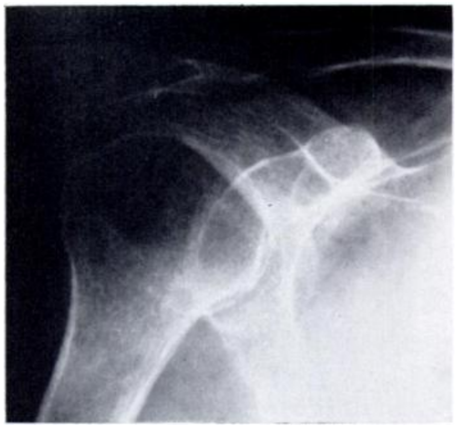


Fig. 4-A

Fig. 4-B

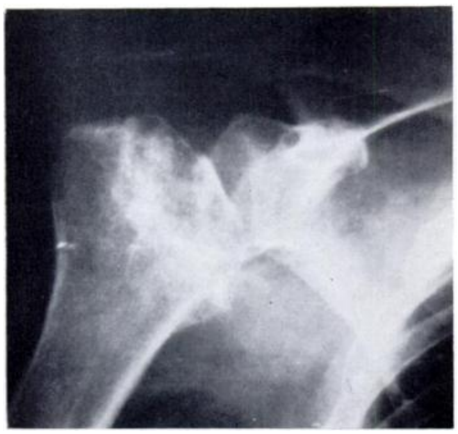


Fig. 4-C

Figs. 4-A, 4-B, and 4-C: Anteroposterior roentgenograms of head-segment displacement at the anatomical neck, Group II. This lesion can go unrecognized and lead to disability from malunion or avascular necrosis.
Fig. 4-A: Original roentgenogram made with the humerus internally rotated, resulting in failure to recognize the lesion.
Fig. 4-B: Same fracture visualized four months later with the humerus externally rotated, showing the displacement.
Fig. 4-C: Similar lesion, complicated by avascular necrosis, two years after injury.

dislocation [20], and *impacted fracture-dislocation* [22]. However, these terms fail to specify the type of rotatory displacement in a specific lesion. Indeed, the role of muscle attachments in producing displacement has received surprisingly little attention.

The Four-Segment Classification

The classification adopted is based, not on the level of the fracture nor on the mechanism of injury but on the presence or absence of displacement of one or more of the four major segments. Since all minimally displaced fractures pose analogous problems in treatment and prognosis, it seems logical that they be grouped together, regardless of the number of fracture lines. Displaced fractures require more accurate identification in order to depict both the effect of muscle attachments on free fragments, as well as the circulatory status and continuity of the articular surface. The classification illustrated was formed to identify the types of displacement that were actually encountered (Fig. 3).

Group I, Minimum Displacement

This group includes all fractures, regardless of the level or number of fracture lines, in which no segment is displaced more than 1.0 centimeter or is angulated more than 45 degrees. This group constitutes over 85 per cent of proximal humeral fractures [14]. These lesions present similar problems in management. The fragments are usually held together by soft tissue or are impacted, permitting early functional exercises; however, a brief period of immobilization may be required before the head and shaft rotate as one.

Group II, Articular-Segment Displacement

Pure displacement at the anatomical neck without separation of one tuberosity or both is quite rare. This lesion can escape notice unless a good anteroposterior roentgenogram of the upper end of the humerus is obtained (Fig. 4-A) and may lead to disability because of malunion or avascular necrosis (Figs. 4-B and 4-C).

Group III, Shaft Displacement

This fracture occurs just distal to the tuberosities at the level of the surgical neck and is displaced more than 1.0 centimeter or is angulated more than 45 degrees. Although fissure fractures may be present proximally, the rotator-cuff

FIG. 5-A

Figs. 5-A, 5-B, and 5-C: Anteroposterior roentgenograms illustrating the three types of shaft-segment displacement seen in Group-III fractures.

Fig. 5-A: Angulated fracture, same malunion as in Figs. 2-A and 2-B, showing maximum abduction.

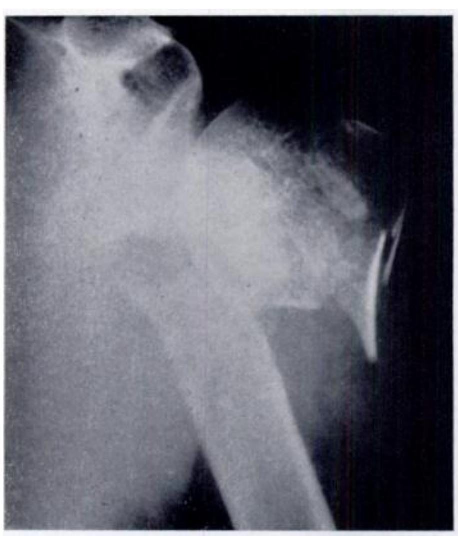


FIG. 5-B

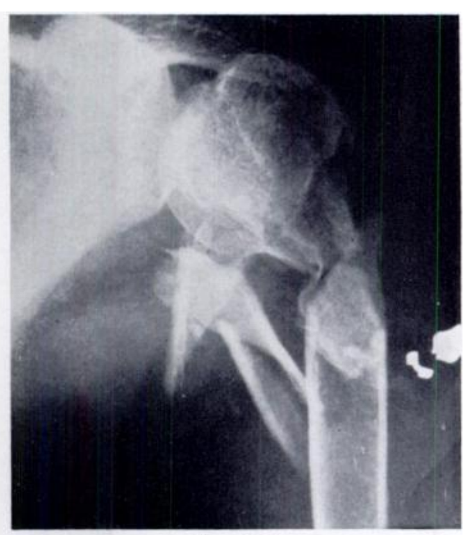


FIG. 5-C

Fig. 5-B: Non-contact fracture with the shaft displaced medially by the pectoralis major and the head held in neutral rotation by the intact rotator cuff.

Fig. 5-C: Comminuted fracture, twisted by placing the arm across the chest in a sling.

FIG. 6-A

FIG. 6-B

Fig. 6-A through 6-E: Original anteroposterior roentgenograms illustrating Group-IV and Group-V fractures.

Fig. 6-A: Group-IV two-part fracture. The greater tuberosity is displaced but the head remains in normal position, with or without an undisplaced surgical-neck component.

Fig. 6-B: Group-IV three-part fracture. The greater-tuberosity displacement is associated with an unimpacted surgical-neck fracture which permits the head to be internally rotated by the subscapularis so that the articular surface faces posteriorly.

attachments are intact and hold the head in neutral rotation. The head is only slightly abducted unless tilted by an overriding shaft. Epiphyseal fractures are of this category [18]. Three types are seen in adult patients.

The *angulated surgical-neck fracture* is impacted. Residual angulation of more than 45 degrees causes permanent limitation of abduction and elevation (Figs. 2-A, 2-B, and 5-A). The periosteal sleeve is usually intact posteriorly and affords considerable stability when closed reduction is accomplished by traction and elevation of the arm forward beyond the pivotal position.

The *separated surgical-neck fracture* is one in which the shaft is displaced medially and anteriorly, pulled by the pectoralis major. This fracture is often unstable after closed reduction (Fig. 5-B), and immobilization in a position to relax the pectoralis is helpful. The displacement is made worse by placing the arm in abduction or in a tight sling. Instability and interposition of soft tissue may lead to non-union. Associated neurovascular damage is not uncommon.

The *comminuted surgical-neck fracture*, in which fragmentation extends distally for several centimeters, often undergoes twist displacement when the arm is internally rotated across the chest, because the tuberosities and head are held in neutral rotation by the intact rotator cuff. Intermediate fragments may be displaced by the pectoralis (Fig. 5-C). This fracture can be adequately aligned by overhead ulnar-pin traction applied in neutral rotation to relax the pectoralis.

Group IV, Greater-Tuberosity Displacement

The greater tuberosity or one of its facets for tendon attachment is retracted more than 1.0 centimeter from the lesser tuberosity. The separation is pathognomonic of a longitudinal tear in the rotator cuff. The tear usually occurs at the rotator interval (Fig. 1), but, when only the posterior part of the greater tuberosity is retracted, the tear occurs posterior to this interval. In the two-part pattern, the articular segment remains in a normal relationship with the shaft, although a minimally displaced fracture of the surgical neck may be present (Fig. 6-A). In the three-part pattern, in addition to the retraction of the tuberosity, displacement at

FIG. 6-C

FIG. 6-D

Fig. 6-C: Group-V two-part fracture. The lesser tuberosity is displaced but the head remains in normal position, with or without an undisplaced surgical-neck component.
Fig. 6-D: Group-V three-part fracture. The lesser-tuberosity displacement and unimpacted surgical-neck fracture permit the head to be externally rotated and abducted by the supraspinatus and external rotators as the articular surface faces anteriorly.

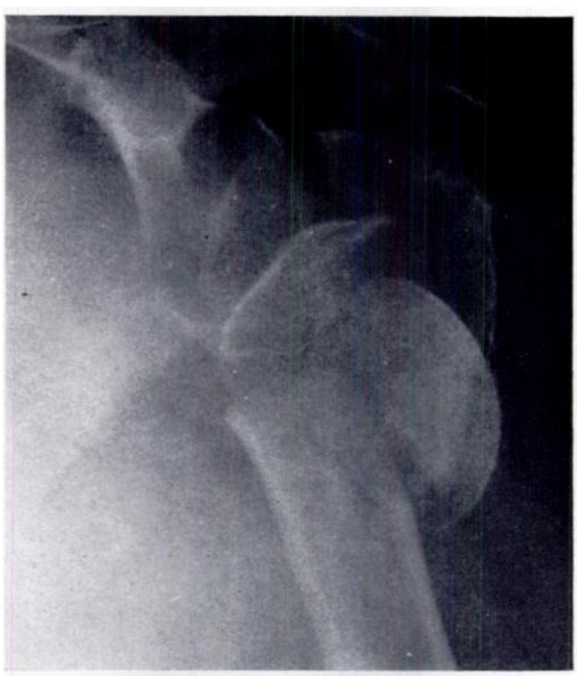
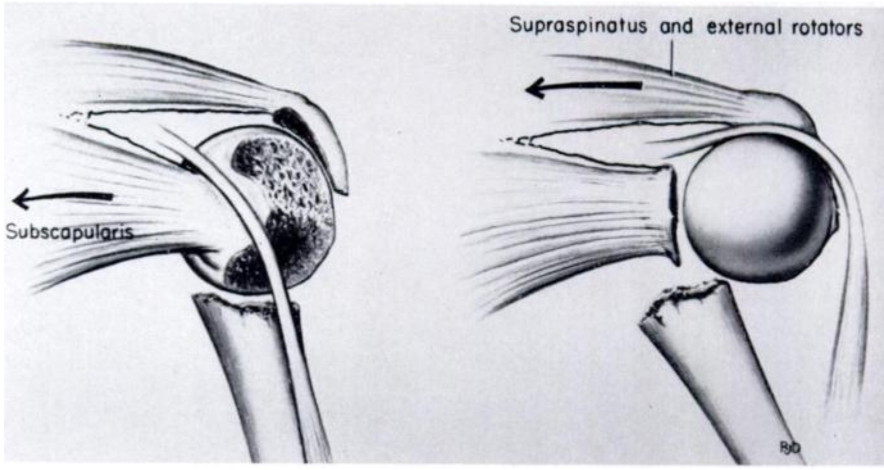


FIG. 6-E

Groups IV and V merge in the four-part fracture. Both tuberosities are displaced and the head presents at the defect in the rotator interval.

the surgical neck is also present which allows the articular segment to be internally rotated by the subscapularis. This exaggerates the rotator-cuff defect and causes the articular segment to face posteriorly (Figs. 6-B and 7). This is a much more serious displacement. The attached muscles act to prevent closed reduction. Nevertheless, a good source of blood supply to the head remains because soft parts are attached to



A FIG. 7 B

Drawings contrasting the rotatory displacements of the two types of three-part fractures, Groups IV and V. *A:* Detachment of the greater tuberosity, Group IV, with an unstable surgical-neck fracture, allows the head to be internally rotated, exaggerating the rotator-cuff defect. *B:* Detachment of the lesser tuberosity, Group V, and shaft allow the head to be externally rotated and abducted.

the articular segment anteriorly. If this source of blood supply [12] is preserved during an open reduction, the prognosis for survival of the humeral head would appear to be much better than that of the four-part fracture in which the head is detached (Fig. 6-D).

Group V, Lesser-Tuberosity Displacement

The two-part lesion occurs as an isolated avulsion or in association with an undisplaced fracture of the surgical neck (Fig. 6-C). Displacement of the lesser tuberosity spreads the anterior fibers at the rotator interval and produces a bone prominence. Neither defect appears to be of clinical importance. In the three-part displacement, however, the displacement at the surgical neck allows the articular segment to be externally rotated and abducted by the supraspinatus and external rotators. This exaggerates the rotator-cuff defect and interferes with closed reduction. The articular surface is made to face anteriorly (Figs. 6-D and 7). At open reduction, articular cartilage is found presenting at the gaping tear in the rotator cuff, a situation which suggests that the head is dislocated, a false fracture-dislocation. However, the head segment retains abundant soft-part attachments posteriorly and adequate blood supply. Open reduction can be readily accomplished by derotating the head and approximating the tuberosities and cuff. In the four-part fracture, both tuberosities are retracted and, as in all four-part lesions, the blood supply to the humeral head has been severed. The articular segment is usually displaced laterally between the retracted tuberosities (Fig. 6-E). When the head is displaced laterally and out of contact with the glenoid, the term *lateral fracture-dislocation* is descriptive. However, the pathomechanics seem clearer when this lesion is classified as a severely displaced fracture rather than a fracture-dislocation.

Group VI, Fracture-Dislocation

This fracture occurs with a true dislocation which implies ligamentous damage and injury outside the joint, in turn implying a greater threat of pericapsular bone formation. The displacement of the humeral head may be anteroinferior, posterior, or superior; but no instance of superior displacement, associated with a fracture of

Fig. 8-A

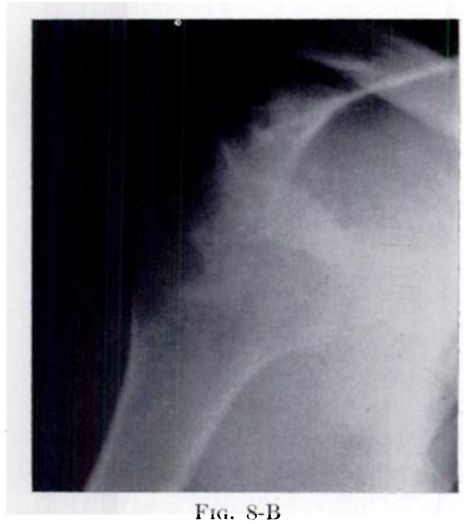


Fig. 8-B

Figs. 8-A through 8-D: Original anteroposterior roentgenograms illustrating anterior fracture-dislocations, Group VI. Segment distribution is important in estimating the circulation of the head.

Fig. 8-A: An unusual two-part surgical-neck lesion with both tuberosities in continuity with the head.

Fig. 8-B: Two-part greater-tuberosity displacement, a common injury.

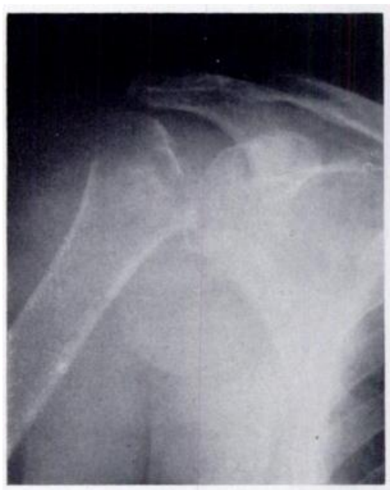


Fig. 8-C

Fig. 8-D

Fig. 8-C: Three-part lesion. The lesser tuberosity and its soft-part attachments remain to provide considerable blood supply to the head.

Fig. 8-D: Four-part lesion in which the head is detached.

the proximal end of the humerus, was encountered in this study. In the two-part and three-part fracture-dislocations (Figs. 8-A, 8-B, and 8-C), the blood supply to the humeral head is usually adequate because one of the tuberosities, with soft-tissue attachments, remains in continuity with the articular segment. The lesser tuberosity always remains attached to the humeral head in anterior three-part fracture-dislocations while the greater tuberosity remains to provide circulation to the head in posterior three-part fracture-dislocations. In four-part fracture-dislocations the head is detached (Fig. 8-D). Neurovascular symptoms occur more commonly with anterior four-part displacements.

Displaced fractures of the articular surface are classified with fracture-dislocations because, while part of the articular cartilage has been crushed by impact

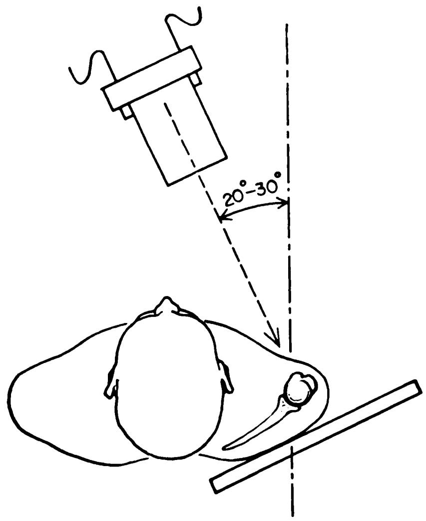


FIG. 9-A

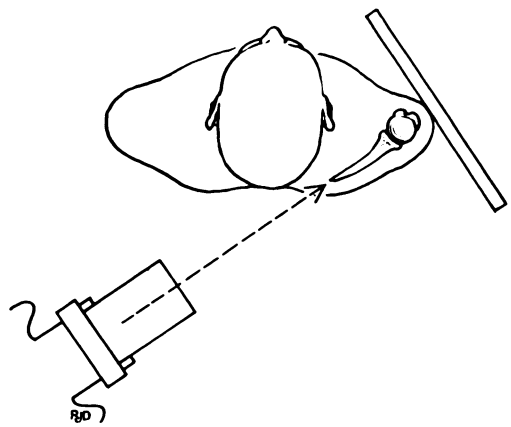


FIG. 9-B

Figs. 9-A and 9-B: Drawings to show the technique for obtaining anteroposterior and lateral roentgenograms of the upper end of the humerus. The patient is erect and leaning against the cassette.

Fig. 9-A: The anteroposterior roentgenogram of the upper end of the humerus is made perpendicular to the scapular plane by placing the tube 30 degrees medial to the sagittal plane.

Fig. 9-B: The lateral roentgenogram of the upper end of the humerus is made in the scapular plane.

against the glenoid and stays within the joint space, other fragments of cartilage are extruded from it. The impression fracture is commonly encountered with a posterior dislocation but rarely occurs to a significant extent with an anterior dislocation. When the impression defect is small and the lesion is recognized early, closed reduction is effective. When the impression involves more than 20 per cent of the articular surface, redislocation tends to occur unless the main articular fragment is stabilized, as by transplantation of the subscapularis tendon [13] into the defect in the head. When the articular defect involves more than 50 per cent of the cartilage-covered surface, the joint is unstable and dislocation readily recurs despite transplantation of the subscapularis. A prosthesis may be used at times to render this lesion stable. The head-splitting fracture results from a central impact which may extrude fragments of cartilage both anteriorly and posteriorly. The articular surface is fragmented into many disconnected pieces.

Roentgenographic Appraisal of the Lesion

Recognition of the position and relationships of the four major segments is essential to the application of this system of classification. As in the case of most other fractures, oblique projections can be confusing. It is helpful to obtain two roentgenograms of the upper end of the humerus made at right angles to each other, supplemented when necessary with transthoracic, rotational, and axillary roentgenograms.

It is usually possible to make the two initial projections with the patient erect and the arm in a sling (Figs. 9-A and 9-B). One view of the upper end of the humerus is perpendicular to the scapular plane and the second is parallel to the scapular plane. With this information, and with careful positioning, axillary or rotational roentgenograms of the upper end of the humerus can be made as required. The distance between the greater and lesser tuberosities is used to indicate the severity of tuberosity displacement.

TABLE I

CRITERIA FOR EVALUATION OF RESULTS *

1. *Pain* (*35 units*)	
a. None/ignores	35
b. Slight, occasional, no compromise in activity	30
c. Mild, no effect on ordinary activity	25
d. Moderate, tolerable, makes concessions, uses aspirin	15
e. Marked, serious limitations	5
f. Totally disabled	0
2. *Function* (*30 units*)	
a. Strength	
Normal	10
Good	8
Fair	6
Poor	4
Trace	2
Zero	0
b. Reaching	
Top of head	2
Mouth	2
Belt buckle	2
Opposite axilla	2
Brassiere hook	2
c. Stability	
Lifting	2
Throwing	2
Pounding	2
Pushing	2
Hold overhead	2
3. *Range in Motion* (*25 units*)	
Flexion (sagittal plane)	
180	6
170	5
130	4
100	2
80	1
less	0
Extension	
45	3
30	2
15	1
less	0
Abduction (coronal plane)	
180	6
170	5
140	4
100	2
80	1
less	0
External rotation (from anatomical position with elbow bent)	
60	5
30	3
10	1
less	0
Internal rotation (from anatomical position with elbow bent)	
90 (T-6)	5
70 (T-12)	4
50 (L-5)	3
30 (gluteal)	2
less	0
4. *Anatomy* (*10 units*) (rotation, angulation, joint incongruity, retracted tuberosities, failure metal, myositis, non-union, avascular necrosis)	
None	10
Mild	8
Moderate	4
Marked	zero to 2
Total points	100 units

* Excellent, above 89 units; satisfactory, 80 units; unsatisfactory, 70 units; failure, below 70 units

Evaluation of Results

Assessment of the results of treatment depends not only on an accurate definition of the specific lesion under discussion but also on an objective interpretation of functional recovery. The criteria for *good*, *fair*, and *poor* results have varied with each author and have been difficult to compare. An objective system that can be generally accepted for the future judging of long-term results is needed [4].

The numerical rating method employed in our clinic for several years is shown in Table I. This system is based on 100 units. *Pain*, the most important consideration to the patient, is assigned 35 units. The result in any patient with significant pain is graded a failure. *Functional range*, more important in the shoulder than in most joints, is accorded a greater unit value than *strength* and *anatomy* [4]. The results in 117 patients with three-part and four-part fractures have been rated by this method and are reported in the succeeding article.

Discussion

Existing classifications of fractures of the proximal part of the humerus are oversimplified and inadequate. It is essential to the understanding of the more complex shoulder injuries that fractures of a similar type be grouped together and separated from the more serious or less serious lesions. Any proponent of a method of treatment who fails to take this into account is likely to add confused reports to the already perplexing literature. Yet, since displaced fractures are relatively uncommon, it is desirable that comparable data be gathered from a number of sources in order to obtain answers to therapeutic questions.

It is generally agreed that fractures with minimum displacement, regardless of the level or number of fracture lines, can be satisfactorily treated by early functional exercises. These lesions can be separated as one large group. Most two-part displacements, with the exception of the greater tuberosity and of certain unstable fractures of the surgical neck, can be adequately controlled by closed means. The real problems arise in the case of three-part and four-part displacements and in the fractures with massive defects in the articular surface.

Three-part fractures present the problem of marked anatomical distortion. Some of the tendons causing rotatory displacement are accompanied by vessels to the articular segment. It may appear most difficult to restore good anatomical relationships by closed means, yet necrosis with resorption of the head rarely occurs. In this group, it would seem important in the future to compare the results of closed treatment with those of open reduction. What degree of imperfection in reduction is acceptable? If open reduction yields better results, how can the technique and the method of fixation be improved?

In four-part fractures the circulation to the head is destroyed. Can the disconnected articular segment enter into bone union and survive [20] or will it disintegrate? What are the relative merits of prosthetic replacement compared with those of other open or closed procedures in which the articular fragment is retained?

Articular crushing in large impression fractures and head-splitting fractures can be logically treated by prosthetic replacement. Other techniques may be developed in the future. But regardless of the method of treatment, if we are to make orderly progress, it is essential that the lesion under consideration be clearly defined and the result considered objectively.

One further deterrent to progress in the treatment of complicated fractures of the shoulder has been the prevalent misconception that these injuries occur in very elderly patients who do not require optimum results. Occasionally this is true, but as the exception rather than the rule. The patients in my series had an average age of fifty-five years and the majority were in their most productive years.

Summary

On the basis of roentgenographic appearance and anatomical lesions in 300 displaced fractures and fracture-dislocations of the proximal end of the humerus, a new classification was made of these injuries. Existing classifications were found to be inadequate to describe the lesion encountered. The new classification was based on the presence or absence of displacement of each of the four major segments: articular surface of the humeral head, greater tuberosity, lesser tuberosity, and shaft. Careful roentgen examination was found necessary to apply this system, including anteroposterior and lateral roentgenograms of the proximal end of the humerus made vertical to and parallel with the scapular plane. A numerical rating scale for evaluating the results of treatment is described because, in addition to a clear definition of the lesion, objective criteria for rating results are essential for future progress in the treatment of the more complex shoulder injuries.

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Anterior Acromioplasty for the Chronic Impingement Syndrome in the Shoulder: A PRELIMINARY REPORT

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Anterior Acromioplasty for the Chronic Impingement Syndrome in the Shoulder

A PRELIMINARY REPORT *

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Impingement of the rotator cuff beneath the coraco-acromial arch has been recognized as one of the causes of chronic disability of the shoulder [1,5,6,7,9,10]. Complete acromionectomy [1,5,10] and lateral acromionectomy [6,9] at various levels have been advocated for the condition. Disappointment with the results of these procedures, because of weakening of the leverage of the deltoid muscle, displacement of the attachments of the origin of the deltoid, formation of sinuses with bursal or joint fluid draining through the skin, deep scars, and, in the case of lateral acromionectomy, the persistence of symptoms because of residual impingement, stimulated us to a new study of the role, in the impingement syndrome, of the undersurface of the acromion.

This paper describes relevant anatomical findings and the rationale, the indications, the technique, and the preliminary results of anterior acromioplasty, which has been a procedure performed in our clinic since 1965.

Anatomical Considerations

Inspection of 100 dissected scapulae with special attention to the acromion revealed alterations attributable to mechanical impingement in eleven. The ages of the cadavera were unknown but the majority were in the sixth decade or older. A characteristic ridge of proliferative spurs and excrescences on the undersurface of the anterior process was seen frequently, apparently caused by repeated impingement of the rotator cuff and humeral head, with traction on the coracoacromial ligament, and it was quite prominent in eight specimens (Fig. 1-A). Eburnation with erosion of the acromion was thought to be a later manifestation, and was found in three specimens (Fig. 1-B). Without exception, it was the anterior lip and undersurface of the anterior third that was involved. In one scapula, the eburnation and erosion, accompanied by an old massive cuff tear, extended somewhat further toward the center of the acromion but the posterior third was spared.

My observations at surgery have consistently supported the hypothesis that the critical area for degenerative tendinitis and tendon rupture is centered in the supraspinatus tendon, extending at times to include the anterior part of the infraspinatus tendon and the long head of the biceps [3,7] (Fig. 2). However, it has not been adequately emphasized that, with the arm in the anatomical position, all of these structures lie anterior to the acromion. With internal rotation, the position in which the arm is often used, they are brought even more anterior. With external rotation, the facet for the insertion of the supraspinatus lies just lateral to the anterior third of

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FIG. 1-A

FIG. 1-B

Figs. 1-A and 1-B: Photographs of the undersurface of the acromion of elderly cadavera.
Fig. 1-A: Showing a large anterior acromial spur and excrescences of the anterior third, thought characteristic of chronic impingement with traction on the coraco-acromial ligament. Spatial relations can be determined by the location of the articular facet for the clavicle.
Fig. 1-B: Another specimen showing erosion of this area and eburnation, which appeared to be a later manifestation.

the acromion (Fig. 3). Thus, elevation of the arm in internal rotation or in the anatomical position of external rotation causes the critical area to pass under the coraco-acromial ligament or the anterior process of the acromion. The critical area does not touch the posterior two-thirds of the acromion. With scapular rotation the acromion is tilted backwards, leaving the anterior process as the leading edge.

At about 80 degrees of abduction, the critical area of the supraspinatus tendon passes beneath the acromioclavicular joint and this joint tilts with overhead elevation of the arm. With the joint in this position, it is logical to assume that excrescences on the undersurface of the anterior margin of the acromion may impinge on the cuff. Arthrograms seem to substantiate this point.

One thesis of this study is that a lateral acromionectomy not only weakens the deltoid unnecessarily, which is especially bad when the rotator cuff is deficient, but also removes an innocent part of the acromion, that part posterior to the site of pathological involvement. It seems important that the rough surface on which the supraspinatus tendon is rubbing be removed. One should therefore remove the anterior edge and the undersurface of the anterior process along with the attached coraco-acromial ligament. If other pathological areas are discovered at operation, that is, a hypertrophic acromioclavicular joint, or spurs and adhesions at the long head of the biceps or greater tuberosity, they too should be removed. The attachments of the deltoid should be minimally disturbed.

Material

During the years 1965 to 1970, fifty shoulders of forty-six patients were operated on by the method to be described. The pathological findings in the supraspinatus tendon consisted of tendinitis or partial tears in nineteen shoulders, complete tears in twenty, and evidences of residual impingement following lateral acromionectomy in

FIG. 2

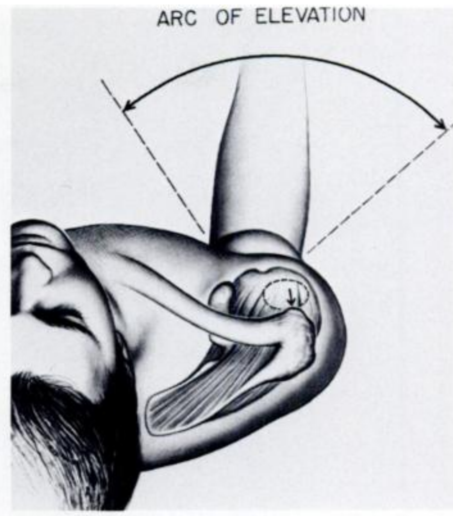

FIG. 3

Fig. 2: Illustrating the relationships of the critical area with the coraco-acromial arch when the arm is held in the anatomical position. Note the overlapping insertion of the infraspinatus and the proximity of the bicipital groove. The critical area is anterior to the acromion.

Fig. 3: Drawing to show that with elevation into any of the functional arcs, the critical zone at the supraspinatus engages the anterior third of the acromion, not the posterior part.

eleven. Patients with roentgenographic evidence of calcification in the tendon, rheumatoid arthritis, fractures, or acute tears were not considered suitable for this study, which was restricted to what was considered mechanical impingement.

The ages of the patients ranged from forty-two to seventy-three years and averaged 51.5 years for those with tendinitis or partial tears and 58.1 years for those with complete tears. Twenty-eight patients were men and eighteen were women. The right shoulder was involved twice as frequently as the left.

Forty-seven shoulders were evaluated from nine months to five years following surgery, twenty-nine by examination and eighteen by questionnaire and records. Three shoulders had not been followed for the minimum period. Follow-up roentgenograms were obtained in all but six. The average duration of follow-up was two and one-half years.

Indications for Surgery

The procedure to be described was used in patients either with long-term disability from chronic bursitis and partial tears of the supraspinatus tendon, or with complete tears of the supraspinatus associated with tears of varying degree of the adjacent rotator cuff. The first lesion is regarded as an early stage of the second and the two lesions comprise the impingement syndrome. Calcific deposits in the rotator cuff did not necessarily occur at the critical area of impingement, and they were regarded as chemical irritants. Patients with such deposits were usually responsive to simple treatment and were not considered for the procedure under discussion. Nine patients in this series had a history of having had such deposits and were found to have scarred or torn supraspinatus tendons, with or without minute amounts of calcium which, when present, were inapparent roentgenographically.

Since the physical and roentgenographic findings in the two categories of patients were indistinguishable, arthrograms were required to demonstrate whether the tears were complete. The physical signs for both groups of patients included crepitus and tenderness over the supraspinatus tendon, a good range of assisted motion but a

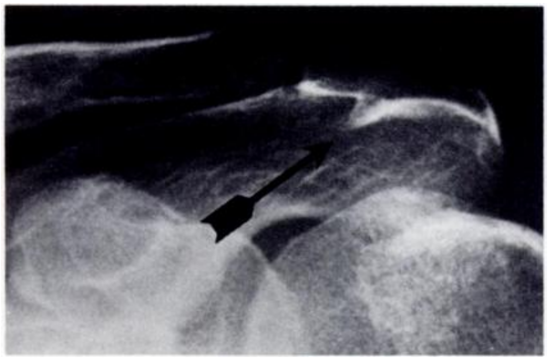

FIG. 4-A

FIG. 4-B

Figs. 4-A and 4-B: Roentgenograms of an anterior acromial spur in a man aged fifty-six years. A three-centimeter complete tear of the supraspinatus was found at surgery.

Fig. 4-A: Anteroposterior roentgenogram showing the spur on the acromion and a corresponding excrescence at the greater tuberosity and bicipital groove.

Fig. 4-B: Axillary roentgenogram of the same patient showing that the spur is located at the anterior third of the acromion. Roentgenographic findings at the acromion are not always evident and, when present, may be compatible with normal function although the patient appears to be more vulnerable to minor trauma.

painful arc of active elevation from 70 degrees to 120 degrees, and pain at the anterior edge of the acromion on forced elevation. Patients with partial tears seemed more prone to have a lesser range of motion. The only common roentgenographic finding was the presence of cysts or sclerosis of the greater tuberosity, but on close inspection many roentgenograms showed corresponding areas of proliferation at the anterior edge of the acromion (Figs. 4-A and 4-B).

Patients suspected of having incomplete tears were advised not to have surgery until the stiffness of the shoulder had disappeared, and the disability had to persist for at least nine months before surgery was performed. Many patients not included in the series were suspected of having impingement but responded well to conservative treatment. This suggests that while such patients had pathological changes in the cuff that were vulnerable to swelling and inflammation following minor trauma, the acute reaction was reversible. In this series, all patients with incomplete tears had had symptoms for from ten months to ten years, averaging four years. The effects of a xylocaine injection beneath the acromion or into the acromioclavicular joint was a useful guide as to what the procedure would accomplish.

The patients in this series who had complete tears had had symptoms for from six weeks to twelve years. The symptoms sometimes were intermittent and often became more intense a few months prior to surgery. When a complete tear was suspected and there was no response to conservative treatment for six weeks, arthrography was advised. If the arthrogram was positive, surgery was recommended. In the occasional patient who was suspected of having a massive cuff avulsion, because of a history of minor trauma followed by complete inability to raise the arm, we tried to make the arthrogram and to do the repair promptly before there was permanent shortening of the cuff muscles.

A special indication for anterior acromioplasty was residual impingement and chronic disability following partial lateral acromionectomy. The shoulders of those patients were decompressed anteriorly according to the same principle. We tried to use the old skin incision as much as possible and, at times, we did a reconstruction of the central part of the origin of the deltoid.

This procedure has also been used at the time of glenohumeral arthroplasty for rheumatoid and degenerative arthritis. These cases are not included in this study. It

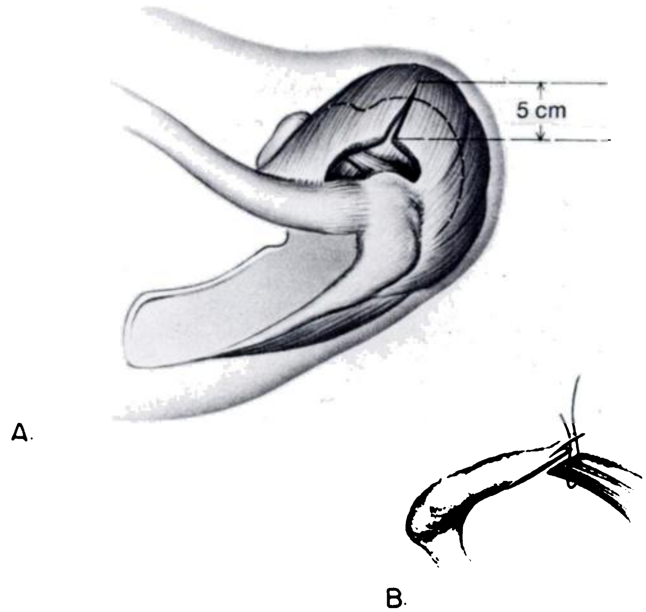

FIG. 5

Illustrating detachment and repair of the deltoid origin. *A:* The muscle is split from above downwards five centimeters and is detached from the anterior third of the acromion and acromioclavicular joint capsule. The tendinous origin on the anterior third of the acromion is elevated dorsally prior to removing bone, exposing the anterior edge of the acromion and providing a rim of tissue for repair. *B:* Secure closure of the deltoid is accomplished by suturing the lateral flap to the rim of tendinous tissue on the acromion as shown. The medial flap is sutured to the capsule of the acromioclavicular joint or, when the joint has been excised, to the trapezius muscle. The split is closed last.

was thought that the inclusion of results of combined procedures for other types of disease would introduce too many variables to permit an analysis of the subacromial impingement syndrome.

Operative Technique and Postoperative Regimen

The patient was placed high on the table, positioned so that the point of the affected shoulder protruded over the corner of the table. The shoulder, which was draped free, could be fully extended without interference from the table. Folded towels were placed under the scapula. The head was supported with an armboard, avoiding hyperextension. The table was adjusted to the beach chair position. The anesthesiologist was draped from the field; we preferred intratracheal anesthesia.

An incision, about nine centimeters long, was made obliquely in Langer's lines from the anterior edge of the acromion to just lateral to the coracoid. The deep fascia was incised and the deltoid muscle was split from above downward, in the direction of its fibers, five centimeters distal to the acromioclavicular joint. Further splitting jeopardizes the axillary nerve. By sharp dissection, anticipating cutting the acromial branch of the thoraco-acromial artery, the deltoid was detached from the front of the acromion and acromioclavicular joint capsule (Fig. 5). This exposed the coraco-acromial ligament. The claviculopectoral fascia, extending laterally from this ligament, was divided to permit placing a wide elevator under the acromion. With traction on the arm the undersurface of the anterior process was palpated manually for sharp edges and osteophytes and to determine the thickness of the acromion. To facilitate repair of the deltoid, the stump of its tendinous origin on the anterior acromion was elevated upward exposing the front of the acromion and the attachment of the coraco-acromial ligament (Fig. 5). A thin, sharp, nineteen-millimeter osteotome was directed horizontally in a posterolateral direction (Fig. 6) to remove the anterior edge and lateral portion of the undersurface of the anterior process. This wedge-shaped piece of bone, which was usually about 0.9 centimeter thick anteriorly and 2.0 centimeters long and which included the entire attachment of the coraco-acromial ligament, was removed and the ligament was cut across proximal to the coracoid. With the aid of an elevator the undersurface was inspected for any residual fragments of bone or prominences. The undersurface of the acromioclavicular joint was next palpated and if excrescences were present, or if an arthritic joint had been symptomatic, the distal 2.5 centimeters of the clavicle was excised and the prominences on the acromial side of this joint were removed.

FIG. 6

To depict removal of the anterior lip and undersurface of the anterior process of the acromion. *A:* A thin nineteen-millimeter osteotome is seen directed posterolaterally removing the anterior edge with the attached coraco-acromial ligament and the deep surface. *B:* The osteotomy is directed just lateral to the articular facet for the clavicle. *C:* Having removed this wedge-shaped fragment, the deep margins of the acromioclavicular joint are palpated, and if prominent, or more exposure of the supraspinatus is required, this joint is excised.

This approach placed the supraspinatus in the center of the field and provided a wider exposure than would be expected. Because of the slope of the acromion, with hyperextension of the shoulder, the humerus was brought forward and with internal rotation the teres minor could readily be visualized. With flexion and external rotation the subscapularis was well exposed. At this stage, with patience and persistence, in most cases the torn end of a supraspinatus tendon could be adequately brought into contact with the humerus where a groove was cut to allow repair without tension when the arm was at the side. In the more difficult cuff repairs, the distal part of the clavicle had to be excised as has been advised by Bateman, to enhance mobilization of the supraspinatus, but with care to avoid excessive traction on the suprascapular nerve.

Prior to closure of the incision, the long head of the biceps and its groove were routinely inspected. This tendon was rarely transplanted because it is thought to aid the stability of the shoulder joint. Osteophytes in the biceps groove or on the greater tuberosity and thickened bursal tissues were removed.

The repair of the deltoid was important. The medial flap was first sutured to the capsule of the acromioclavicular joint (Fig. 6) or when the distal end of the clavicle had been excised, to the trapezius muscle. The lateral flap was sutured to its tendinous stump of origin that had been reflected upward on the dorsum of the acromion. The split in the deltoid was closed last.

Postoperatively, active forward elevation was prohibited for ten days to give the deltoid a chance to reattach. Assisted external rotation was thought to be especially important, and so were pendulum exercises. They were begun on the third or fourth day and, depending on the status of the cuff, the motions were progressively increased until there was full assisted overhead extension, done first with the patient supine. Abduction splints were not used postoperatively except in a few complicated secondary repairs and then early assisted external rotation exercises were stressed. I have worked primarily for recovery of the range of motion. Strength comes later with purposeful use.

Findings and Results

The results were graded as satisfactory or unsatisfactory. In a satisfactory result, the patient was satisfied with the operation and had no significant pain. He had full use of the shoulder, less than 20 degrees of limitation of overhead extension, and at least 75 per cent of normal strength. In an unsatisfactory result, these criteria were not met.

Chronic Bursitis with Fraying or Partial Tear of the Supraspinatus

The period of hospitalization following surgery in this group averaged seven days. At surgery, all nineteen patients with this type of lesion were also found to have proliferative bursitis and a prominence of the coraco-acromial ligament and anterior third of the acromion. There were distinct excrescences in eight. Irregularities in the greater tuberosity were common. Minute calcium deposits inapparent roentgenographically were found in six. The long head of the biceps was abnormal in five and ruptured in one. It was transplanted in three. The acromioclavicular joint was found to be involved by hypertrophic arthritis in three and it was excised in two of the patients.

There were two patients in this group with significant shoulder stiffness preoperatively and they required a number of months to be rehabilitated. One patient, who was discharged from the hospital on the second day, partially detached his deltoid by too vigorous activity and a large hematoma developed. There were no other significant complications.

The results of the sixteen shoulders evaluated were: fifteen satisfactory and one unsatisfactory. Three shoulders were not evaluated, two because of an insufficient interval since surgery and one in a patient who could not be located. Those with satisfactory ratings had normal deltoids, full range, and strength. The unsatisfactory rating was in a patient who had arthritis of the cervical spine and of the acromio-

TABLE I

CLINICAL SERIES AND RESULTS, 1965 TO 1970

	Acromioplasty	With Acromioclavicular Joint Excision	Satisfactory Results
Proliferative bursitis with tendinitis or partial tears of the supraspinatus	19	2	15 of 16
Complete tears of supraspinatus	20	2	19 of 20
Impingement after lateral acromionectomy	11	4	4 of 11
Total	50	8	38 of 47

clavicular joint, which was not excised. It was thought that his acromioclavicular joint should have been excised.

Complete Tears of the Supraspinatus

No previous surgery had been performed in the twenty shoulders in this group. All were found to have degenerative changes in the tendon as well as complete, but not acute, tears. The lesion was always centered in the supraspinatus tendon and in the overlapping insertion of the infraspinatus. It extended posteriorly for a varying distance. Calcium deposits were noted in three patients. The width of the tears were two centimeters in two, three centimeters in nine, and four centimeters in nine. Their lengths ranged from three centimeters to seven centimeters. While mobilization of the larger lesions required high dissection and preliminary traction on the tendons, the exposure offered by this approach was no handicap and all could be repaired by the McLaughlin technique. The outer portion of the clavicle was excised in two patients.

The results in all twenty shoulders operated on for complete tears (no previous operation) were: nineteen satisfactory, all of which approached normal, and one unsatisfactory. The unsatisfactory result was in a patient in whom seizures occurred and who damaged his shoulder.

Lateral acromionectomies had been performed from six months to four years previously in eleven patients, one for a supraspinatus tendinitis without a tear in the tendon and ten for complete tears of the supraspinatus. All eleven patients had varying degrees of deltoid weakness. The patient who previously had an incomplete lesion and had had one operation for biceps tendinitis and also a lateral acromionectomy was found to have marked anterior acromial excrescences and to have a three-centimeter full-thickness tear. Of the ten patients who had prior cuff repairs, two had healed sinuses between the shoulder joint and the old skin incision and all were found to have anterior impingement. The cuff was found to be intact in six. Two patients had massive attenuation of the cuff and retraction of the tendons of the cuff muscles. The outer clavicle was removed to facilitate repair in four patients. The central part of the deltoid was found reattached to the humerus in six patients.

The results in the eleven patients who previously had had lateral acromionectomies, all of whom had less pain but residual weakness, were rated, four as satisfactory and seven as unsatisfactory. Of the unsatisfactory results, three were borderline. Two more, who had massive, retracted, cuff tears, became much more comfortable but the shoulders were quite weak. Advancement of the supraspinatus muscle, as described by Debeyre and associates, was later attempted in one without improvement. The remaining two unsatisfactory results were in patients whose rotator tendons were found intact, but they had marked deltoid deficiencies and bouts of pain related to fatigue and, in one patient, an osteoarthritic acromioclavicular joint.

This patient was one of the early cases—in retrospect we should have excised the joint at the same time that anterior acromioplasty was done.

Over-All Results

There were no postoperative infections. In five patients subcutaneous hematomas developed that resolved spontaneously. The scars were well healed. Excessive new-bone formation, which has been described as a serious problem following partial lateral acromionectomy [1], did not occur in this series. Since only the anterior half of the deltoid was detached and the central portion remained intact, this muscle quickly responded to rehabilitation and, in acute cases, recovered normal strength. In contrast, a deficient deltoid played a major role in the high incidence of unsatisfactory results in those patients who had had lateral acromionectomies.

Discussion

The majority of patients in the group having incomplete tears of the supraspinatus had been diagnostic problems for years. Many had had arthrograms which did not prove diagnostic. The previous provisional diagnosis had most frequently been bicipital tenosynovitis. As has been stated, one third of the patients in this group were found at operation to have abnormalities of the biceps tendon. In those patients the abnormalities in the tendon were thought to have developed because of the proximity of the long head of the biceps to the critical area of impingement. The biceps tendon and adjoining tissues were normal in two-thirds of the patients in this group. Some of the patients had cysts in or excrescences on the greater tuberosity of the humerus, presumably caused by the impingement. At times these excrescences extended into the bicipital groove and were associated with scarring of the long head of the biceps. The close relationship of bicipital tenosynovitis to impingement becomes obvious when one considers how often this tendon and adjoining structures were abnormal when the cuff was completely torn. We now consider it unwise to operate on the biceps tendon alone without having considered the possibility of a concomitant element of subacromial impingement.

The value of anterior acromioplasty is thought to be that it relieves pain and inflammation from chronic impingement; that technically it improves exposure of other involved structures and allows appropriate measures to be taken with reference to them; and that it retards the wear caused by persistent impingement and may prevent rupture of the supraspinatus tendon or of the long head of the biceps, or both. The recent literature suggests that the repair of complete cuff tears requires more complicated techniques [4,8], but judging from a review of the operative findings in our clinic over the past ten years, it is a rare cuff tear that cannot be repaired through this simple approach. This is in agreement with Bateman who has evolved a similar anterior approach with the objective of resection of the acromioclavicular joint. However, it is important that the occasional patient with a massive tear of the supraspinatus tendon be treated promptly, before fixed shortening of the cuff muscles makes it unlikely that an effective repair can be accomplished by any method. The rare patient with an irreparable tear can be made more comfortable if impingement is relieved and can gain surprising function if the deltoid is permitted to remain strong.

Summary

Impingement on the tendinous portion of the rotator cuff by the coraco-acromial ligament and the anterior third of the acromion is responsible for a characteristic syndrome of disability of the shoulder. A characteristic proliferative spur and ridge has been noted on the anterior lip and undersurface of the anterior process of the acromion and this area may also show erosion and eburnation. The treatment of the

impingement is to remove the anterior edge and undersurface of the anterior part of the acromion with the attached coraco-acromial ligament. The impingement may also involve the tendon of the long head of the biceps and if it does, it is best to decompress the tendon and remove any osteophytes which may be in its groove, but to avoid transplanting the biceps tendon if possible. Hypertrophic lipping at the acromio-clavicular joint may impinge on the supraspinatus tendon when the arm is in abduction and, if the lip is prominent, this joint should be resected. These are the principles of anterior acromioplasty.

Fifty shoulders in forty-six patients have been subjected to anterior acromioplasty during the past five years. Nineteen had proliferative bursitis and tendinitis or partial tears of the supraspinatus, without roentgenographic evidence of calcium deposits, and twenty had complete tears of the supraspinatus and the results in these thirty-nine patients from one to five years following surgery were good. Eleven patients with residual impingement following partial lateral acromionectomy were improved but their results were impaired by pre-existent deltoid weakness and scar. Anterior acromioplasty may offer better relief of chronic pain in carefully selected patients with mechanical impingement, while it provides better exposure for repairing tears of the supraspinatus, and may prevent further impingement and wear at the critical area without loss of deltoid power.

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Biomechanical analysis of human ligament grafts used in knee-ligament repairs and reconstructions

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Biomechanical Analysis of Human Ligament Grafts used in Knee-Ligament Repairs and Reconstructions*†

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ABSTRACT: Virtually all types of collagenous tissues have been transferred in and around the knee joint for intra-articular and extra-articular ligament reconstructions. However, the mechanical properties (in particular, strength) of such grafts have not been determined in tissues from young adult donors, where age and disuse-related effects have been excluded. To provide this information, we subjected ligament graft tissues to high-strain-rate failure tests to determine their strength and elongation properties. The results were compared with the mechanical properties of anterior cruciate ligaments from a similar young-adult donor population. The study indicated that some graft tissues used in ligament reconstructions are markedly weak and therefore are at risk for elongation and failure at low forces. Grafts utilizing prepatellar retinacular tissues (as in certain anterior-cruciate reconstructions) and others in which a somewhat narrow width of fascia lata or distal iliotibial tract is utilized are included in this at-risk group. Wider grafts from the iliotibial tract or fascia lata would of course proportionally increase ultimate strength. The semitendinosus and gracilis tendons are stronger, having 70 and 49 per cent, respectively, of the initial strength of anterior cruciate ligaments. The bone-patellar tendon-bone graft (fourteen to fifteen millimeters wide, medial or central portion) was the strongest, with a mean strength of 159 to 168 per cent of that of anterior cruciate ligaments.

Patellar tendon-bone units, based on grip-to-grip motions, were found to be three to four times stiffer than similarly gripped anterior cruciate ligaments, while gracilis and semitendinosus tendon preparations had values that were nearly identical to those of anterior cruciate ligaments. Fascia lata and patellar retinacular graft tissues showed much lower stiffnesses than did the anterior cruciate ligaments.

CLINICAL RELEVANCE: The surgeon controls the initial structural properties of a ligament reconstruction by the type and size of graft selected. The data reported here for the initial mechanical properties of grafts allows a more rigorous evaluation of other biological grafts, not previously available. Weaker grafts, which are more apt to fail prematurely than those of greater strength, probably also require longer postoperative protection to allow time for remodeling. The longer protection times may not allow for increased graft strength. One note of caution is also required: if wider distal iliotibial-tract grafts are used to increase initial strength, iliotibial tract function may be adversely affected. Tissues of greater width also require larger drill-holes if bone fixation is used, and therefore additional time may be required for bone ingrowth and graft incorporation. Use of a bone-tendon-bone graft has a distinct theoretical advantage for earlier graft incorporation at the fixation site and higher initial graft strength, thereby allowing earlier motion of the knee and shorter periods of disuse and immobility.

Some biological grafts used in reconstruction of the anterior cruciate ligament function in a useful manner, providing joint stability and reduced functional disability[6,18,22]. However, the long-term success of such grafts still remains highly unpredictable. In some instances they may elongate or fail under low forces, or remain in the joint as flimsy, collagenous tissues providing no ligament restraint[14]. In this study we examined one factor governing the success of a biological substitute: namely, the initial structural mechanical properties of the grafts prior to implantation.

The purpose of this study was to determine the structural mechanical properties of nine graft tissues that are commonly used in ligament reconstruction procedures. It was our goal to compare one graft with another and also to compare each graft with the mechanical properties of the normal anterior cruciate ligament, studied previously[16]. It was our contention that some ligament grafts are markedly low in their initial strength, stiffness, and energy to failure when compared with the ligament to be replaced. For a majority of these grafts this is the first time that their mechanical behavior has been determined in young adult tissues in which the effects of older age and disuse are not present. The ability to predict graft properties is helpful in selecting

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TABLE I

TISSUE DIMENSIONS*

Tissue	No. of Specimens	Length† (mm)	Area (mm^2)	Width (mm)
Anterior cruciate ligament[16]	6	26.9 ± 1.1	44.4 ± 4.0	‡
Bone-patellar tendon-bone				
Central	7	48.7 ± 3.8	50.5 ± 2.8	13.8 ± 1.4
Medial	7	48.8 ± 2.8	49.9 ± 3.8	14.9 ± 1.1
Semitendinosus	11	36.6 ± 3.1	14.0 ± 0.5	‡
Fascia lata	18	46.7 ± 2.7	8.2 ± 0.4	15.6 ± 0.8
Gracilis	17	41.9 ± 2.2	7.6 ± 0.2	‡
Distal iliotibial tract	10	39.1 ± 2.5	37.3 ± 3.5	18.0 ± 1.6
Quadriceps tendon-patellar retinaculum-patellar tendon				
Medial	7	30.7 ± 4.0	28.5 ± 4.7	14.4 ± 1.9
Central	6	30.4 ± 4.2	17.4 ± 5.3	16.3 ± 3.5
Lateral	7	30.6 ± 2.3	28.6 ± 5.7	13.7 ± 1.8

* Data are given as mean and standard error of the mean.

† This is a mean over-all length, representing an average of the longest and shortest fiber bundles, and should not be construed as the length of the longest bundles[16].

‡ Width measurements were not made, as these represent whole tissues.

an appropriate graft. Certain ligament substitutes can be scaled to the appropriate structural properties of the anterior cruciate ligament and other ligaments by careful attention to tissue dimensions (length, width, and thickness) at the time of surgery.

Many other factors determine the success of ligament reconstructive procedures, including graft placement, tension and fixation, revascularization[3,18], remodeling of collagenous tissues[5], and postoperative rehabilitation and protection during the healing period[22]. We have considered only the initial mechanical properties of a ligament graft prior to implantation.

Problems associated with the other factors will ultimately require solution before cruciate substitution is routinely recommended.

Methods

We tested ninety specimens of human tissue, including tendons, fascia lata, distal iliotibial tract, and quadriceps tendon-prepatellar tissue-patellar tendon (Table I). Specimens were obtained at autopsy from eighteen young people who were 26 ± 6 years old (mean and standard deviation), 1.73 ± 0.1 meters in height, and 739 ± 229 newtons in weight. There were fourteen male and four female donors. The causes of death included trauma (thirteen), bronchial pneumonia (one), acute cardiac arrest (two), and unknown causes (two).

Donor tissues were obtained in a manner similar to the procedures that are followed when such grafts are prepared at surgery. The gracilis and semitendinosus tendons were sectioned proximally at their muscle junctions and distally at their tibial insertions. Each bone-patellar tendon-bone specimen consisted of either the central or medial portion (40 per cent of the width of the entire tendon), including the tibial tubercle and the entire patella. The quadriceps tendon-patellar retinaculum-patellar tendon specimens, as described by Reider et al., were divided into central, medial, and lateral portions. The quadriceps tendon was first transected at the muscle junction. The collagen fiber bundles passing over the surface of the patella (tendinous fibers of the rectus femoris) were then carefully dissected, making every attempt not to cut into the tissue. Three specimens were damaged during this process and were discarded. Excess fat and surrounding soft tissue were removed from all specimens prior to testing.

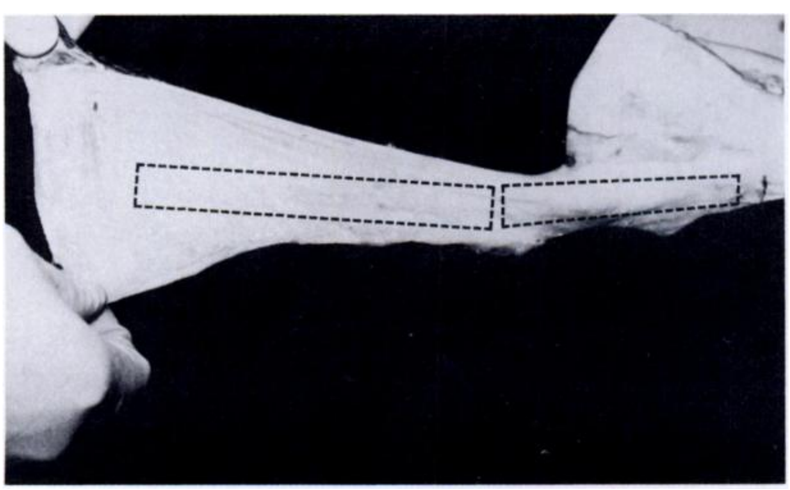

FIG. 1

Fascia lata and distal iliotibial tract. At the left is a seven to ten-centimeter-wide sheet of fascia lata and the region from which fascial specimens were taken. At the right the fascia narrows to form the condensed fibers of the distal iliotibial tract immediately above its tibial insertion. This preparation, sometimes called the iliotibial band, was removed as a single specimen.

Specimens of fascia lata were obtained from a seven to ten-centimeter-wide strip taken from the middle of the thigh to just proximal to the lateral femoral condyle. Sixteen-millimeter-wide strips were then cut under a dissecting microscope. The cuts extended along the direction of the primary longitudinal fibers. Specimens were selected from the region shown in Figure 1 as it has thicker, more parallel fiber bundles, and it is this portion that is placed intra-articularly during reconstruction of the anterior cruciate ligament. The more distal, condensed portion of the iliotibial tract, just proximal to its tibial insertion, was taken as a separate specimen. This portion corresponds to the tissue used in certain intra-articular and extra-articular reconstructions, either alone or in combination with fascia lata.

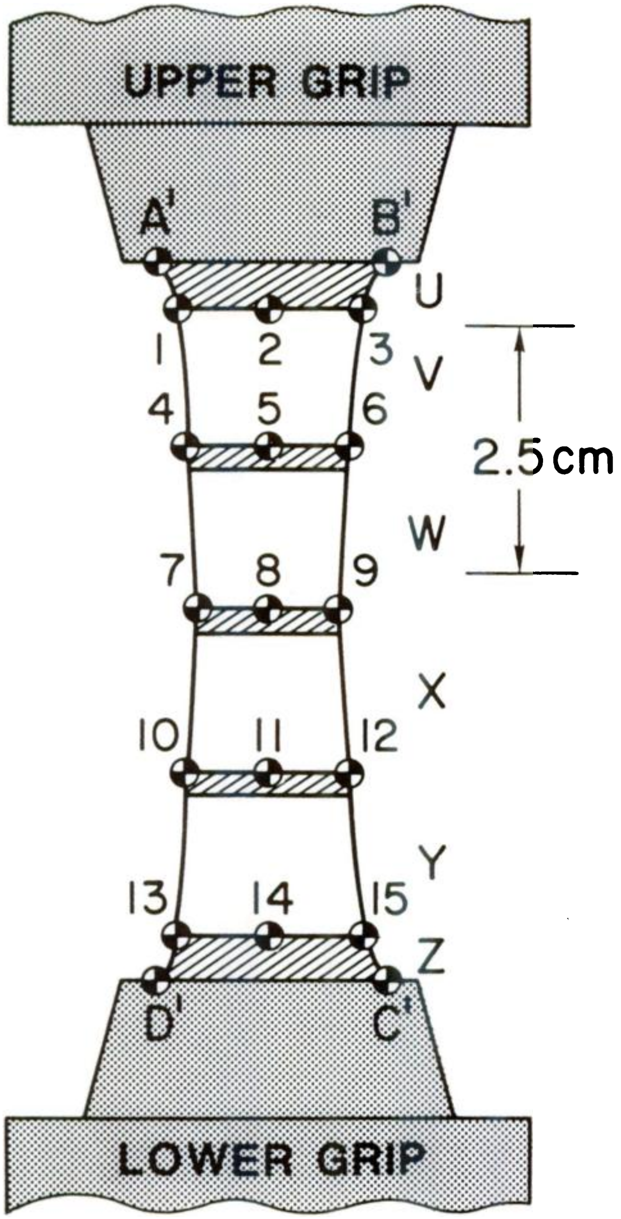

FIG. 2

Local surface-strain matrix for a gracilis tendon specimen. Points A′ and B′ are along the edge of the upper stationary grip of the Instron, while C′ and D′ are on the lower grip. Points 1 through 15 indicate the locations of digitized points along each ink band. Axial strains were calculated between corresponding points (for example, 1 to 4 and 5 to 8) for each frame of the test.

To minimize dehydration, each specimen was immediately wrapped in saline-moistened paper towels, followed by a plastic wrap and aluminum foil, and then was stored in a freezer at −30 degrees Celsius. Before testing, the specimens were removed from the freezer, thawed while protected by the wrapping, and moistened with saline solution during dissection, area measurement, mounting, and testing, following procedures described previously[1,5,24].

Area measurement: The cross-sectional area of each specimen was determined at four to six locations using an area micrometer designed as a modification of the method reported by Ellis[4,5,7]. Each graft was gently pressed into a rectangular slot (2.4, 5.0, or 8.1 millimeters wide) under a constant load using calibrated weights placed on a pan connected to a plunger that fitted into the appropriate slot. Weights were selected to produce an average compressive stress on the tissue of 0.12 megapascal. The area was computed from the average gap between the plunger and the bottom of the slot at two minutes after load application. That time-period was selected from a pilot study performed on nineteen tissue specimens (see Results). Specimens were kept moist with saline solution to prevent fluid loss.

Mounting: A special gripping system using wedge-action grips with three sets of inserts for different sizes of specimens was used. Each insert has smooth, sinusoidally-shaped teeth to allow a greater length of tissue to be grasped. The last tooth of each insert has a larger radius of curvature to reduce stress concentrations in the tissue at the grip edge. The bone ends of the bone-patellar tendon-bone preparations were potted in methylmethacrylate cement using the cavity of the wedge-action grips (lined with aluminum foil) as a mold. Aluminum plates were used over the ends of the grips to secure the bone and cement while allowing free passage of the patellar tendon.

Width and length measurements: In the tissues that were divided longitudinally, the width of the specimen was measured with the specimen in the grips under a small pre-load. Caliper readings were taken at four or more locations along the length of the specimen and were averaged. In patellar tendon-bone units, four length measurements were made between the bone insertions along the posterior aspect of the tendon and were averaged. For other specimens, initial grip-to-grip length was determined with the tissue mounted in the grips and under a small pre-load. The length of the anterior cruciate ligament for purposes of comparison was taken as an average of the shortest posterior portion and longest anteromedial portion[16].

Testing: Specimens were loaded to failure in tension at a displacement rate of 100 per cent of the initial length of the specimen per second. This permitted an identical strain rate of all specimens. Force was measured using either a LeBow load-cell, model 6467-103 or model 3132. Actuator displacements were measured with a Schaevitz linear variable displacement transducer. Data acquisition was performed using a ModComp-II computer which sampled and recorded force and actuator displacement 2000 times per test.

Tissue Strains

Tissue strain during the loading test was measured in two ways. Nominal strain was determined as the ratio of grip-to-grip displacement to the initial length of the specimen. The second method involved direct measurement of local surface strains[26]. This was determined in a subset of fifteen grafts using high-speed filming of the failure test[27].

The filming procedure was accomplished by positioning the optical axis of a motor-driven, pin-registered sixteen-millimeter camera (Milliken DBM-4) perpen-

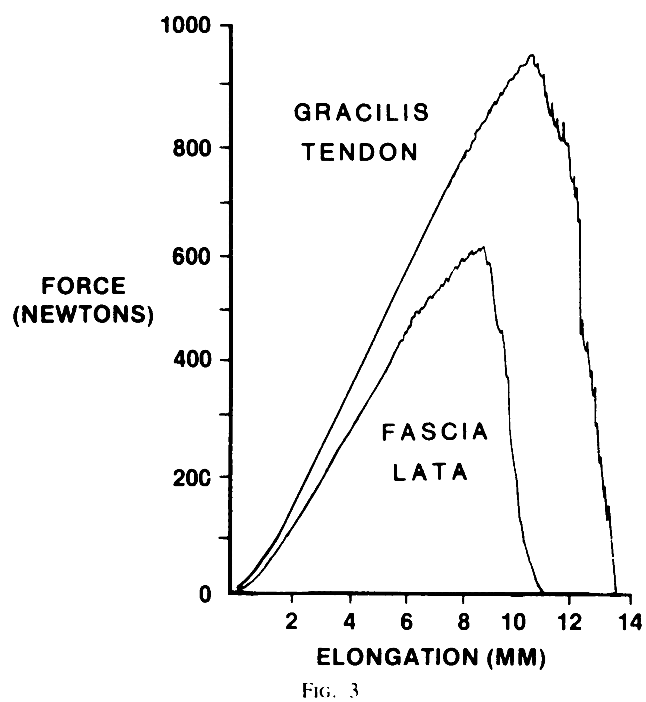

FIG. 3

Typical force-elongation failure curves for a gracilis tendon and fascia lata are shown. At the lower left of each curve is the non-linear toe region that occurs on initial application of load. Also displayed are the nearly linear regions over which the stiffness is measured. The energy to failure is given by the area under each curve.

TABLE II

MAXIMUM LOADS FOR THE HUMAN ANTERIOR CRUCIATE LIGAMENT AND ITS REPLACEMENTS*

	Maximum Load (N)	Per Cent of Anterior Cruciate	Maximum Load/ Unit Width (N/mm)	Maximum Stress (MPa)
Measured values				
Anterior cruciate ligament-bone[16] (n = 6)†	1725 ± 269	100	†	37.8 ± 3.8
Bone-patellar tendon-bone				
Central third (n = 7)	2900 ± 260‡	168	208 ± 24	58.3 ± 6.1‡
Medial third (n = 7)	2734 ± 298‡	159	162 ± 13	56.7 ± 4.4‡
Semitendinosus (n = 11)	1216 ± 50	70	†	88.5 ± 5.0¶
Gracilis (n = 17)	838 ± 30§	49	†	111.5 ± 4.0¶
Distal iliotibial tract (18-mm width) (n = 10)	769 ± 99§	44	44 ± 6	19.1 ± 2.9#
Fascia lata (16-mm width) (n = 18)	628 ± 35#	36	39 ± 2	78.7 ± 4.6¶
Quadriceps-patellar retinaculum-patellar tendon				
Medial (n = 7)	371 ± 46¶	21	24 ± 4	15.4 ± 3.4#
Central (n = 6)	266 ± 74¶	15	17 ± 3	16.1 ± 1.8¶
Lateral (n = 7)	249 ± 54¶	14	19 ± 4	9.7 ± 1.5¶
Calculated values**				
Distal iliotibial tract				
25-mm width	1068	62		
Plus adjacent 10 mm of fascia	1468	85		
Plus adjacent 20 mm of fascia	1868	108		
Fascia lata (45-mm width)	1800	104		

* Data are given as mean and standard error of the mean.
† Width measurements were not made.
‡ Statistically different from the maximum value for the anterior cruciate ligament: $p < 0.05$.
§ $p < 0.01$.
\# $p < 0.005$.
¶ $p < 0.001$.
** Calculated by adjusting test values to new specimen widths.

dicular to the front surface of each specimen. The nominal speed of the camera was set at 400 frames per second. The camera was fitted with a ninety-millimeter Zoomar lens, located at an average of seventy-five centimeters from the tissues. Black India-ink bands were marked on the surface of the tissue specimens at regular intervals along their length and at the tissue-grip interfaces (Fig. 2). Bands were drawn across the width of the tissue specimen perpendicular to the direction of the applied tensile loads.

High-speed-film records were synchronized (± 2.5 milliseconds) with the load-elongation analog data from the mechanical testing system. The records were digitized as frames were projected onto a digitizer/computer (Hewlett-Packard 9864/9830) with an overhead pin-registered projection system (Vanguard M16C/S2). The error associated with successive, separate digitizing of the same magnified configuration on the tissue was less than 0.10 millimeter. Rectangular coordinates of the positions of the grips and of the fifteen ink-band points on the surface of the tissue were digitized and stored on digital cassette tapes. Computer programs were developed to determine the local axial surface displacements between digitized points and the related local strains at eleven distinct time-periods during the test.

Data Analysis

The structural and material properties that we examined for each substitute were stiffness, maximum load, maximum stress, elongation to maximum load, energy to failure, and tissue strains. For each parameter statistical comparisons were made among the ligament grafts and the previously reported results with the anterior cruciate ligament[16] using the two-tailed Welch modification of the Student t test.

Structural parameters based on grip-to-grip motion were obtained as previously described[5,16,17,21] from force-elongation curves, demonstrated in Figure 3 for typical isolated specimens of gracilis tendon and fascia lata and in Figure 4 for the patella-patellar tendon-tibia and femur-anterior cruciate ligament-tibia preparations. Two other parameters (local stiffness and local energy to failure) were computed based on local strain results. The slope of the linear region (grip or local stiffness) was determined from a least-squares linear-regression analysis. The intercept of the regression line with the elongation axis was taken as a measure of the length of the toe region.

Maximum force as well as grip and local elongations at maximum force and energies to failure (the area under the curve) were also determined.

Since the initial lengths of the tissues varied, the force-elongation curve for each graft was adjusted or normalized to the average length of the anterior cruciate ligaments[16]. In particular, normalized values for stiffness and energy to failure were

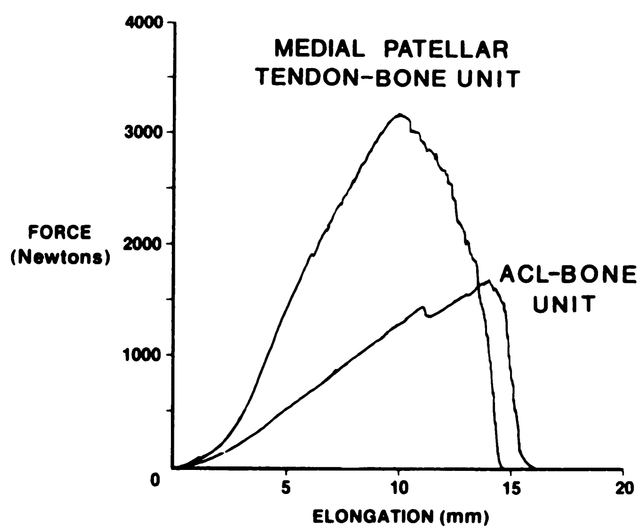

FIG. 4

Typical force-elongation failure curves are shown for a bone-patellar tendon-bone preparation and a bone-anterior cruciate ligament-bone unit. Note the much larger stiffness, maximum load, and failure energy (area under the curve) for the tendon, and its abrupt failure. Elongations are similar and are based on grip-to-grip motion.

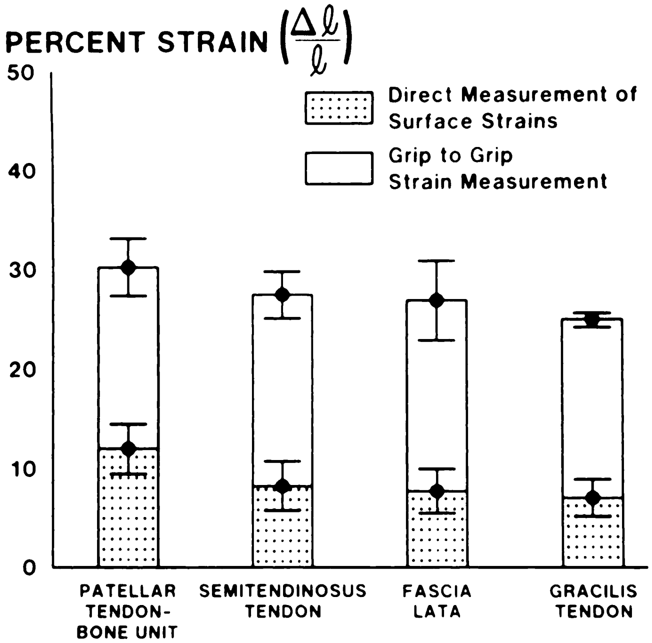

FIG. 5

A comparison is shown of the average strains obtained by direct surface measurement compared with the strains obtained from grip-to-grip measurement. Mean values and standard errors are shown for each tissue type. The number of specimens in each group is given in Table I. More details can be found elsewhere.

computed for all tissue groups based on grip-to-grip motions. Similar values were also calculated for the subset of fifteen grafts from four tissue groups for which local strain measurements were available. Due to the surgeon's need to produce appropriately dimensional grafts, normalized stiffnesses were also expressed per unit of width of the graft.

Results

Ligament and Graft Dimensions

The dimensional properties (Table I) for the grafts (including average values for anterior cruciate ligaments from young adult donors[16]) showed that the mean areas of the patellar tendon-bone units were substantially larger than those of all other substitutes except the distal iliotibial tract. These cross-sectional areas (used for computing maximum stress) were determined after two minutes of compression based on values obtained from the pilot study. Area measurements on ten tendon, five fascia, and four retinacular specimens showed that two-minute values were 4.1 ± 0.2 per cent and 2.2 ± 0.1 per cent (mean and standard error) less than thirty and sixty-second readings, respectively, and 5.7 ± 0.6 per cent greater than values after ten minutes of load application.

Structural Properties

The maximum load results (Table II) indicate that the strongest grafts were the bone-patellar tendon-bone specimens. The central and medial portions of this graft developed 168 and 159 per cent, respectively, of the strength of the anterior cruciate ligament. These were the only tissues whose maximum loads were greater than those of the ligament being replaced. The next largest maximum loads were those of the semitendinosus and gracilis tendons (70 and 49 per cent of the strength of the anterior cruciate ligament, respectively). The quadriceps-patellar retinaculum grafts were the weakest structures, bearing only 14 to 21 per cent of the average anterior-cruciate load. The mean load values for each graft, with the exception of the semitendinosus, were significantly different from those for the anterior cruciate ligament. The maximum load per unit of width of tissue (Table II) was also calculated for the grafts whose width could be appropriately increased at surgery. The medial portion of the patellar tendon developed 162 newtons per millimeter of tissue, whereas the distal iliotibial tract and fascia lata were approximately 25 per cent of this value

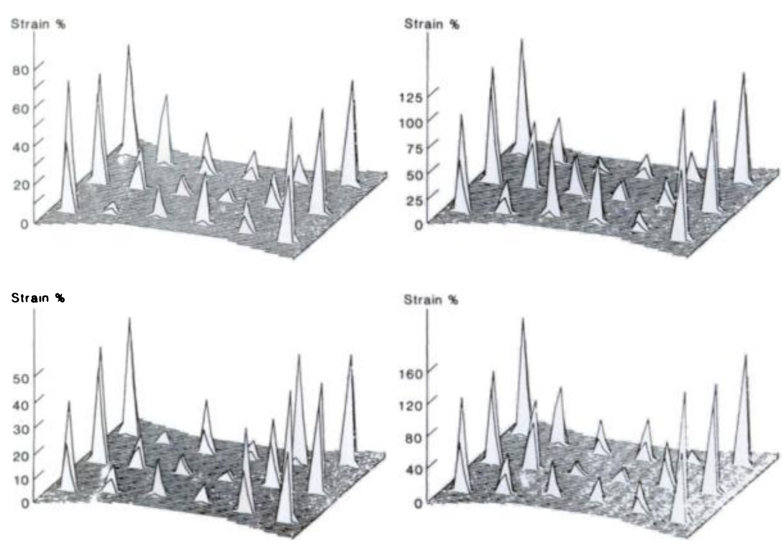

FIG. 6

The variation in local surface strains is shown at maximum load for four patellar tendon-bone units. Each peak is proportional to the local strain (change in length per unit of length) in that region. Note the very large local strains at the patellar (left) and tibial (right) ends of the insertions. The results for the other tissue types that were filmed appear in the report of Zernicke et al. The double peaks seen at each location on the surface are simply a result of the computer code that was used for strain determination.

TABLE III

NORMALIZED GRAFT-TISSUE STIFFNESS AND ENERGY TO FAILURE BASED ON LOCAL STRAINS AND GRIP MOTION*

	Stiffness (KN/m)		Stiffness/Width (KN/m/mm)		Energy to Failure (Nm)	
	Local†	Grip	Local†	Grip	Local†	Grip
Tissue-bone units						
Anterior cruciate ligament-bone[1n] (n = 6)	‡	182 ± 33	‡	‡	‡	12.8 ± 2.2
Bone-patellar tendon-bone						
Central third	1153.5 ± 193.1§	685.2 ± 85.6#	74.6 ± 11.5§	27.4 ± 3.0	4.1 ± 1.8§	12.8 ± 2.4
Medial third		650.6 ± 85.4#		23.4 ± 2.3		12.8 ± 2.2
Isolated tissues						
Semitendinosus	559.5 ± 155.7	186.1 ± 9.2	‡	‡	3.2 ± 0.6	8.9 ± 0.5
Gracilis	482.8 ± 83.8	170.9 ± 11.0	‡	‡	1.2 ± 0.2	3.5 ± 0.4¶
Fascia lata (16-mm width)	614.0 ± 270.6	117.7 ± 4.6	38.4 ± 16.9	4.7 ± 0.4	1.2 ± 0.3	3.0 ± 0.4¶

* Normalized (adjusted) to anterior cruciate-ligament length to account for differences in tissue lengths. Data are given as mean and standard error of the mean.

† Based on film tests for the patellar (n = 4), semitendinosus (n = 3), and gracilis tendons (n = 5) and the fascia lata (n = 3).

‡ Not measured in this study.

§ Results grouped together for three medial and one central patellar tendon-bone unit.

\# Statistical comparisons of the Welch modification of Student's t test (two-tailed) of each value as compared with the value for the anterior cruciate ligament: $p < 0.001$.

¶ $p < 0.005$.

and the patellar retinaculum specimens, approximately 10 to 15 per cent of this value. The gracilis and semitendinosus tendons developed the largest maximum stresses (maximum load divided by initial cross-sectional area) and the distal iliotibial tract and retinacular tissues developed the smallest values (Table II).

Local Strain

In comparing local surface strains measured directly on the tissue with strains based on grip-to-grip measurements (obtained by actuator travel), both taken at maximum load, we found that the grip-to-grip measuring technique significantly overestimated[27] the average local strains by a factor of two and one-half to almost four ($p < 0.001$) (Fig. 5). No significant differences were found among average grip-to-grip strains for the tissues, whose values ranged from 24.9 to 30.2 per cent. Average mid-region local strains (zones V, W, X, and Y, away from the tissue ends, Fig. 2) were considerably less, ranging from 7 to 12 per cent elongation. There was substantial variation in the local strain measurements along the grafts. Among individual specimens, this amounted to more than a tenfold variation in strain values at maximum stress from the proximal to distal ends of the tissue. The central locations (zones W and X; Fig. 2) generally showed lower strain values than those measured nearer the ends (zones V and Y). Examples of the variations in local strains are shown in Figure 6 for the four patellar tendon-bone units that were loaded to failure and were filmed.

Normalized Stiffness and Energy to Failure

Comparison of the local stiffnesses for the four tissue groups that were filmed (Table III) showed that the patellar tendon-bone unit developed the largest stiffness (1153.5 ± 193.1 kilonewtons per meter), being 1.9 to 2.4 times the local stiffnesses for the two tendons and the fascia. Only the values for the patellar and gracilis tendons were significantly different from each other, however ($p < 0.05$). Local stiffness for the patellar tendon-bone unit was 1.7 to 1.8 times the corresponding grip-to-grip values (Table III). By contrast, the isolated semitendinosus and gracilis tendons and the fascia lata showed much larger ratios of local stiffness to grip stiffness (2.8 to 5.2). Only the gracilis and semitendinosus tendons exhibited significant differences between local-stiffness and grip-stiffness values ($p < 0.05$).

The mean stiffness values based on grip-to-grip motion for the medial and central patellar tendon-bone units were 650.6 and 685.2 kilonewtons per meter, almost four times that of the anterior cruciate ligament (182 kilonewtons per meter) (Table III). The stiffness values for the other isolated tissues varied by almost 1.6 times but these results could not be directly compared with those from tissues with bone ends due to differences in gripping techniques.

The grip-to-grip failure energy for the patellar tendon-bone unit was 3.1 times the local values for the four tendons tested. Surprisingly, energies for the anterior cruciate ligament and patellar tendon-bone units were identical (12.8 newton-meters). Local energy measurements for the anterior cruciate ligament were not made, precluding comparison with the value for the patellar tendon-bone unit.

Discussion

This study presents, for the first time, the mechanical properties of substitutes for the human anterior cruciate ligament using tissues obtained from young adult donors. Certain qualifications should be noted before considering our results. First, our strength data is only one of many criteria on which to select an appropriate graft for ligament reconstruction. Equally important to the success of the procedure are care in graft preparation at surgery, adequate placement and fixation of the ends of the graft, and a complex remodeling process including revascularization[18]. It may not be correct to assume that the use of a high-strength graft alone increases the success rate of a reconstruction. Within these stipulations, the data do allow the surgeon to: (1) consider graft strength and stiffness in selecting an appropriate replacement, and (2) modify certain tissue widths when required. At the same time, increasing the width of a graft may have deleterious side effects. These include decreased bone ingrowth at fixation sites due to the necessity for larger drill-holes in the bone, some compromise in lateral restraints if a wider fascial or distal iliotibial-tract graft is taken, and, in the case of patellar tendon grafts, potential alterations in patellofemoral tracking or even postoperative rupture of the patellar tendon if too much tissue is removed.

A second qualification of our data relates to the reported values for strain, stiffness, and energy. We have not found it possible to prevent tissue slippage while directly gripping soft tissue. Although we have taken special precautions in our grip design, gripping effects continue to be recognized as a major problem[1,26]. Thus we have greater confidence in the data based on local strains for the tendons and fascia. Grip-stiffness and energy values for the thicker distal iliotibial tract and retinacular tissues have not been presented because of the potential for slippage, leading to errors in elongation measurements. We suggest that any such errors due to the strain-measurement technique must be taken into account in the interpretation of both our results and data in the literature.

A third qualification to our data is that the reported mechanical properties of the grafts are compared with the properties of the normal anterior cruciate ligament only for uniaxial loading tests. The anterior cruciate ligament exhibits a complex fiber geometry, where different fiber lengths allow ligament function in different planes of knee motion[2,9,12,15]. Obviously none of the graft tissues that we tested can closely simulate the microgeometry of a normal anterior cruciate ligament at implantation. It is not known whether graft-remodeling ever occurs, to allow any graft to truly function in the subtle control of joint motions. It is our hypothesis that such ligament grafts act only as gross checkreins for joint displacements, rather than providing the more exact control of complex motions that depend on normal ligament geometry.

Within these qualifications, certain aspects of this study may be applied to the clinical problem of selecting the appropriate human tissue graft for ligament reconstruction. The maximum load may be the most important factor to consider, in that it must be sufficient to withstand the large anticipated *in vivo* loads that first produced the injury[2,11,16,22]. However, there are few tissues to choose from. The weakest grafts, relying on patellar retinacular tissues as load-bearing structures, have only 14 to 21 per cent of the strength of a normal cruciate. Small-width grafts of fascia lata and distal iliotibial tract have only 36 and 44 per cent of normal anterior-cruciate strength, respectively. These grafts would be expected to have lower success rates and require longer postoperative programs of protection and soft-tissue remodeling, if in fact the latter occurs. Even the gracilis and semitendinosus tendons could develop loads of only 49 and 70 per cent of that of the anterior cruciate. Only the medial and central thirds of the patellar tendon developed maximum loads that were greater than the value for the anterior cruciate ligament.

Our strength values for the anterior cruciate ligament and for the graft replacements are markedly different from the data in previous studies; this is due, we believe, to the fact that we used tissues obtained from young trauma victims. Trent et al. measured a very broad range of failure strengths (285 to 1719 newtons) for anterior cruciate ligament-bone units. Their values, which were 16 to 99 per cent of our strength values, were for donors ranging from twenty-nine to fifty-five years old. Unfortunately, the strength and age data were not correlated. Gratz, in 1931, recorded the results of one test for fascia lata from a "young athletic individual". The tissue failed at a maximum load of 294 newtons (sixty-six pounds), or 47 per cent of our average fascia lata strength and 17 per cent of our cruciate ligament value. Also, the width of the tissue was almost identical to what we tested. Kennedy et al.[13] tested isolated anterior cruciate ligaments from an older donor population (mean age, sixty-two years) and reported maximum strength values that were approximately one-third of our value. They recently reported correspondingly low values for anterior cruciate replacement grafts[14]. In this study Kennedy et al. calculated strength ratios (ratio of tissue-graft strength obtained from older donors to anterior cruciate-ligament values from older donors), believing that the ratios in younger adults were the same and that the deleterious effects of age would be the same for all tissues. However, they reported no data to verify that hypothesis. We previously reported a two to threefold decrease in ligament maximum stress, strain energy, and elastic modulus with advancing age for the anterior cruciate ligament[16]. We do not know if other collagenous tissues exhibit a similar decline in mechanical properties. However, our data emphasize the need for caution in extrapolating cadaver-tissue properties to functional ligament properties of healthy active adults[11].

Caution is also warranted in comparing our study with the others cited. Besides the effects of donor age on tissue properties, differences in the choice of grips are equally important. Specimens must be held with minimum slipping or crushing effects. While slippage produces errors in elongation measurements, crushing can result in premature failure and lower strength values. As yet we know of no standardized grips for adequately grasping collagenous tissues. While our gripping system did produce more reproducible results with less tissue damage, further improvements are required.

The surgeon may modify the over-all dimensions of certain ligament grafts, thereby significantly affecting strength properties. For example, our calculations showed that a forty-five-millimeter width of fascia lata is approximately equal to the strength of a normal anterior cruciate ligament from a young donor (Table II). For the distal iliotibial tract, however, the maximum width usually available for transfer in most knees is about twenty-five millimeters. This corresponds to only about 62 per cent of maximum failure load for an anterior cruciate ligament. Graft strength can be increased by including additional fascia adjacent to the condensed fibers of the iliotibial tract. Our calculations showed that an additional seventeen millimeters of fascia would theoretically provide a strength equivalent to that of the anterior cruciate ligament. However, in taking a ligament graft, the surgeon should realize that graft strength increases only if the full width of the added tissue fibers extends from one end of the insertion to the other, with the entire tissue capable of bearing load. In prepatellar retinacular grafts, in which the tissue is rolled from the edges of the patella, only retinacular tissue directly in line with the patellar tendon is initially load-bearing. Extra tissue increases the bulk but not the strength of the graft unless it eventually incorporates during the healing process. This also applies to distally based iliotibial-band specimens, in that the entire width used must have a direct osseous insertion into or adjacent to Gerdy's tubercle if over-all graft strength is to be increased.

activity forces except for the prepatellar retinacular tissues. However, all grafts undergo even further weakening due to tissue necrosis after implantation[3,6,14]. For example, patellar tendon grafts in primates drop to 15 per cent of their pre-implantation strength by six weeks after surgery[3]. This suggests the need for initial graft strength to approach or even exceed the maximum load values of a normal anterior cruciate ligament. Unless tissue width can be increased, the majority of grafts that are presently utilized fall well below this ultimate strength value. The use of two grafts, such as a tendon and a strip of fascia lata, may significantly increase mechanical strength, and our data allow approximate calculations to be made for surgeons performing such procedures. The width of the patellar tendon grafts (fourteen millimeters) in this study represents six times the calculated activity-force limit and more than one and one-half times the ultimate strength of the anterior cruciate ligament. The usual width of patellar tendon tissues selected for substitutes ranges from ten to thirteen millimeters, representing approximately one-third of the existing patellar tendon. The overriding concern in selecting the width of this tissue is based, we believe, on leaving sufficient tendon so as not to disturb patellofemoral tracking or lead to a problem with

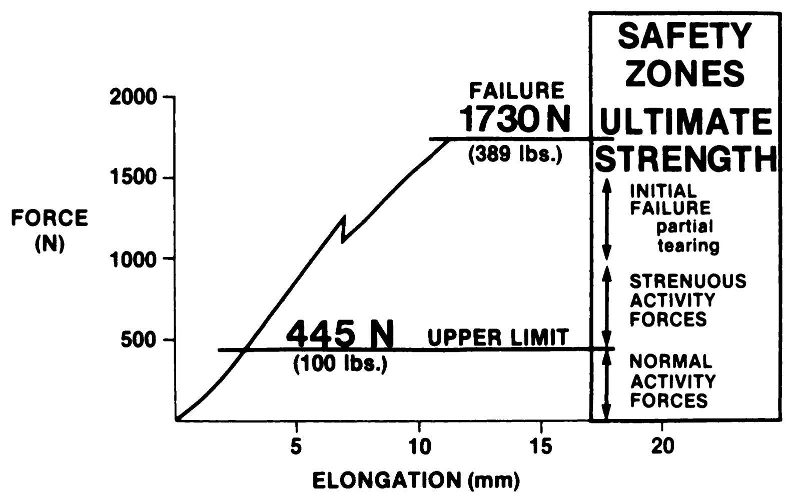

FIG. 7

A hypothetical load-elongation curve for the anterior cruciate ligament-bone unit is shown along with the idealized safety zones to be considered in evaluating a ligament replacement. The goal is to achieve the highest force zone possible. Some grafts of lesser strength may function as long as lower levels of force are maintained. The cruciate ligament curve shown does not represent any single failure test that was performed.

What the strength of a ligament graft ideally should be depends on the forces to which the graft may be subjected after implantation and on the margin of safety desired by the surgeon, particularly for patients who are athletically active. While the ultimate strength of an anterior cruciate ligament may be 1730 newtons (389 pounds) we hypothesize that it is loaded only to approximately 454 newtons (100 pounds) for most activities[11,16,18]. An idealized force-elongation curve for the anterior cruciate ligament-bone unit is shown in Figure 7, with these safety zones. Although never actually measured, there appears, from the literature, to be a built-in biological safety margin of a four or five-to-one ratio of ultimate strength to *in vivo* force. All of the replacements that we tested exceeded the level of normal

tissue rupture. This represents a potentially significant drawback in the use of patellar tendon grafts which requires further study. The use of narrow-width grafts for acute anterior or posterior cruciate reconstruction may also be justified if there are sufficient remaining fibers of the cruciate ligament that may be incorporated into the over-all repair.

The tabulated stiffness or resistance to loading for a given elongation indicates how a graft performs during normal *in vivo* loading rather than near failure. Local stiffnesses and stiffnesses per unit of width provide some insight into how the middle region of the tissue responds, away from the grips. The larger local stiffness for the patellar tendon-bone unit probably reflects its larger cross-sectional area and more parallel bundle structure compared with the fascia lata.

The fact that the local values for the isolated tissues are much larger than the grip stiffnesses reflects the slippage problem occurring at the specimen-grip interface. This was not seen with patellar tendon, which showed the lowest ratio of local stiffness to grip stiffness (1.7 to 1.8). These results also permit a direct comparison of the tendon-bone unit and the anterior cruciate ligament-bone preparation.

If a philosophical note is warranted, we may say that intra-articular cruciate substitution is a rather complex operative procedure, with many factors still to be studied. It requires selection of a graft with appropriate mechanical properties, meticulous surgical technique, correct fixation sites, correct adjustment of graft tension, postoperative protection allowing time for remodeling, and a careful and detailed rehabilitation program[18,19]. A succession of biological remodeling events, out of the control of the surgeon, is ultimately required to achieve a successful result. This includes revascularization, collagen formation and fiber alignment, and remodeling of tissue-fiber microgeometry. To what extent all of this occurs is presently unknown. The appropriate risks and benefits of biological ligament substitution must be weighed on this basis[19,20].

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The Carpal-Tunnel Syndrome: SEVENTEEN YEARS' EXPERIENCE IN DIAGNOSIS AND TREATMENT OF SIX HUNDRED FIFTY-FOUR HANDS

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The Carpal-Tunnel Syndrome

Seventeen Years' Experience in Diagnosis and Treatment of Six Hundred Fifty-Four Hands *

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Carpal-tunnel syndrome, the name now commonly applied to compression neuropathy of the median nerve at the wrist, is the most common cause of burning pain, numbness, and tingling in the thumb, index and long fingers, and in the lateral half of the palm. Progressive atrophy of the thenar muscles, with or without pain and numbness in the median-nerve distribution in the hand, may also be caused by compression of the median nerve beneath the transverse carpal ligament.

The median nerve passes directly beneath the transverse carpal ligament and lies superficial to the nine flexor tendons of the digits within the close confines of the carpal tunnel. It is at this level that the median nerve is so easily compressed by any condition that increases the volume of the structures within the carpal tunnel. Even a slight swelling of the synovial sheath of the flexor tendons may be sufficient to force the median nerve up against the firm, inelastic transverse carpal ligament, causing motor and sensory changes in the structures supplied by the distal portion of the nerve. The median nerve may anastomose to a variable extent with the ulnar and even the radial nerves; these connections explain the frequent variability both in motor and in sensory findings in median-nerve palsy.

The median nerve may be directly damaged or secondarily compressed by an acute or old traumatic lesion of the carpus. Post-traumatic compression of the median nerve may be minimum at first and then gradually progress to a complete paralysis. Such a syndrome could be aptly termed *tardy median-nerve palsy* because of its similarity to the much more common tardy ulnar-nerve palsy. The terms *tardy median-nerve palsy* and *carpal-tunnel syndrome* should not be used interchangeably, because the former term implies a traumatic origin and the majority of patients with carpal-tunnel syndrome give no history of antecedent injury to the forearm, wrist, or hand.

In 1854 Paget discussed compression of the median nerve at the wrist secondary to trauma. In 1913, Marie and Foix, at the autopsy of a patient with advanced atrophy of the thenar muscles but no history of injury, demonstrated neuromata in both median nerves just proximal to the transverse carpal ligament. They were the first to recommend decompression of the median nerve by sectioning the transverse carpal ligament in order to prevent paralysis of the thenar muscles. Moersch, in

* Read at the Annual Meeting of the American Society for Surgery of the Hand, New York, N. Y., January 8, 1965.

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1938, also recommended section of the transverse carpal ligament in a patient with bilateral median neuritis, but no operation was performed. In 1946, Cannon and Love reported on thirty-eight cases of tardy median-nerve palsy, in nine of which the patient was treated by section of the transverse carpal ligament. Three of these nine patients had no definite history of antecedent trauma. Brain, Wright, and Wilkinson, in 1947, first focused attention on spontaneous compression of the median nerve in the carpal tunnel by their detailed report of six patients treated successfully by sectioning the transverse carpal ligament.

In November 1947, I made my first diagnosis of carpal-tunnel syndrome and, in 1949, reported on four patients, three of whom were treated surgically for this condition. Seventy-one patients were also reported on in 1956. The present paper reports a study of the carpal-tunnel syndrome in 654 hands of 439 patients seen at the Cleveland Clinic before August 1, 1964. Since 1960, approximately fifty patients a year have been treated for carpal-tunnel syndrome in this clinic.

Diagnosis

The diagnosis of carpal-tunnel syndrome must be considered in any patient who has hypesthesia or paresthesia in the distribution of the median nerve in the hand or in any patient who has weakness or paralysis of the abductor pollicis brevis or opponens pollicis. Women are much more apt to have the syndrome than men; in the Cleveland Clinic series 293 of the 439 patients (67 per cent) were women.

More than half of the patients were between forty and sixty years of age (Table I). The youngest patient was twenty and the oldest eighty-seven years old.

TABLE I

AGE RANGE OF 439 PATIENTS WITH CARPAL-TUNNEL SYNDROME

Years	No. of Patients
20 to 29	13
30 to 39	48
40 to 49	111
50 to 59	132
60 to 69	85
70 to 79	41
80 to 89	6
Not recorded	3
Total	439

The usual history is that of progressive weakness and clumsiness in the hands associated with hypesthesia and tingling in the distribution of the median nerve distal to the wrist joint. Although mild symptoms may have been present for many years, the more severe symptoms, for which the patient seeks medical attention, may have developed quite recently, often associated with a sudden change to more strenuous manual labor. The symptoms are usually bilateral and are worse in the dominant hand.

In the 654 hands in this series, symptoms had been present for less than six months in 197 (32 per cent), from six months to two years in 150 (24 per cent), from two to ten years in 176 (28 per cent), from ten to twenty years in fifty-seven (9 per cent), and for more than twenty years in thirty-eight (6 per cent). The duration of symptoms in thirty-six hands was not recorded.

Strenuous use of the hand almost always aggravates the symptoms, although the increased numbness and tingling in the fingers may not be noted until the hand has been resting for several hours after the activity.

Pain at night, often severe enough to prevent sleep, is a frequent complaint. The patient is awakened by burning pain in the thumb and index and long fingers. Hanging the hand out of bed, exercising the fingers, or vigorous shaking of the hand often cause prompt lessening of pain. Although pain may be referred to the forearm, elbow, or shoulder, there are never any subjective or objective sensory changes proximal to the wrist joint. Numbness and tingling in the hand is usually aggravated by a sustained grasp, such as holding a knife or broom, driving a car, or turning a lever.

A sensory disturbance in the distribution of the median nerve distal to the wrist joint is the most constant clinical finding. At the time of examination only fifty-four hands (8 per cent) in this series were reported to show no demonstrable loss of sensation.

Hypesthesia was demonstrated in 517 hands (79 per cent). The hypesthesia may be minimum, usually in the distal phalanx of the long finger; but the patient will readily point out the portion of the hand in which paresthesia and numbness occur after strenuous use of the hand, and this area will invariably coincide with the sensory distribution of the median nerve. Often the patient insists that "the whole hand gets numb and tingly at night," but careful interrogation will bring out the fact that the little finger is spared. Since the little finger receives all of its sensory supply from the ulnar nerve, this digit is never involved in the true carpal-tunnel syndrome. All of the fingers may feel stiff and swollen, especially on arising in the morning, but these symptoms improve or disappear with resumption of active use of the hands.

Hyperesthesia to pinprick in the distribution of the median nerve in the hand,

FIG. 1-A

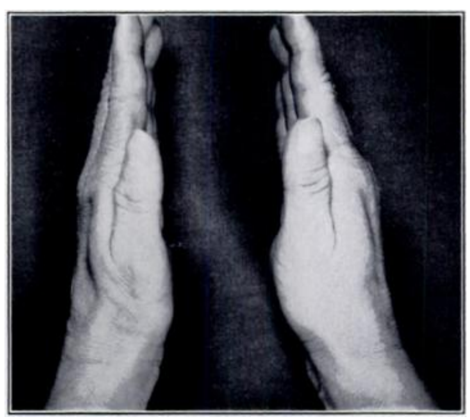

FIG. 1-B

Fig. 1-A: Hands of a woman, forty-six years old, with bilateral carpal-tunnel syndrome of two years' duration. The patient had not observed the moderate thenar atrophy of her left hand.

Fig. 1-B: The thenar atrophy of the left hand becomes much more obvious when the thenar eminences are compared in profile.

comparing the patient's reaction to pinprick here with that to pinprick on the normal little finger, was present in twenty-nine hands (4.6 per cent). Paresthesia alone in the same distribution was recorded as being present in thirty-nine hands (6 per cent). The records failed to describe the sensory findings in fifteen hands.

Thenar atrophy almost always is preceded by hypesthesia in the median distribution for many months or many years. Atrophy of the opponens pollicis, abductor pollicis brevis, and flexor pollicis brevis was observed in various degrees in 261 (41 per cent) of the hands included in this series. Many patients note weakness and clumsiness in their thumbs, but are unaware of the thenar-muscle atrophy until the examining physician shows it to them. The thenar atrophy may not be noticed when the examiner looks down on the palm of the hand, but it will be readily appreciated when the profiles of the thenar eminences are compared (Figs. 1-A and 1-B). The abductor pollicis brevis has been described as the muscle most often initially involved in this syndrome, and weakness in this muscle is an early sign of median-nerve compression. Testing of this muscle was not recorded in a sufficiently large number of patients in this series to draw firm conclusions as to the efficacy of this test as an early diagnostic aid.

No atrophy was present in 374 hands and there was no record of the presence or absence of atrophy in nineteen hands in this series.

Tinel's sign, a tingling sensation radiating out into the hand produced by light percussion over the median nerve at the wrist, is a valuable sign in the diagnosis of carpal-tunnel syndrome. In 452 (73 per cent) of the hands in this series Tinel's sign was present; in 169 it was absent; in thirty-three there was no note regarding Tinel's sign.

In performing the so-called wrist-flexion test, the patient is asked to hold the forearms vertically and to allow both hands to drop into complete flexion at the

Fig. 2

The wrist-flexion test is positive when numbness and paresthesia in the median-nerve distribution in the hand are reproduced or exaggerated by holding the wrists in complete flexion for from thirty to sixty seconds.

wrist for approximately one minute (Fig. 2). In this position the median nerve is squeezed between the proximal edge of the transverse carpal ligament and the adjacent flexor tendons and radius. Maintaining this position for a long time eventually causes numbness and tingling over the distribution of the median nerve in the normal hand. However, when the median nerve is already somewhat compressed within the carpal tunnel, further compression by this maneuver causes almost immediate aggravation of the numbness and paresthesia in the fingers. The patient often volunteers "This is the pain that wakes me up at night." In interpreting this wrist-flexion test, one must remember that the test will not be positive if there is already an advanced degree of sensory loss in the hand. For 139 hands in this series, the wrist-flexion test was not performed or was not recorded. For the remaining 515, the test was positive in 380 (74 per cent) and negative in 135. In the wrists treated surgically, no explanation was found at operation for the presence or absence of a positive wrist-flexion test.

Sustained extension of the wrist may also aggravate the symptoms of carpal-tunnel syndrome, but I have not found this to be a consistently reliable diagnostic sign. Firm pressure of the examiner's thumb over the median nerve at the wrist may also increase the pain, numbness, and tingling in the distribution of the median nerve. This test is seldom positive, however, until there has been sufficient pressure on the nerve in the tunnel to cause the nerve to become swollen proximal to the ligament. When this occurs, there is seldom any question about the correct diagnosis.

Another diagnostic test [3] is the production of increased pain and paresthesia in the distribution of the median nerve by inflating a pneumatic cuff on the arm to a pressure above the systolic pressure for a minute or two. The irritated and compressed portion of the median nerve in the carpal tunnel is more susceptible to ischemia than the normal nerve. However, some numbness and tingling are produced in the fingers of a normal hand when a tourniquet is applied to the arm. I have, therefore, found the results of the tourniquet test difficult to evaluate, especially in a mild carpal-tunnel syndrome. Although it was not possible to compare the results of the wrist-flexion and tourniquet tests in this series, it is my impression that the wrist-flexion test is much more valuable.

Without a history of trauma to the wrist, one may anticipate that roentgenograms will disclose no abnormality in the osseous contour of the carpal tunnel. The patient who is to be operated on, however, should have a roentgenographic evaluation.

Swelling on the volar aspect of the forearm just proximal to the wrist joint is a rather common finding in patients with the carpal-tunnel syndrome. When the condition is unilateral, this swelling may be much more obvious than in the bilateral cases. Patients with carpal-tunnel syndrome caused by rheumatoid arthritis almost always have swelling, caused by thickening of the flexor synovialis. Swelling on the volar aspect of the forearm proximal to the wrist joint was recorded as being present in sixty-nine wrists, but there were probably minor degrees of swelling in many more wrists. Swelling of the entire hand or of the fingers was recorded as being present in fifty-one wrists.

In sixteen wrists there was a ganglion on the volar aspect, and in three wrists a ganglion was present on the dorsal aspect. No conclusion as to the causal relationship between a ganglion of the wrist and the carpal-tunnel syndrome may be drawn from this series. Two of the wrists with a ganglion were operated on, and the ganglion was found to be occupying some space within the carpal tunnel. In both instances the ganglion could have been causing some pressure on the median nerve, and symptoms were relieved by removal of the ganglion and section of the carpal ligament.

Electrodiagnostic procedures may be helpful when the diagnosis is in doubt. Conduction time for the motor fibers is determined by stimulating the median nerve with a bipolar electrode at the proximal flexion crease of the wrist, and recording the time required for the appearance of the muscle action potential of the opponens pollicis or the abductor pollicis brevis. Normally the conduction delay, or latency, is less than five milliseconds; but, in patients with carpal-tunnel syndrome, the conduction delay may be as long as twenty milliseconds. In a series of thirty-eight patients with the carpal-tunnel syndrome, Johnson and associates found a mean conduction delay of 8.4 milliseconds. I have not employed this procedure in many patients, because the clinical assessment was sufficient to make an accurate diagnosis. Electromyography may be of value in the differential diagnosis between carpal-tunnel syndrome and irritation of the sixth and seventh cervical-nerve roots, especially when the sensory pattern in the hand and the rest of the extremity is equivocal or when there is pain referred into the forearm and shoulder from a median nerve compressed in the carpal tunnel. Nerve conduction time may also be useful in demonstrating objective evidence of postoperative improvement in a patient who maintains that he is no better after surgical treatment. One must remember, however, that median-nerve conduction time of motor impulses may be normal in the presence of an obvious carpal-tunnel syndrome or may be slow in a normal patient.

An accurate diagnosis of carpal-tunnel syndrome may be made if the wrist-flexion test is positive, Tinel's sign is present over the median nerve at the wrist, and all objective sensory findings are strictly limited to the distribution of the median nerve distal to the wrist. These are the three most reliable clinical findings, and in almost every patient found to have the syndrome at least two of the three findings are present. In addition, partial atrophy of the thenar muscles will be present in about half of the cases.

Fig. 3

Roentgenograms of the wrist showing evidence of a large calcific deposit within the carpal tunnel, producing an acute carpal-tunnel syndrome. (Courtesy of John R. Stacy, M. D., Oklahoma City, Oklahoma.)

Pathogenesis

Thickening or fibrosis of the flexor synovialis within the carpal tunnel was the most common cause of the syndrome, being found in 203 of 212 wrists. Biopsy specimens of the flexor synovialis were taken from 181 of the 212 wrists treated surgically. Pathological examination revealed chronic fibrosis or thickening of the synovialis in ninety-one specimens, chronic inflammation compatible with a diagnosis of rheumatoid synovitis in sixty-four specimens, and no pathological change in twenty-six. Although the exact nature of the synovial thickening could not be demonstrated, it is believed that it must be associated with some rheumatic process in the majority of the cases. The improvement noted in many patients after the injection of steroid preparations into the carpal tunnel is consistent with a rheumatic origin of the tenosynovitis. Furthermore, many patients noted transient stiffness and swelling of the small joints of their hands, symptoms thought to result from periarthritis.

Some authors [3,7] have cited ischemia of the median nerve as the cause of carpal-tunnel syndrome. I believe that localized ischemia of the nerve may be associated with compression of the nerve within the carpal tunnel. The rapid disappearance of paresthesia and pain after section of the transverse carpal ligament is consistent with temporary ischemia. At operation the vasa nervorum of many median nerves were seen to disappear abruptly at the proximal edge of the carpal ligament. It was also noted that after division of the carpal ligament and release of the tourniquet, engorgement of the nerve would develop but this engorgement would stop abruptly at the level of the proximal edge of the ligament—the site of major compression.

In cases of long-continued severe compression, the ischemic changes in the nerve may be permanent. Tanzer found vasomotor imbalance to be a prominent feature in fifteen of twenty-five hands with carpal-tunnel syndrome, as manifested by significant sensitivity to cold. Since the median nerve carries with it most of the sympathetic nerve supply of the hand, it seems logical to anticipate certain vasomotor changes arising from irritation or compression of the nerve.

Thickening of the transverse carpal ligament itself may be sufficient to compress the median nerve in certain systemic disorders, such as acromegaly, pleonosteosis, and myxedema. Although there was some slight variation in the thickness of the transverse carpal ligament in the wrists that were operated on, in no instance was it apparent to the surgeon that the ligament itself was the primary cause of the median-nerve compression. Several biopsies were made of the transverse carpal ligament and these revealed no pathological changes.

Any condition that increases the volume of the contents of the carpal tunnel obviously tends to compress the median nerve. Benign tumors, such as lipomata, hemangiomata, and ganglia may encroach upon the carpal tunnel. In this series one hemangioma and two ganglia were found to be causing compression of the median nerve. Deposits of calcium and gouty tophi may also be of sufficient magnitude to produce such pressure (Fig. 3). Amyloid disease, as is often seen in patients with multiple myeloma, may produce the syndrome as the result of thickening of the flexor synovialis and transverse carpal ligament; compression of the median nerve may even be the initial manifestation of the systemic disease [4,5]. In this series, there were four patients with multiple myeloma; one underwent surgical treatment. Special stains on sections of the flexor synovialis from this patient showed amyloid infiltration.

The fact that the majority of patients with carpal-tunnel syndrome are women at or near the menopause suggests that the soft tissues about the wrist may be affected in some manner by hormonal changes. Some clinicians [14,15] have reported at least temporary improvement after the administration of estrogens. Others have found estrogens to be ineffective. At the Cleveland Clinic we have not employed hormonal therapy. However, we have noted the onset or aggravation of symptoms during pregnancy and believe this may be associated with retention of fluid in the tissues about the wrist or perhaps increase of adipose tissue in the carpal tunnel. Chlorothiazide has been effective in controlling the symptoms occasionally, but I have not employed this medication in enough patients to evaluate its efficacy.

Congenital anomalies in the region of the carpal canal have frequently been reported as a cause of median-nerve compression, including distal prolongation of the muscle bellies of the flexor digitorum sublimis and anomalous muscles [16]. Because most of the operations I performed were carried out through transverse incisions, I could not search thoroughly for congenital anomalies in the carpal tunnel. It is my impression, however, that a congenital anomaly is rarely the primary cause of compression.

Based on clinical observations, it is my strong impression that venous stasis is a factor in the production of symptoms. Vasodilatation and venous stasis accompanying sleep and inactivity could well explain the night pain. With engorgement of vessels in the flexor synovialis, increasing the volume of the contents of the carpal tunnel, pressure is applied to the median nerve. Active motion of the flexor tendons could then relieve the pain by mechanically decreasing venous engorgement within the carpal tunnel.

Although any type of trauma which alters the normal contour of the carpal tunnel or damages the median nerve or flexor tendons may produce the syndrome, the findings in this study indicated that local trauma to the wrist was seldom an etiological factor. Only seventy patients (16 per cent) gave a history of wrist injury which could be considered a possible cause of median neuropathy (Table II). Only twenty-

TABLE II

TRAUMA PRECEDING ONSET OF SYMPTOMS IN SEVENTY PATIENTS WTH CARPAL-TUNNEL SYNDROME

Type of Injury	No. of Patients Total	Men	Women
Fractures	27		
Distal end of radius (Colles)		6	7
Carpal bone		6	6
Metacarpal		1	0
Radius and ulna, lower third		0	1
Sprain of wrist	10	5	5
Direct blow to hand or wrist	9	6	3
Laceration of wrist	2	2	0
Operation for flexor graft	1	1	0
Recent excessive use of hands	21	11	10
Total	70	38	32

seven had fractures: thirteen, Colles' fracture; twelve, fractures of one or more carpal bones; one, a fracture through the lower third of the forearm bones; and one, a fracture of the metacarpals. If recent excessive use of the hands was excluded as a possible traumatic cause of the syndrome, only 11 per cent of the patients in the series could be classified as having post-traumatic carpal-tunnel syndrome. Men and women were equally represented in the group with post-traumatic symptoms. The position of acute volar flexion and ulnar deviation of the hand at the wrist (Cotton-Loder position) should be condemned in the treatment of Colles' fracture because of the danger of median-nerve compression. Malunited fractures or fractures with excessive new-bone formation may cause compression of the median nerve. Carpal dislocations, acute sprains of the wrist, or direct blows to the wrist may also traumatize the median nerve. Irregularity of the carpal bones caused by old fractures and advanced post-traumatic arthritis of the wrist have also been reported [2] as causes of the syndrome.

Recent excessive use of the hands was thought to be an etiological factor in only twenty-one of the cases in this series. Brain and associates demonstrated that pressure within the carpal tunnel was three times greater with the wrist extended than with the wrist flexed and concluded that sustained vigorous work with the wrist extended might initiate the syndrome. Tanzer showed that similar increases in pressure within the proximal portion of the carpal tunnel may be produced by both flexion and extension of the wrist; he also demonstrated that the median nerve is compressed against the transverse carpal ligament by simultaneous and forceful flexion of the

TABLE III

Occupation of Patients with Carpal-Tunnel Syndrome

Type of Occupation	No. of Patients Total	Men	Women
Housekeeper or cook	210	3	207
Laborer	26	25	1
Assembly work	18	10	8
Salesman, saleswoman	18	10	8
Clerk, accountant	16	5	11
Mechanic, machinist	15	15	0
Executive	11	11	0
Teacher	9	0	9
Secretary	8	0	8
Nurse	8	0	8
Physician	6	6	0
Dentist	1	1	0
Other professions	8	8	0
Carpenter, painter, electrician	7	7	0
Waitress	5	0	5
Barber, beautician	4	1	3
Farmer	4	4	0
Draftsman	2	2	0
Telephone operator	2	0	2
Dressmaker, tailor	2	1	1
Florist	2	1	1
Dry cleaner	2	1	1
Professional golfer	1	1	0
Retired	14	12	2
No excessive use of hands	29	20	9
Not recorded	11	6	5
Total	439	150	289

wrist and fingers. Occupations that require active finger flexion with the wrist flexed should certainly predispose to a carpal-tunnel syndrome, but fortunately such occupations are not common.

The common, typical, carpal-tunnel syndrome—spontaneous compression neuropathy of the median nerve in the carpal tunnel—is not an occupational disease. A chronic tenosynovitis of the flexor tendons in the carpal tunnel might result from prolonged excessive forceful grasping movements, but such a tenosynovitis is not a common finding in industrial workers. Most patients with a carpal-tunnel syndrome have an aggravation of symptoms after strenuous use of the hands, and the symptoms are usually worse in the dominant hand. In this series, there were sixty-five patients with symptoms limited to the left hand, but only five of them were left-handed. The occupations of the patients in the series are listed in Table III. Men certainly subject their hands to more trauma than do women, but men contributed only 33 per cent of all cases in this series. Excluding the seventy cases directly associated with trauma, men comprised only 29 per cent of the remaining cases. An occupation may aggravate but seldom produces a carpal-tunnel syndrome.

Evidently many persons tend to keep their wrists flexed during sleep. Complete flexion of the wrist maintained while sleeping most certainly produces some compression of the median nerve in the normal wrist. This so-called waking numbness develops in a much shorter period and produces more severe symptoms in a wrist with a mild carpal-tunnel syndrome than in a normal wrist. It is recommended that wrist splints be worn by persons who constantly keep their wrists flexed during sleep to prevent compression of the median nerve.

I agree with Tanzer that there probably is some sort of predisposition to the

TABLE IV

OTHER DISEASES PRESENT WITH CARPAL-TUNNEL SYNDROME

Name of Disease	No. of Patients Total	Men	Women
Trigger finger or thumb	34	8	26
Diabetes mellitus	33	9	24
Rheumatoid arthritis	49	11	38
Periarthritis of shoulder	28	8	20
Tennis elbow	21	4	17
Hypertrophic arthritis carpus	12	3	9
de Quervain's	10	1	9
Dupuytren's	8	4	4
Thoracic outlet syndrome	5	2	3
Lupus erythematosus	4	1	3
Multiple myeloma	4	4	0
Calcific tendinitis at wrist	3	0	3
Psoriasis	3	1	2
Myxedema	3	2	1
Alcoholic neuropathy	3	2	1
Gout	2	2	0
Tietze's	2	1	1
Dyschondroplasia	2	2	0
Primary amyloidosis	1	0	1
Pernicious anemia	1	0	1
Leukemia	1	1	0
Multiple sclerosis	1	1	0
Herpes zoster D-4	1	1	0
Raynaud's	1	0	1
Mycosis fungoides	1	0	1

TABLE V

DATA OF 270 WRISTS OF PATIENTS WITH CARPAL-TUNNEL SYNDROME TREATED BY INJECTIONS

No. of Injections	Total	No Further Symptoms	Improvement (Without Operation) Moderate	Much	None	Incomplete Follow-up	Operation Performed
1	141	27	17	10	15	39	33
2	54	13	14	10	2	7	8
3	32	8	5	3	2	5	9
4	20	2	7	1	2	2	6
5	8	2	1	1	1	1	2
6	5	0	3	1	0	1	0
7	3	0	3	0	0	0	0
9	2	0	0	0	0	0	2
10	2	0	2	0	0	0	0
11	3	0	3	0	0	0	0
Total	270	52	55	26	22	55	60

carpal-tunnel syndrome, the exact nature of which is not known. Many patients offer the information that their parents or grandparents had similar complaints, especially thenar atrophy. One patient in this series sought medical treatment only because she noticed slight atrophy of her right thenar muscles and feared that these muscles might waste away completely as did those of her mother.

Rheumatic conditions of various types about the wrist and hand are more common in women than in men. This fact may account for the much higher incidence of carpal-tunnel syndrome in women. In this series ninety-six patients had some form of associated tenosynovial disorder such as de Quervain's disease, trigger finger, and the like (Table IV).

In addition forty-nine patients were diagnosed as having rheumatoid arthritis, and four, as having lupus erythematosus.

The changes in the median nerve observed at operation shed little light on the pathogenesis of this syndrome. A bulbous swelling of the nerve proximal to the upper edge of the transverse carpal ligament—a so-called false neuroma—was observed in forty-five wrists. This finding was not associated with any pathological or anatomical abnormality in the extremity in thirty-three. In the other twelve, associated abnormalities were de Quervain's disease in three, periarthritis of the shoulder in two, and diabetes, tennis elbow, healed Colles' fracture, an ununited fracture of the carpal navicular, a ganglion, a synovial cyst with myxomatous degeneration, and trigger finger in one each. There was nothing to suggest that a false neuroma was a specific factor in the pathogenesis of the syndrome or that formation of the neuroma was related to any specific anatomical or pathological variation.

Obvious compression of the nerve characterized by flattening, thinning, and narrowing of the nerve beneath the transverse carpal ligament or by a transverse groove in the nerve at the level of the proximal edge of the ligament was found in 151 (71 per cent) of the 212 wrists treated surgically. In the other sixty-one wrists, the nerve was not deformed and there was no gross evidence of compression.

An acute carpal-tunnel syndrome, requiring immediate surgical decompression, was not encountered in this series. A hematoma in the palm, acute thrombosis of a persistent median artery, or an acute suppurative infection within the carpal tunnel might be expected to produce such a situation.

Treatment

Surgical treatment is not required for every patient with a carpal-tunnel syndrome. In this series only 177 patients (40 per cent of the entire group) had one or both hands operated on. Occasionally, a patient has such minor transient symptoms that no treatment whatsoever is indicated. It is obvious that resting the hands or a change of occupation is indicated for the patient who has had a recent onset of symptoms after an unusual amount of manual labor. Splinting the wrist in slight extension may be advisable for a week or two to enforce the necessary period of rest. Splinting of the wrist at night is indicated only in those persons who tend to sleep with their wrists sharply flexed and who are awakened by severe numbness and pain in the median-nerve distribution which can be reproduced by sustained wrist flexion.

The injection of hydrocortisone or some other steroid preparation into the carpal tunnel often gives excellent relief from the hypesthesia or paresthesia in the median distribution. Two hundred and seventy wrists (41 per cent) of the patients in this series were injected one or more times (Table V). The usual amount injected was one milliliter (twenty-five milligrams) of hydrocortisone tertiary-butylacetate or a similar amount of triamcinolone acetonide or methylprednisolone acetate. The injection is made through a 25-gauge needle inserted into the carpal tunnel, medial to the palmaris longus tendon and to the median nerve (Fig. 4). Care must be taken not to inject the steroid solution into the median nerve itself (Fig. 5), but rather to disperse the solution around the flexor tendons. The injection causes a little discomfort immediately, but the patient must be warned about the infrequent possibility of increased pain and swelling in the wrist and hand over the next twenty-four or forty-eight hours. An injection should be given no more frequently than every seven to ten days. If no improvement is obtained with the first injection, it is unlikely that further injections will help. One patient, a man eighty-two years old, received in the Department of Rheumatic Disease twenty-eight injections (seventeen in the left wrist and eleven in the right wrist) over a period of eight years. After the twenty-eighth injection in June 1963, a diagnosis of chemical neuritis involving the median

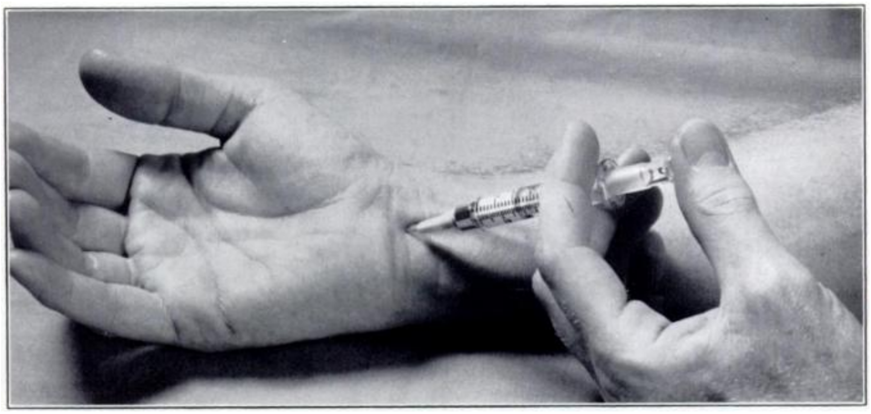

FIG. 4

The carpal tunnel is injected with one milliliter or less of hydrocortisone through a 25-gauge needle inserted just medial to the palmaris longus tendon. A local anesthetic is not necessary.

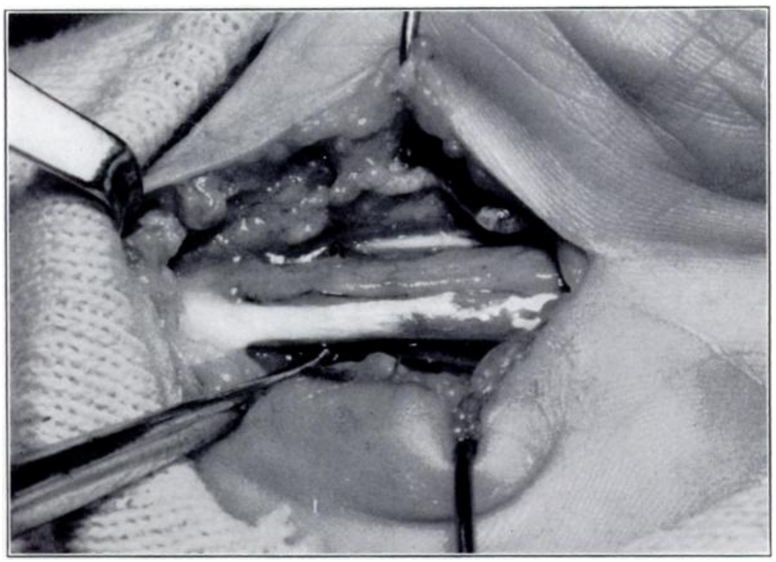

FIG. 5

Exposure of the median nerve in the carpal tunnel of a woman, sixty-four years old. A long-acting steroid preparation had been injected inadvertently into the median nerve one month before operation. Fortunately, the woman eventually had a good result.

nerve was made. Symptoms of this acute neuritis subsequently subsided leaving him with a positive Tinel sign over the median nerve at the wrist and paresthesias in the distribution of the median nerve in the hand. My preference is to give no more than three or four injections before advising surgical treatment. If thenar atrophy is present or if the patient's symptoms are of long duration, injections are seldom of value, and surgical treatment should be recommended immediately.

Prompt relief after injection of a steroid into the carpal tunnel gives additional support to the diagnosis of carpal-tunnel syndrome. The local effect of the steroid in reducing the swelling of the flexor synovialis is almost sure to produce some amelioration of the symptoms of median-nerve compression. Failure to obtain any improvement, however, does not indicate that the diagnosis of carpal-tunnel syndrome is in error.

Many of the patients in this series were given injections by members of the Department of Rheumatic Disease. Some patients received many injections. Of the 270

FIG. 6-A

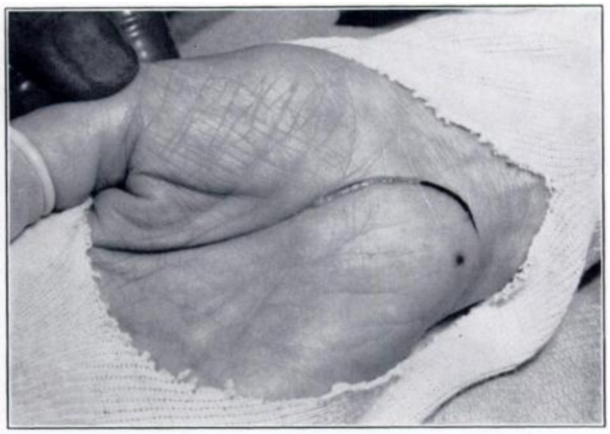

FIG. 6-B

Fig. 6-A: The carpal tunnel may be exposed by an oblique curved incision extending from the hypothenar eminence to the palmar crease. This incision may easily be extended across the wrist and up the volar aspect of the forearm if synovectomy is indicated.

Fig. 6-B: A similar incision may be used extending along the medial margin of the thenar eminence. Care must be taken to avoid injury to the recurrent branch of the median nerve.

wrists injected with a steroid preparation, sixty were eventually operated on (Table V). Fifty-two (24 per cent) of the wrists in the group gave no further symptoms after from one to five injections; eighty-one (38 per cent) showed some improvement, and twenty-two (10 per cent) were not improved. Recently I have been injecting the wrist of almost every patient with a carpal-tunnel syndrome at the time of the initial examination, provided, of course, there is no severe sensory deficit and no thenar atrophy that would require prompt surgical treatment. The injection does no harm if it is carefully performed; and, in early cases of carpal-tunnel syndrome, the prompt relief of paresthesia and night pain is greatly appreciated by the patient.

Sufficient decompression of the median nerve in the carpal tunnel is usually obtained by simply sectioning the entire transverse carpal ligament. This operation is readily performed with the aid of a pneumatic tourniquet under local anesthesia or regional perfusion anesthesia. The patient need not be hospitalized postoperatively. A pressure dressing is applied and is worn for three or four days; and the wrist is immobilized by a splint in neutral position for from seven to ten days or until the wound is healed.

Although most median nerves are compressed in the proximal third of the carpal tunnel, it is imperative that the entire transverse carpal ligament be severed. This may be carried out through a three-centimeter transverse incision in the distal flexion crease at the wrist, but the disadvantage of this approach is that the most distal portion of the ligament must be cut blindly. The ligament should be sectioned through its medial portion to avoid any possible damage to the recurrent branch of the median nerve. After section of the transverse carpal ligament there should be sufficient room in the carpal tunnel to permit a curved Kelly hemostat to slide easily into the palm or to allow the moistened little finger of the surgeon to pass readily along with the median nerve into the palm.

The entire roof of the carpal tunnel may be easily exposed through an oblique incision extending from the hypothenar eminence laterally across the base of the palm to the distal flexion crease at the wrist (Fig. 6-A). A similar incision may also be employed, extending from the thenar eminence medially across the base of the palm to the distal flexion crease of the wrist (Fig. 6-B). With these incisions,

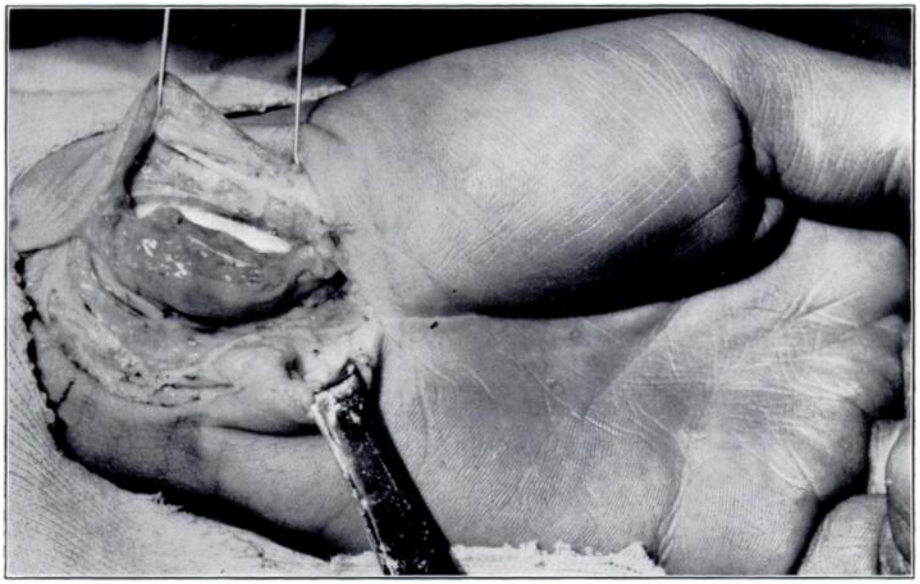

FIG. 7

Chronic inflammation of the flexor synovialis caused a carpal-tunnel syndrome in this man's wrist. Synovectomy was necessary to obtain adequate decompression of the median nerve in the carpal tunnel. The thickened synovial membrane is seen around the flexor pollicis longus tendon; the median nerve is displaced medially.

excellent exposure of the entire carpal tunnel to direct vision is obtained and the entire transverse carpal ligament may be readily divided and a portion excised, if desired. If further exploration of the median nerve or a synovectomy is indicated, either of these incisions may be prolonged as an S-shaped incision up the volar aspect of the forearm. Synovectomy cannot be done easily under local anesthesia alone. In this series fifty-eight hands were operated on under local anesthesia and 154 under general anesthesia. My present preference is to do more of these operations under local anaesthesia.

When the transverse carpal ligament is sectioned, the cut edges of the ligament separate about one-quarter of an inch. If after section of the ligament, the median nerve is not completely decompressed, then partial synovectomy of the flexor synovialis should be performed (Fig. 7). Usually the need for synovectomy may be anticipated when there is swelling on the volar aspect of the forearm proximal to the volar carpal ligament. If there is any possibility that synovectomy may be necessary, the transverse incision should not be used. Although a transverse incision may be prolonged by a gently curved proximal extension of one end and careful elevation of the skin flap, the circulation of the resultant flap is precarious and ischemia of the tip of the flap may ensue. In the 212 hands operated on in this series, synovectomy was necessary in eight (4 per cent). Routine synovectomy is not advisable, since this additional procedure prolongs the postoperative disability and may result in decreased excursion of the flexor tendons.

Routine neurolysis of the median nerve is also inadvisable, since even in long-standing lesions the swelling of the nerve proximal to the transverse carpal ligament does not appear to be a true interstitial neuroma. In none of the wrists that I have operated on has the enlargement of the nerve to palpation had the firm feeling characteristic of a post-traumatic neuroma. The swelling, I believe, is the result of edema proximal to the point of compression.

Occasionally, after section of the transverse carpal ligament, the palmaris longus tendon will be found to lie quite snugly over the median nerve. If there is any indication that the tendon may be pressing on the median nerve, one should not hesitate to cut or to remove a section of this tendon. The palmaris longus tendon was severed in twenty-one wrists in this series and all had satisfactory results. There was no instance in this series when failure to divide the palmaris longus was a cause of failure. However, in one patient with rheumatoid arthritis and persistent symptoms after operation done elsewhere, re-exploration revealed that the palmaris longus tendon was indenting the median nerve because of pressure caused by the marked swelling of the flexor synovialis. Synovectomy and resection of the palmaris longus tendon relieved symptoms in the wrist.

In a patient with carpal-tunnel syndrome, any degree of thenar atrophy is an absolute indication for surgery. Progression of the numbness and paresthesia in the fingers and thumb is also an indication for surgical intervention. Surgical treatment is also advised when the patient's symptoms are incapacitating or of long duration.

Results of Surgical Treatment

There are few operations that are as successful and rewarding as the operation for carpal-tunnel syndrome.

In this study a follow-up period of less than five months was considered inadequate to determine the efficacy of treatment. I re-examined many of the patients and many others were contacted by letter or by telephone. Only twelve of the 177 surgically treated patients (thirteen of 212 hands) were followed for less than five months. Many patients had been followed for more than ten years. Fifteen wrists were operated on by other members of the Department of Orthopedic Surgery, and I performed the remaining 197 operations.

Of the patients surgically treated, both wrists were involved in ninety-nine, the right wrist only in fifty-three, and the left wrist only in twenty-five.

Of the ninety-nine patients with bilateral involvement thirty-eight had operation on both wrists; forty-five on the right wrist only, and sixteen on the left wrist only. When both wrists required surgical treatment, one wrist was operated on at a sitting unless the patient insisted on having both done at the same procedure. Bilateral operation was performed on ten patients, all of whom were considerably incapacitated for at least two days after operation, because with both extremities elevated to prevent edema, use of their hands was restricted. Of the sixty-one patients with bilateral symptoms who had operation on only one side, all were right-handed, except for one who was ambidextrous and had operation on the left side.

Of the fifty-three patients with right-sided involvement and operation on the right wrist, all were right-handed. Of the twenty-five with left-sided involvement and operation on the left side, only two were left-handed.

Thenar Atrophy

Thenar atrophy of greater or lesser degree was present in 120 (56 per cent) of the 212 hands operated on. Eight of these 120 hands with atrophy were either lost to follow-up or were followed for less than five months. Of the remaining 112 hands, seventy-six regained normal or almost normal thenar muscles between six and twelve months after operation; sixteen showed various degrees of improvement in thenar muscle power; twenty showed no improvement, but there was no progression of thenar atrophy, except in one hand.

No clear-cut explanation for the lack of thenar muscle recovery in twenty hands was apparent. The appearance of the nerve at operation in these hands was not remarkable. Twelve had neuromata, but these were no more severe than the neuromata of the patients who had no atrophy or whose atrophy disappeared after operation; the other eight nerves were not remarkable when they were exposed.

In the hand with progression of atrophy after operation re-exploration revealed incomplete severance of the distal portion of the transverse carpal ligament after the first operation which had been performed through a transverse incision at the wrist.

There was also no correlation between the duration of symptoms and postoperative disappearance of atrophy.

As a rule, the shorter the duration of thenar paralysis the quicker the recovery of muscle function. However, the duration of thenar atrophy was often difficult to establish, since many patients were not aware that their hands had any atrophy until their attention was called to this finding at the time of the initial examination. Furthermore, atrophy was rarely the initial symptom of the syndrome, and the onset of the atrophy was always gradual. Of the twenty hands that showed no postoperative improvement in thenar muscle power, seven were known to have had atrophy for more than twenty years; two, for more than ten years; five, for more than two years; and six, for one year or less. No firm prognosis in regard to the return of the thenar muscle power is possible. Formerly I believed that if the paralysis had existed for more than one year, the outlook for recovery after decompression of the median nerve was poor. I now know that thenar atrophy may exist for at least three years and still be relieved by section of the transverse carpal ligament. In one woman in this series who maintained that she had had atrophy of the thenar muscles for ten years, the atrophy had cleared up completely seventeen months after operation. At least nine patients had atrophy for three years or longer, and all regained thenar muscle power postoperatively.

Hypesthesia without Thenar Atrophy

Of the ninety-two hands surgically treated without thenar atrophy four (four patients) were lost to follow-up. Of the remaining eighty-eight hands, sixty-nine obtained excellent results from operation, with return of normal sensation and function; seventeen were improved but still had some impairment of sensation in the distribution of the median nerve; and two (two patients) were not improved. One of the hands not improved was that of a diabetic patient in whom a reflex sympathetic dystrophy developed and then gradually improved after many months. In the other hand showing no improvement in sensation one year after operation, there was some diminution of the preoperative burning pain in the palm.

As in the case of thenar atrophy there was no correlation between the postoperative improvement and the duration of symptoms or the operative findings.

Hypesthesia with Thenar Atrophy

Of the 112 adequately followed surgically treated hands with thenar atrophy and diminished sensation, eighty-five regained normal sensation postoperatively, twenty-three were improved but still had some impaired sensation in the median-nerve distribution, and four hands in four patients were not improved. Of these four patients, one, nine years after operation, had regained most of the thenar-muscle power and had no pain in the hand but still had the same mild sensory impairment that was present before operation; the second, eighty-three years old, showed no improvement at seven months; the third, eight months after operation, no longer had the night pain and forearm pain that she had had before operation, but her preoperative median hypesthesia remained unchanged; and the fourth, with only a six-month follow-up, had no relief of symptoms. No reason for the failure of surgery in these four patients was apparent.

Reoperations

Two hands were operated on a second time—one as previously noted, because of progression of thenar atrophy, the other because of recurrence of numbness in the median-nerve distribution. The first patient was found to have incomplete severance of the distal portion of the transverse carpal ligament after the first operation which was performed through a transverse incision at the wrist. After the second operation, she regained normal sensation, muscle power, and function; her hand remained normal during the fifteen years that she has been followed.

The second patient had a re-exploration of the carpal tunnel nearly three years after the first procedure when repair of a spontaneous rupture of the extensor pollicis longus tendon was performed. At exploration scar tissue was found surrounding the median nerve. Lysis of the nerve and removal of scar tissue, combined with the tendon repair, restored normal motion of the thumb and resulted in some sensory improvement, although slight hypesthesia in the median distribution of the hand persisted. There was no apparent explanation for the excessive scarring. The patient had an old ununited fracture of the carpal scaphoid sustained twenty-eight years before re-exploration, but nothing was found at operation to suggest that this non-union had contributed to the scarring. There was no history of infection after the first operation and no evidence of rheumatoid arthritis.

When recommending an operation for carpal-tunnel syndrome, the surgeon may be quite confident that his patient will be relieved of pain in the median-nerve distribution; but, if the sensory loss is profound and of many years' duration, the patient must be advised that normal sensation in the hand will not necessarily be restored.

Complications

In the 212 hands operated on, there were no serious postoperative complications. In one man, some redness and induration developed about the incision but there was no drainage and the result was satisfactory. There were no other postoperative infections. The previously mentioned woman with diabetes, in whom a postoperative sympathetic dystrophy developed, eventually recovered almost completely. When last seen she had slight loss of motion in the proximal interphalangeal joints but no pain, muscle atrophy, or hypesthesia.

There were fourteen patients who underwent surgery for the carpal-tunnel syndrome elsewhere after they were examined and diagnosed at the Cleveland Clinic. Ten of these patients obtained good results. One patient noted only slight improvement and two patients were unimproved. The remaining patient was a practicing neurologist, who after consultation at the Cleveland Clinic, returned to his office and performed an operation on his own wrist under local anesthesia. He managed to sever a portion of the transverse carpal ligament, enough to relieve his pain but not enough to prevent progressive thenar atrophy.

Summary

At the Cleveland Clinic the diagnosis of carpal-tunnel syndrome has been made in 654 hands of 439 patients during the last seventeen years. The typical patient with this syndrome is a middle-aged housewife with numbness and tingling in the thumb and index, long, and ring fingers, which is worse at night and worse after excessive activity of the hands. The sensory disturbances, both objective and subjective, must be directly related to the sensory distribution of the median nerve distal to the wrist; but pain may be referred proximal to the wrist as high as the shoulder. There is usually a positive Tinel sign over the median nerve at the wrist, and the wrist-flexion test I described is also usually positive. About half of the patients also have some degree of thenar atrophy.

If steroid injections into the carpal tunnel give only transient relief, treatment

should be by complete section of the transverse carpal ligament. This procedure will almost always relieve the patient's pain and numbness in the hand, and in many cases will also cure the paralysis of the thenar muscles, which may be present.

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Injuries Involving the Epiphyseal Plate

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Injuries Involving the Epiphyseal Plate

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Injuries involving the epiphyseal plate present special problems in diagnosis and management. The dread complication of serious disturbance of growth is usually predictable and, in certain circumstances, can be prevented. Thus, knowledge of the prognosis for a given injury to the epiphyseal plate in a particular child is of considerable importance to the surgeon, who has the dual responsibility of treating the child and advising the parents. The purpose of this presentation is to discuss epiphyseal-plate injuries from both the clinical and the experimental points of view.

APPLIED ANATOMY AND HISTOLOGY

Each epiphysis has its own plate through which skeletal growth occurs; it is important that a distinction be made between the epiphysis and the epiphyseal plate.

Type of Epiphyses

Two types of epiphyses exist in the extremities, namely, pressure epiphyses and traction epiphyses (Fig. 1); there are significant differences between the two.

Pressure epiphyses: A pressure epiphysis, situated at the end of a long bone, is subjected to pressures transmitted through the joint into which it enters. In this sense it may be considered an articular epiphysis; furthermore, its epiphyseal plate provides longitudinal growth of the long bone. Pressure epiphyses may be divided into two types depending on whether their nutrient vessels enter the epiphyses directly (lower femoral epiphysis) or indirectly (upper femoral epiphysis). The significance of these two types of blood supply will be discussed in a subsequent section.

Traction epiphyses: A traction epiphysis is the site of origin or insertion of major muscles or muscle groups and is therefore subjected to traction rather than to pressure. Since it does not enter into the formation of a joint, it is non-articular, and it does not contribute to longitudinal growth of the long bone. Examples of traction epiphyses are the lesser trochanter of the femur and the medial epicondyle of the humerus.

Applied Histology of the Epiphyseal Plate

A knowledge of the microscopic features of the normal epiphyseal plate is pivotal in understanding the problems associated with the various injuries to which it may be subjected. The three main types of injuries are separation of the epiphysis through its epiphyseal plate, fractures that cross the epiphyseal plate, and crushing injuries of the plate itself.

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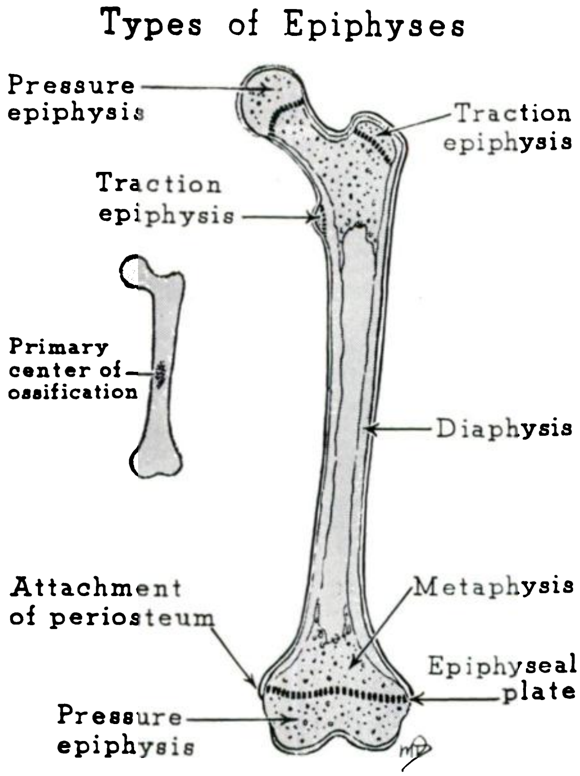


FIG. 1

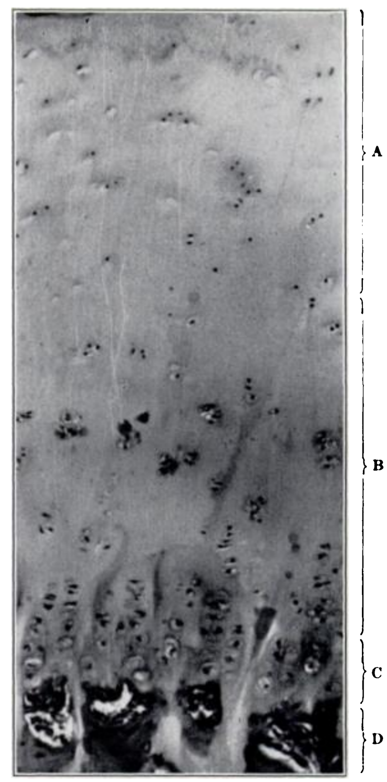


FIG. 2

Fig. 1: Types of epiphyses.
Fig. 2: Normal human epiphyseal plate showing the various layers. *A*, resting cells; *B*, proliferating cells; *C*, hypertrophying cells; and *D*, endochondral cells (metaphysis).

As seen in longitudinal section, the normal epiphyseal plate consists of four distinct layers (Fig. 2): (1) resting cells, (2) proliferating cells, (3) hypertrophying cells, and (4) endochondal ossification. The space between the cells is filled with cartilage matrix or intercellular substance. This intercellular substance, not the cells, provides the strength of the epiphyseal plate, particularly its resistance to shear. In common with the intercellular substance of other sorts of connective tissues, that of cartilage is made up of collagen fibers embedded in an amorphous cement substance containing chondroitin sulphuric acid. Because the refractive indices of these two components are the same, the collagen fibers cannot be identified in ordinary preparations, but they can be seen by special techniques, such as phase-contrast microscopy.

In the matrix of the epiphyseal plate, the collagen fibers are arranged longitudinally and no doubt play a role similar to that of steel rods in reinforced concrete. In the first two layers of the plate, the matrix is abundant and the plate is strong. In the third layer (hypertrophied cells), the matrix is scanty and the plate is weak. On the metaphyseal side of this layer, however, the matrix is calcified, forming the so-called zone of provisional calcification. The addition of calcification seems to reinforce this part of the third layer, since the plane of cleavage after separation lies in the third layer at approximately the junction of the calcified and uncalcified parts.

It seems logical, then, that the constancy of the plane of cleavage is the direct result of the structural details of the normal plate. The great significance of the constant location of the plane of cleavage following complete epiphyseal separation

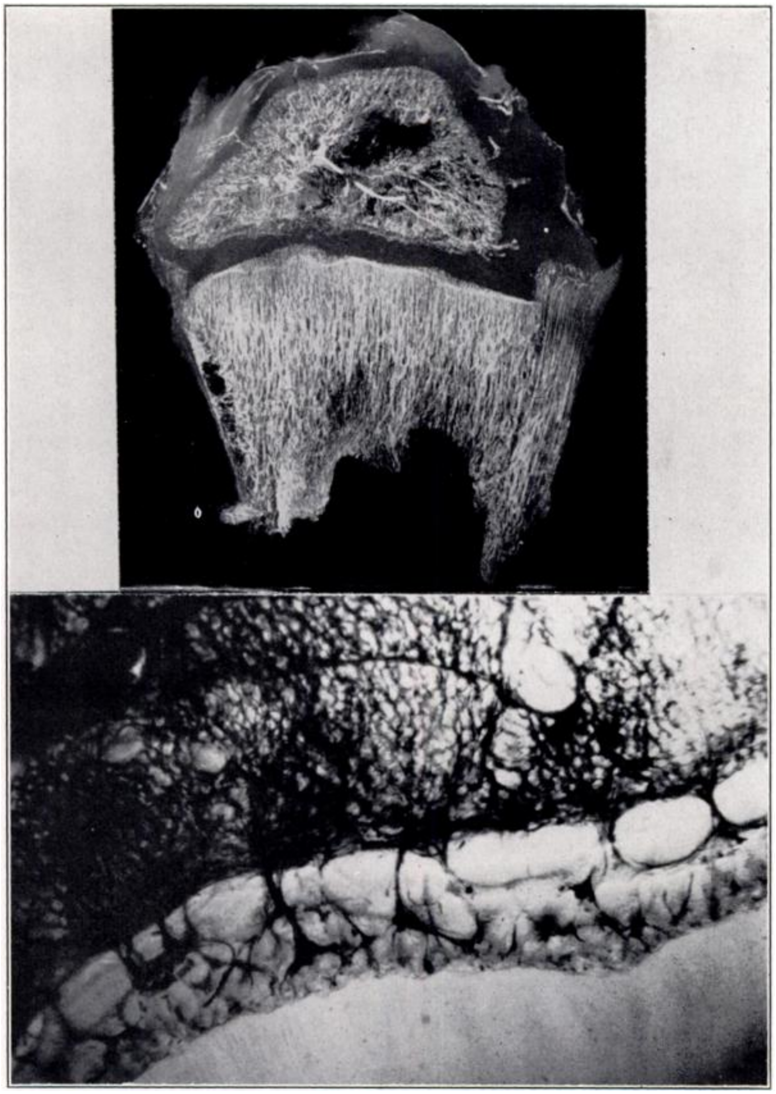


FIG. 3

Distal radial epiphysis in the rabbit. Top: Low-power microangiogram, showing the general pattern of epiphyseal and metaphyseal vessels. Bottom: High-power view (Spalteholz India-ink technique) showing the anastomosing network of vessels arising from the epiphysis and penetrating its cortical bone plate to terminate in vascular tufts in the resting layer of the epiphyseal plate.

is that the growing cells remain attached to the epiphysis. Thus, if the nutrition of these cells is not damaged by the separation, there is no reason why normal growth should not continue. The crux of the problem, then, is not the mechanical damage to the plate, but whether the separation interferes with the blood supply of the epiphysis.

Fractures that cross the epiphyseal plate and crushing injuries of the epiphyseal plate present additional problems that will be discussed later.

Mechanism of Nutrition in Epiphyseal Plates

Injection studies demonstrate two separate systems of blood vessels to the epiphyseal plate [19]. The epiphyseal system arises from vessels in the epiphysis that penetrate the bone plate of the epiphysis and end in capillary tufts or loops in the layer of resting cells of the plate (Fig. 3). The metaphyseal system arises in the

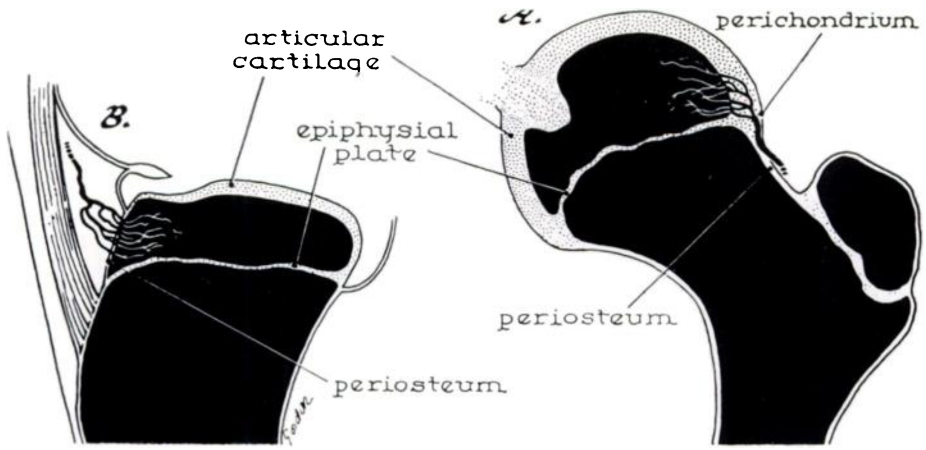


FIG. 4-A

The two methods by which blood vessels enter epiphyses.

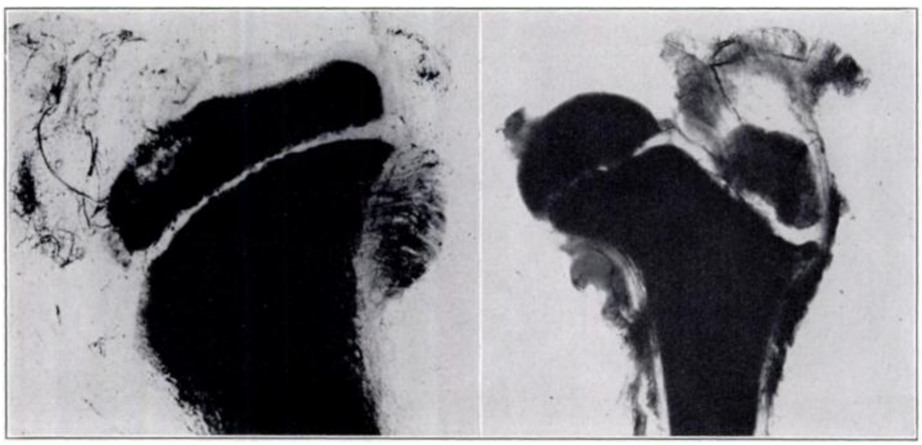


FIG. 4-B

Injected specimens from a monkey, showing nutrient vessels to the femoral head and upper tibial epiphysis. (Figs. 4-A and 4-B reprinted from Prognosis of Epiphyseal Separation by G. G. Dale and W. R. Harris. J. Bone and Joint Surg., 40-B: 117, Feb. 1958.)

marrow of the shaft, and ends in vascular loops in the layer of endochondral ossification. By selectively damaging one or other of these two systems, it can be shown that the former is responsible for the nutrition of the proliferating cells, while the latter is responsible for the nutrition of the cells involved in endochondral ossification [20].

The nutrient vessels of the epiphysis (from which the terminal vascular loops to the epiphyseal side of the plate are derived) enter in one of two ways (Figs. 4-A and 4-B)[12]. The first, and commoner, occurs when the sides of the epiphysis are covered with periosteum. The nutrient vessels penetrate the side of the epiphysis at a point remote from the epiphyseal plate. The second, decidedly less common, occurs when the entire epiphysis is intra-articular and, hence, covered with articular cartilage. The nutrient vessels then enter the epiphysis by traversing the rim of the epiphyseal plate. It is easy to see that the vessels to this type of epiphysis might be ruptured in the event of epiphyseal separation. The upper femoral epiphysis is the main example of this type; the upper radial epiphysis probably belongs to this group as well.

Relative Strength of the Epiphyseal Plate

The cartilaginous epiphyseal plate is obviously weaker than bone, and yet fractures through bone are much commoner in childhood than epiphyseal separations. The explanation for this apparent paradox probably is that only shearing forces and avulsion forces are capable of separating an epiphysis.

The epiphyseal plate is also weaker than normal tendons and ligaments in children. For this reason, injuries that may result in complete tear of a major ligament in the adult actually produce a separation of the epiphysis in the child. For example, an abduction injury of a child's knee results in epiphyseal separation rather than in rupture of the medial collateral ligament of the knee; abduction injury of the elbow avulses the medial epicondyle instead of rupturing the medial ligament of the elbow. Thus, tears or ruptures of major ligaments are very uncommon in childhood. Every child suspected of having torn a major ligament should have roentgenographic examination of the epiphyses of the area.

Similarly, the epiphyseal plate is not as strong as the fibrous joint capsule. Hence, traumatic dislocation of major joints, such as the shoulder, hip, and knee,

TABLE I

MAJOR LONG BONES: PERCENTAGE CONTRIBUTION TO GROWTH OF THE EPIPHYSES

Humerus		Femur	
Upper end	80%	Upper end	30%
Lower end	20%	Lower end	70%
Radius		Tibia	
Upper end	25%	Upper end	55%
Lower end	75%	Lower end	45%
Ulna		Fibula	
Upper end	20%	Upper end	60%
Lower end	80%	Lower end	40%

are decidedly less common in childhood than epiphyseal separations in these locations. For example, the injury that usually produces an anterior dislocation of the shoulder in an adult is likely to produce separation of the upper humeral epiphysis in a child.

Relative Growth at the Ends of Major Long Bones

In the lower extremity, longitudinal growth occurs more in the region of the knee than of the hip or ankle. By contrast, in the upper extremity there is more longitudinal growth at the shoulder and wrist than at the elbow. The approximate percentages of growth at the ends of major long bones, as determined by several workers, are shown in Table I.

INJURIES INVOLVING PRESSURE EPIPHYSES

Of all injuries to the long bones during childhood approximately 15 per cent involve the epiphyseal plate [6,11].

Age and Sex Incidence

Although injuries to the epiphyseal plates may occur at any age during childhood, they are somewhat commoner in periods of rapid skeletal growth, in the first year, and during the prepuberty growth spurt. These injuries—and others—are more frequent in boys than in girls, presumably because of the more active physical life of boys.

Site

In general, epiphyseal plates that provide the most growth are most commonly separated by injury. This is not true, however, of two types of epiphyseal injury—fractures that cross or crush the epiphyseal plate.

The lower radial epiphyseal plate is by far the one most frequently separated by injury; indeed, injuries to this epiphyseal plate are nearly as frequent as all other injuries to the epiphyseal plates combined [13]. In order of decreasing frequency, slipping is found in the lower ulnar, lower humeral (lateral condyle), upper radial (head), lower tibial, lower femoral, upper humeral, upper femoral (head), upper tibial, and phalangeal epiphyseal plates.

Etiology of Injuries to the Epiphyseal Plate

Trauma to an epiphyseal plate is usually one of four main types: shearing, avulsion, splitting, or crushing. Each mechanism tends to produce a characteristic type of lesion. The injury may be either closed or open. Open injury, although rare, is more likely to be associated with disturbance of growth.

Certain diseases, such as scurvy, rickets, osteomyelitis, and endocrine imbalance, make the epiphyseal plate more vulnerable to injury and therefore predispose to pathological separation of the epiphysis.

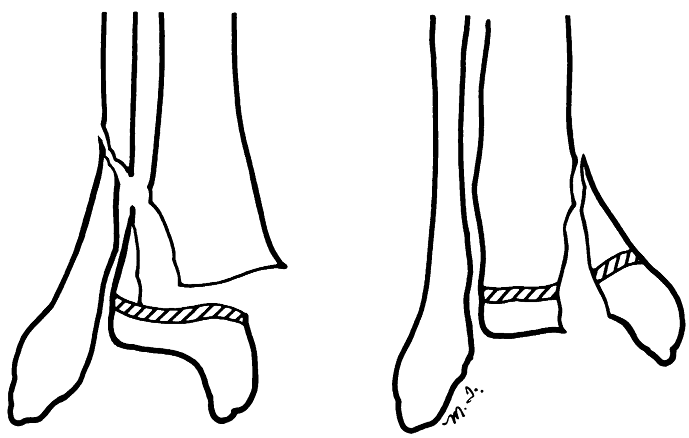


FIG. 5

Diagram to show the two basic types of epiphyseal injury: left, separation of the epiphysis; right, fracture at right angles to the diameter of the plate. (Reprinted from Epiphyseal Injuries by W. R. Harris. Instructional Course Lectures, The American Academy of Orthopaedic Surgeons, Vol. 15, p. 206. Ann Arbor, J. W. Edwards, 1958.)

Iatrogenic damage to epiphyseal plates is preventable. Such damage may occur during overzealous manipulation of deformities or during such operative procedures as removal of a tibial-bone graft, curettage of a metaphyseal bone cyst, excision of metaphyseal tumors (exostoses), and injudicious use of metal fixation across epiphyseal plates.

Experimental Epiphyseal Injuries

Experimental epiphyseal injuries are easy to produce. Study of such experimental injuries provides the basis of determining both clinical treatment and prognosis. Experimental epiphyseal injuries will be discussed under two headings: (1) separation of all or part of the epiphysis from the shaft, and (2) a fracture that crosses the epiphyseal plate (Fig. 5). In general, the former has a good prognosis; the latter, a bad one.

EPIPHYSEAL SEPARATION

Gross Appearance

Epiphyseal separation can be produced in a growing animal by closed manipu-

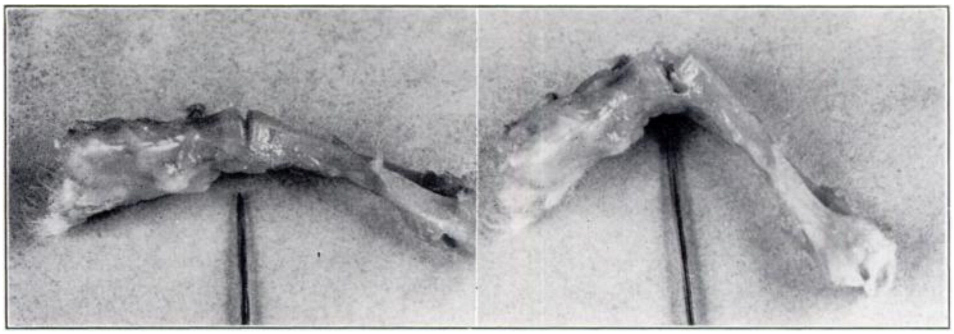


FIG. 6

Fig. 6: Separation of the distal radial epiphysis in the rabbit, showing the hinge effect of the intact periosteum.

Fig. 7: Separation of the distal radial epiphysis in the rabbit; the plane of cleavage almost always occurs through the layer of hypertrophied cells.

FIG. 7

lation, for example, by manual hyperextension of the forepaw. Study of the dissected specimen reveals that the periosteum on the "convex" side of the epiphyseal-plate displacement is ruptured, while on the "concave" side the periosteum is intact and acts as a hinge (Fig. 6). The hinge, which is slack when the epiphysis is in the displaced position, becomes taut when the epiphysis is reduced. This prevents overreduction and also makes the reduction stable, so that the simplest form of external fixation keeps the epiphysis correctly reduced.

Microscopic Appearance

The most striking microscopic feature of experimental separation is the constancy of the plane of cleavage. This cleavage is almost invariably on the diaphyseal side of the epiphyseal plate through the area of hypertrophied cartilage cells (Fig. 7). The fracture line occasionally deviates into the shaft, leaving a triangular fragment of the metaphysis attached to the epiphysis.

Healing after Experimental Epiphyseal Separation

Epiphyses Partly Covered with Articular Cartilage

When the distal radial epiphysis is separated from its shaft, at first there is a remarkable increase in thickness of the proliferating layer of the epiphyseal plate (Fig. 8). This is because the separation temporarily interferes with endochondral ossification, and the hypertrophied cartilaginous cells are not reabsorbed in the usual way. This increased thickness reaches its peak in about ten days. Thereafter, endochondral ossification resumes, and very rapidly the histological features return to normal. After three weeks, healing is complete, and it is difficult to recognize that anything has happened to the plate [12].

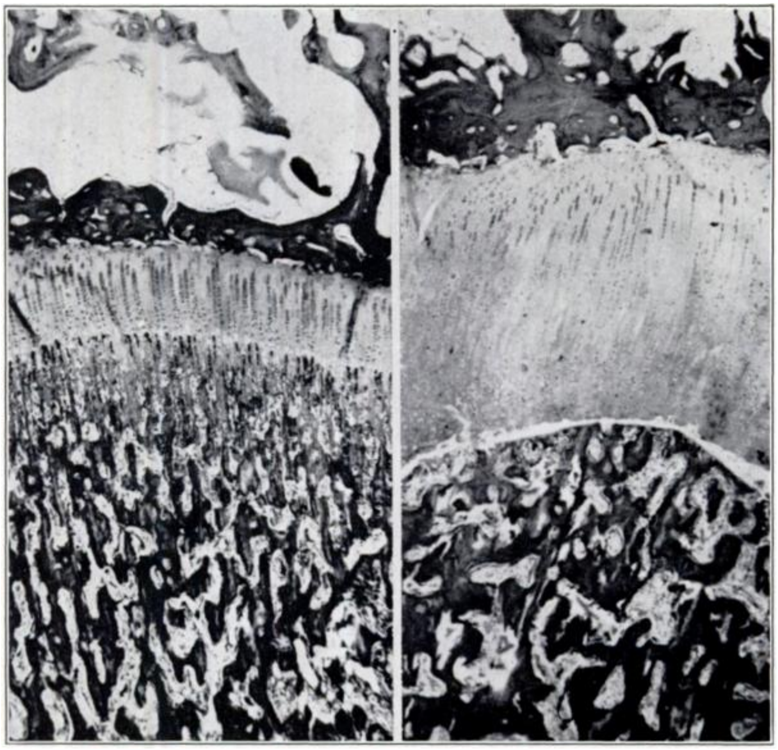


FIG. 8

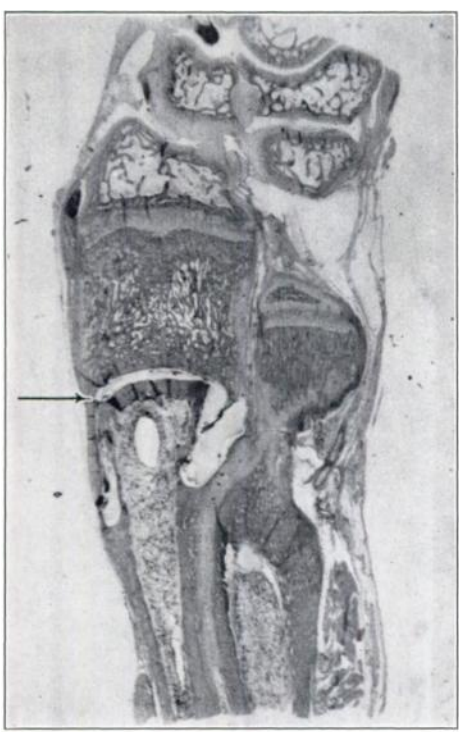


FIG. 9

Fig. 8: Ten days after separation of the distal radial epiphysis in a rabbit. Note the enormous thickening of the separated plate (right) in comparison with the untreated side (left).

Fig. 9: Continued growth on the distal radial epiphysis three weeks after a sheet of teflon had been interposed between the separated epiphysis and the shaft. Arrow indicates site of teflon.

The remarkable capacity of this sort of epiphysis for continued growth after separation can be shown even more dramatically when an impermeable membrane, such as teflon, is interposed between the separated epiphysis and shaft [14]. After three weeks, the epiphysis has grown away from the teflon membrane and normal endochondral ossification has resumed, leaving a pseudarthrosis in the shaft at the site of the separation (Fig. 9).

Epiphyses Entirely Covered with Articular Cartilage

When the upper femoral epiphysis is separated in young animals healing follows quite a different course [15]. Within three to five days avascular necrosis of the epiphysis can be recognized both by the empty bone lacunae and by atrophy of the marrow. At the same time growth in the epiphyseal plate ceases, as is shown by marked narrowing of the cartilaginous plate and atrophy and irregular arrangement of the cells (Fig. 10). New bone growing up from the femoral neck unites

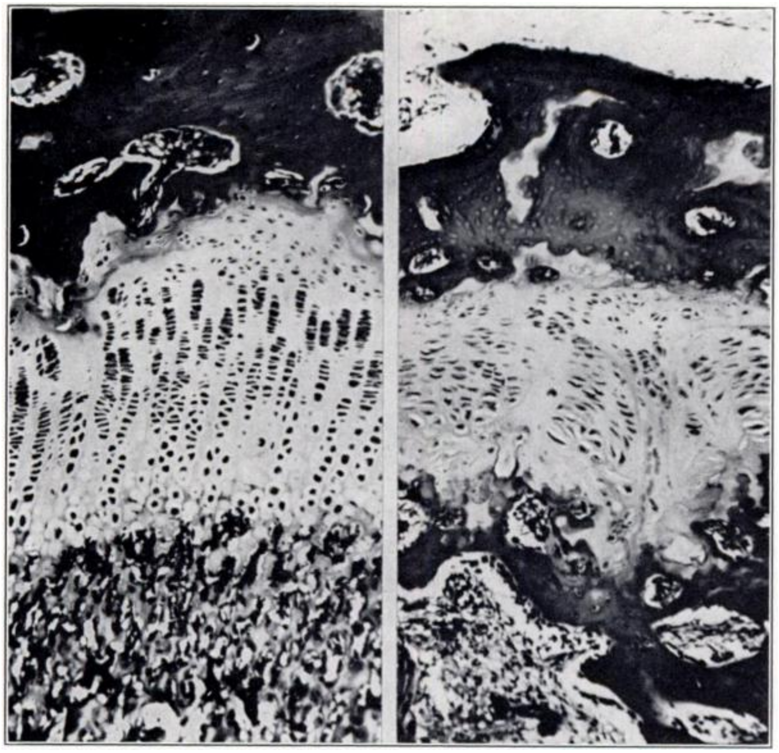


FIG. 10

Marked narrowing and disorganization of the upper femoral epiphyseal plate in a rabbit ten days after separation; note also the avascular necrosis of the bone in the epiphysis (normal control on left).

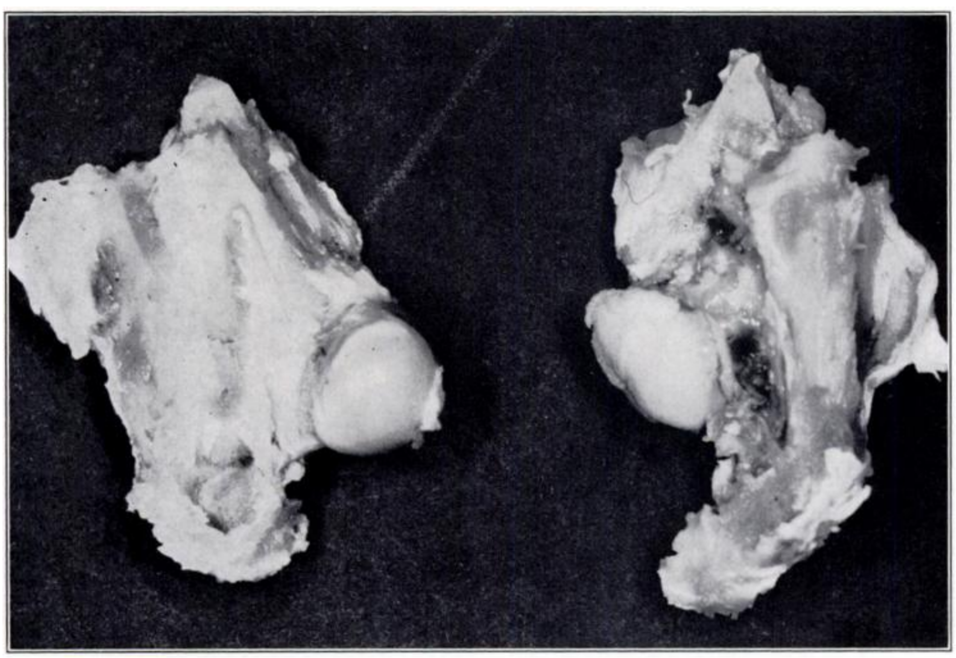


FIG. 11

Avascular collapse of the proximal femoral epiphysis (left) in a rabbit six weeks after separation with normal side for comparison (right). (Figs. 10 and 11 are reprinted from Histological Changes in Experimentally Displaced Upper Femoral Epiphysis in Rabbits by W. R. Harris and K. W. Hobson. J. Bone and Joint Surg., 38-B: 915, 918, Nov. 1956.)

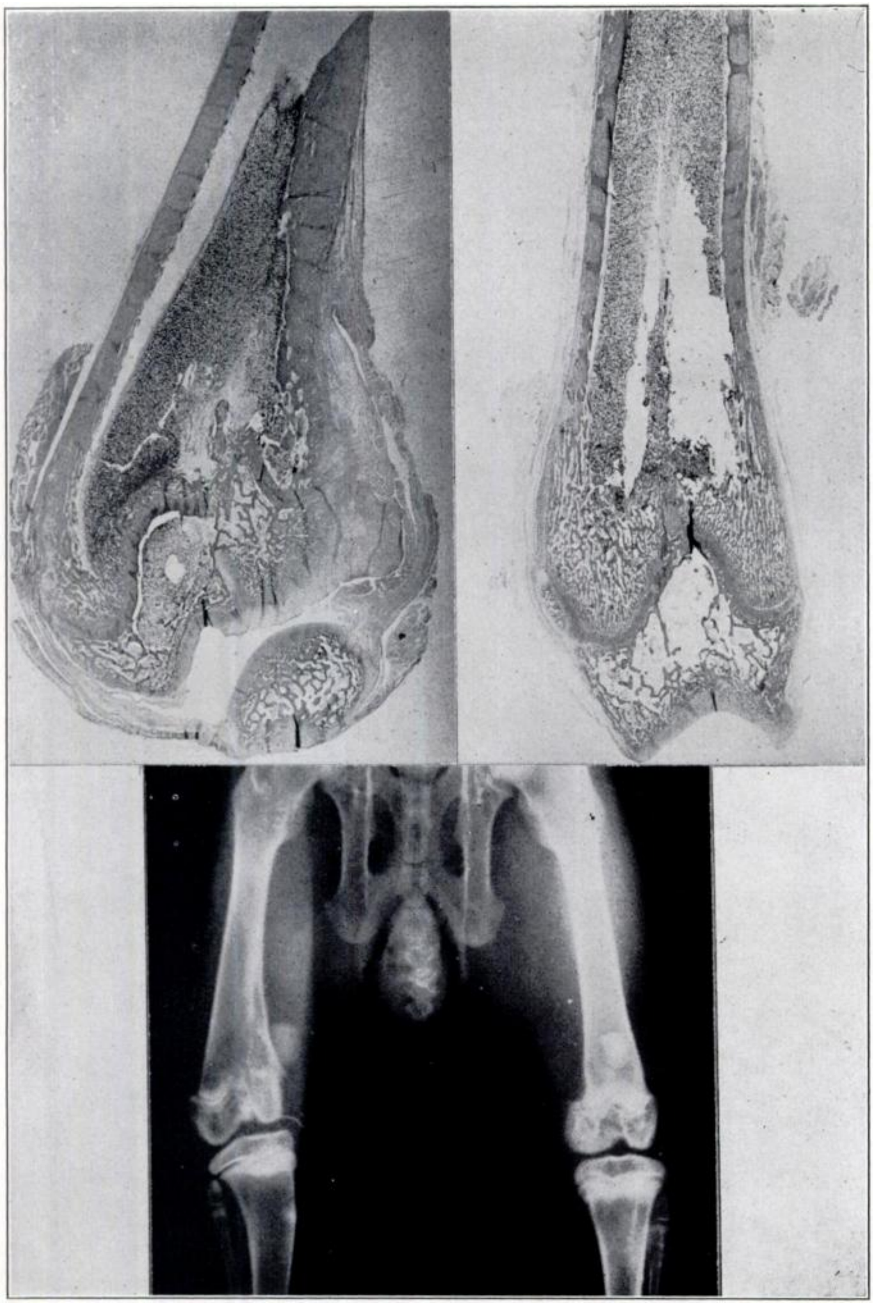


FIG. 12-A

Top: Distal femoral epiphyses of a rabbit six weeks after an experimental fracture traversing the left epiphyseal plate. Bottom: Roentgenogram of the same epiphysis.

the neck with the head, eventually penetrates the remnants of the epiphyseal plate, and reossifies the epiphysis which by then is totally necrotic. Generally, this process is so time-consuming that the typical features of avascular collapse occur (Fig. 11).

In studying such material, one notes that the remnants of the epiphyseal plate seem to act as a barrier to successful reossification of the epiphysis and that if this barrier were removed, reossification would be more rapid and more nearly complete. The experiment was repeated in exactly the same manner as before,

FIG. 12-B

Top: Distal femoral epiphyses in a rabbit six weeks after experimental fracture and accurate open reduction of the left epiphysis. Bottom: Roentgenogram of the same epiphysis. (The screw was placed in the epiphysis for technical convenience. In clinical cases, it is advisable to place the screw across the metaphysis if the fragments are big enough.)

except that the remnants of the epiphyseal plate were deliberately excised before reducing the separation. Although the head again underwent avascular necrosis, it was very rapidly reossified, so that avascular collapse of the epiphysis did not occur [15].

These observations indicate that the prognosis concerning future growth after complete epiphyseal separation ultimately depends on the fate of the nutrient vessels to the epiphysis.

FRACTURES THAT CROSS THE EPIPHYSEAL PLATE

These injuries present a completely different problem, because the injury causes mechanical interference with the growth of the epiphyseal plate without necessarily damaging its blood supply. This injury can be produced experimentally by exposing an epiphysis surgically, and, with a small osteotome, creating a vertical fracture extending from the epiphysis across the epiphyseal plate into the diaphysis. Microscopically, this procedure creates a gap in the epiphyseal plate. This gap then fills with bone, so the epiphysis is fused to the metaphysis in this area.

If there is no longitudinal displacement of the fragments, the epiphyseal plate in each continues to grow for a surprising length of time, but finally premature closure of each piece occurs, and the extremity ends up shorter than its fellow, but without deformity. However, if there is longitudinal displacement of one fragment in relation to the other, fusion occurs between the epiphysis of one fragment and the metaphysis of the other. When this happens, premature fusion of the plate occurs first (and sometimes only) in the displaced fragment, thus producing an increasing deformity of the end of the bone.

The tendency to produce deformity can be prevented by accurate reduction of the experimental separation and by holding the fragments in position with some form of internal fixation, such as a transverse screw, between the two fragments of metaphysis. While the gap in the epiphyseal plate never completely heals, if it has been closed sufficiently bone does not seem to grow across it. In an experimental series in which accurate reduction was maintained, there was no deformity and little, if any, decrease in the length of this limb compared with the other side at the conclusion of growth (Figs. 12-A and 12-B).

SOME CLINICAL APPLICATIONS

Epiphyseal Separations

In this injury the growing cells remain in the epiphysis, and the prognosis is good unless the injury simultaneously damages the nutrient vessels to the epiphysis. Vascular damage occurs most readily in epiphyses that are entirely covered by articular cartilage. This accounts for the high incidence of avascular necrosis of the femoral head in slipped femoral epiphysis. When the blood supply to an epiphysis appears to be destroyed, avascular collapse can be prevented by deliberately removing the remnants of the plate from the epiphysis, thus facilitating more rapid reossification.

Healing of the epiphyseal separations when there is no vascular damage is very rapid and is complete in three weeks. Thus, there seems to be little indication for continuing external immobilization beyond this interval, particularly as the hinge effect of the periosteum makes the reduction stable.

Fractures That Cross the Epiphyseal Plate

In this type of injury the gap created in the epiphyseal plate fills with bone. Premature closure of the plate and a shortened extremity result. If there has been longitudinal displacement of the fragments, the limb will be deformed as well. Both shortening and deformity can be prevented, at least experimentally, by accurate reduction with internal fixation. It thus seems worth while to perform reduction in clinical cases, particularly if the child is young and considerable

FIG. 13

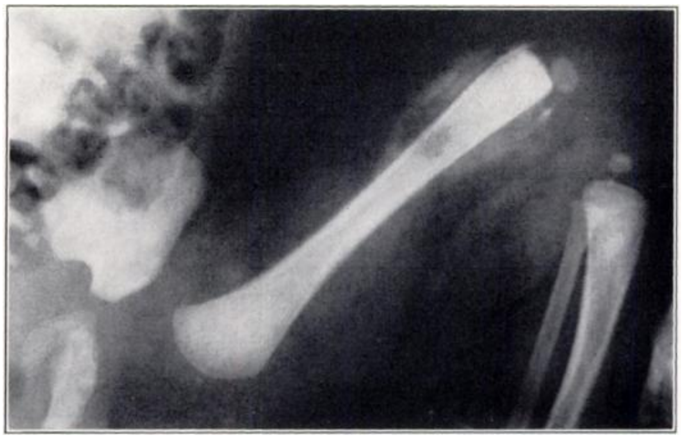


FIG. 14-A

Fig. 13: Type I epiphyseal-plate injury: separation of the epiphysis.

Fig. 14-A: Birth injury, lower femoral epiphysis (Type I). Roentgenogram made ten days after birth shows slight posterior displacement of the epiphysis and considerable subperiosteal formation of new bone.

FIG. 14-B

Roentgenogram made one year after birth injury shows virtually no deformity.

growth is anticipated. Because of the disastrous outcome when the blood supply to the epiphysis is damaged, such open procedures should be carefully performed, and if internal fixation is used it should be in the metaphysis rather than the epiphysis.

DIAGNOSIS OF EPIPHYSEAL-PLATE INJURIES

Clinical Diagnosis

While the accurate diagnosis of epiphyseal-plate injuries depends on roentgenographic examination, such an injury should be suspected clinically in any child who shows evidence of fracture near the end of a long bone, dislocation, ligamentous rupture, or even severe sprain of a joint. It must be remembered that an epiphysis may be displaced at the moment of injury and then return to its normal position, in which case clinical examination is likely to be of considerable importance in recognizing the nature of the injury. The history of the mechanism of injury, while often inadequate, may lead one to suspect a crushing type of epiphyseal-plate injury which is difficult to detect roentgenographically.

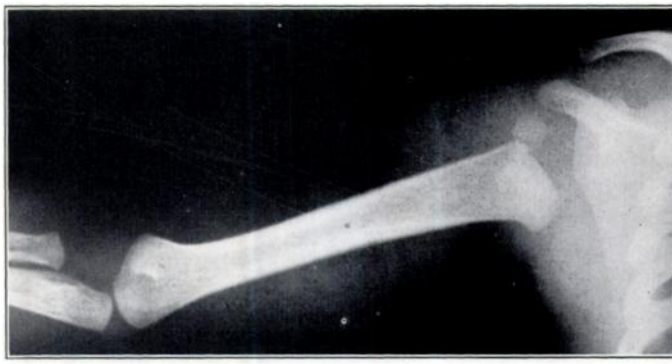


FIG. 15-A

FIG. 15-B

Fig. 15-A: Type I injury of the upper right humeral epiphysis in early childhood. Humeral epiphysis remains in normal relationship with glenoid cavity but not with metaphysis.
Fig. 15-B: After reduction, normal relationship between epiphysis and metaphysis is restored.

FIG. 15-C

Ten days after reduction subperiosteal new-bone formation is apparent. No subsequent disturbance of growth.

Roentgenographic Diagnosis

Accurate interpretation of the roentgenograms of bones and joints in children necessitates a knowledge of the normal appearance of epiphyses and epiphyseal plates at various ages. Two views at right angles to each other are essential, and if doubt still exists it is prudent to obtain comparable views of the opposite uninjured extremity. The diagnosis of separation of an epiphysis before its ossification center has appeared is very difficult, but such a separation can be suspected if there is displacement of the metaphysis and roentgenographic evidence of associated soft-tissue swelling.

Possible Effects on Growth of Injury Involving the Epiphyseal Plate

Fortunately, most epiphyseal-plate injuries are not associated with any disturbance of growth. After separation of an epiphysis through its epiphyseal plate there may be a slight and transient acceleration of growth, in which case no significant deformity ensues.

The clinical problem associated with premature cessation of growth depends

FIG. 16-A

FIG. 16-B

Fig. 16-A: Type I pathological separations of both lower femoral and tibial epiphyses. Note roentgenographic evidence of scurvy.
Fig. 16-B: Two weeks after administration of vitamin C. Note ossification of subperiosteal hematomata. No subsequent disturbance of growth.

on several factors including the bone involved, the extent of involvement of the epiphyseal plate, and the amount of remaining growth normally expected in the involved epiphyseal plate.

If the entire epiphyseal plate ceases to grow, the result is progressive shortening without angulation. However, if the involved bone is one of a parallel pair (such as tibia and fibula or radius and ulna), progressive shortening of the one bone will produce progressive deformity in the neighboring joint. If growth in one part of the epiphyseal plate ceases but continues in the rest of the plate, progressive angulatory deformity occurs.

Cessation of growth does not necessarily occur immediately after injury to the epiphyseal plate, and, indeed, growth arrest may be delayed for six months or even longer. Furthermore, there may be a period of retardation before growth ceases completely.

CLASSIFICATION OF EPIPHYSEAL-PLATE INJURIES

Epiphyseal-plate injuries have been classified both generally and specifically (for a given epiphysis) by several authors [1-5,9,16]. The following classification is based on the mechanism of injury and the relationship of the fracture line to the growing cells of the epiphyseal plate. The classification is also correlated with the prognosis concerning disturbance of growth.

Type I (Fig. 13)

There is complete separation of the epiphysis from the metaphysis without any bone fracture. The growing cells of the epiphyseal plate remain with the epiphysis.

This type, the result of a shearing or avulsion force, is more common in birth

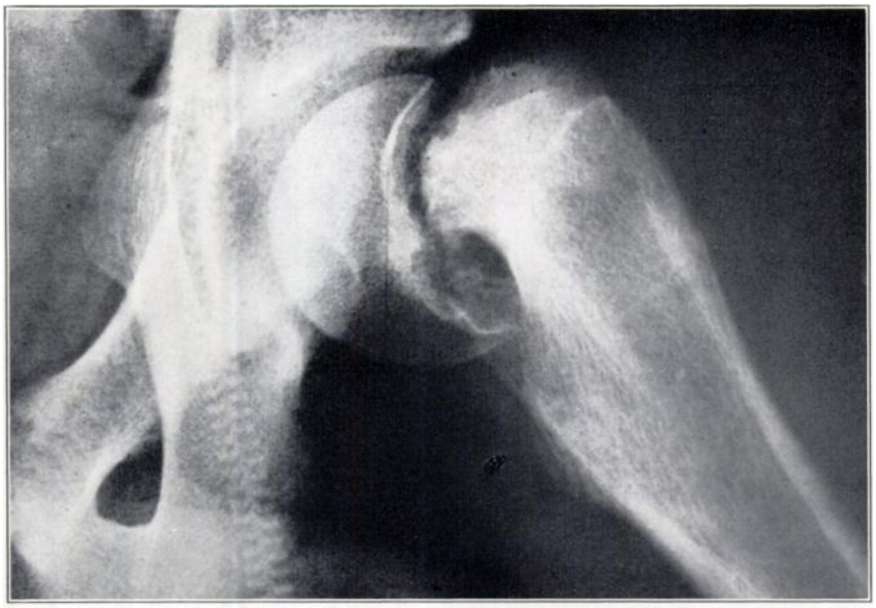


FIG. 17

Type I pathological separation of upper femoral epiphysis associated with endocrine imbalance.

FIG. 18-A

FIG. 18-B

Fig. 18-A: Obvious multiple fractures of the pelvis. Less obvious is the Type I traumatic separation of the right upper femoral epiphysis.

Fig. 18-B: Two months later, the right femoral head is dense, indicating avascular necrosis.

injuries (Figs. 14-A and 14-B) and in early childhood when the epiphyseal plate is relatively thick (Figs. 15-A, 15-B, and 15-C). It is also seen in pathological separations of the epiphysis associated with scurvy (Figs. 16-A and 16-B), rickets, osteomyelitis, and endocrine imbalance (Fig. 17). Wide displacement is uncommon because the periosteal attachment is usually intact.

Reduction is not difficult, and the prognosis for future growth is excellent unless the epiphysis involved is entirely covered by cartilage (for example, upper end of femur). In this case, the blood supply frequently is damaged with consequent premature closure of the epiphyseal plate (Figs. 18-A through 18-D).

Type II (*Fig. 19*)

In this commonest type of epiphyseal-plate injury, the line of separation

Fig. 18-C

Ten years after injury, there is marked shortening of femoral neck and coxa vara.

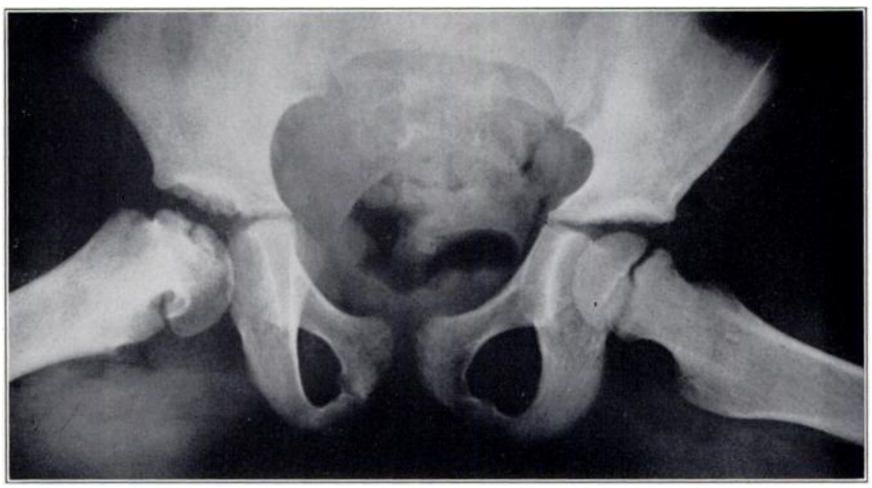


Fig. 18-D

Ten years after injury, there is residual coxa plana and marked shortening of femoral neck.

extends along the epiphyseal plate to a variable distance and then out through a portion of the metaphysis, thus producing the familiar triangular-shaped metaphyseal fragment sometimes referred to as Thurston Holland's sign. This injury usually occurs in children more than ten years old and is the result of either shearing injury or an avulsion force. The periosteum is torn on the convex side of the angulation but is intact on the concave side—the side on which the metaphyseal fragment is seen.

Reduction is relatively easy to obtain and maintain; because of the intact periosteal hinge and the metaphyseal fragment, overreduction cannot occur. The growing cartilage cells of the epiphyseal plate remain with the epiphysis; thus the prognosis for growth is excellent if the circulation to the epiphysis is intact, as it nearly always is (Figs. 20-A through 21-B).

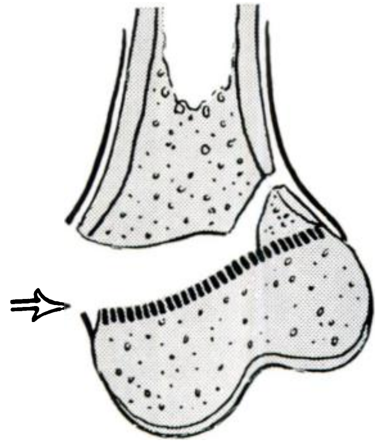


FIG. 19

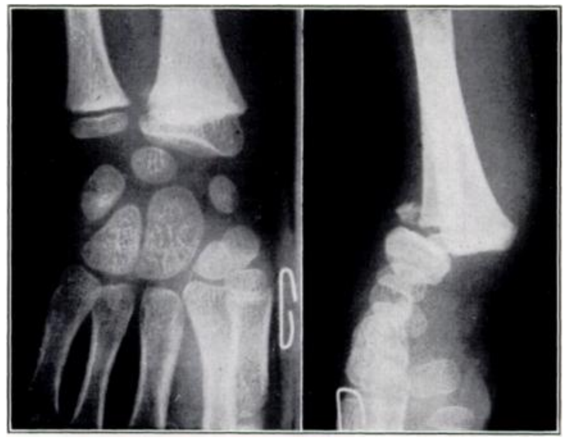


FIG. 20-A

Fig. 19: Type II epiphyseal-plate injury: fracture-separation of the epiphysis.
Fig. 20-A: Type II injury left lower radial epiphysis. Note the triangular metaphyseal fragment in lateral view.

FIG. 20-B

Type II injury right lower radial epiphysis in same patient with associated fracture lower end of ulna.

Type III (Fig. 22)

The fracture, which is intra-articular, extends from the joint surface to the weak zone of the epiphyseal plate and then extends along the plate to its periphery. This injury is uncommon, but when it does occur it is usually in either the upper or lower tibial epiphysis and is due to an intra-articular shearing force.

Accurate reduction is essential, not so much for the epiphyseal plate as for the restoration of a smooth joint surface. Open operation may be necessary to obtain such reduction (Figs. 23-A, 23-B, and 23-C). As in Type I and Type II injuries, the prognosis is good providing the blood supply to the separated portion of the epiphysis is intact (Figs. 24-A and 24-B).

Type IV (Fig. 25)

The fracture, which is intra-articular, extends from the joint surface through

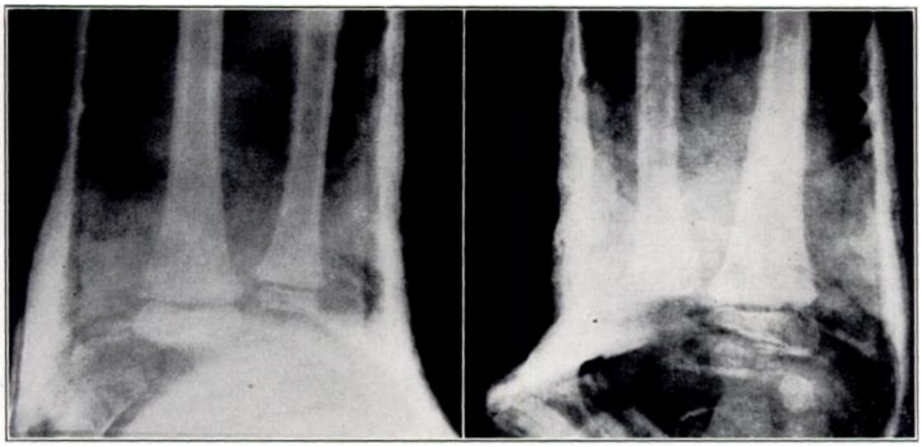


FIG. 20-C
Anteroposterior view of both wrists after closed reduction.

FIG. 20-D
Lateral view of both wrists after reduction. No subsequent growth disturbance.

FIG. 21-A
Type II injury lower tibial epiphysis. Note the large metaphyseal fragment.

the epiphysis, across the full thickness of the epiphyseal plate, and through a portion of the metaphysis, thereby producing a complete split. The commonest example of this type of injury is fracture of the lateral condyle of the humerus (Figs. 26-A and 26-B). Perfect reduction of a Type IV injury to the epiphyseal

FIG. 21-B

Position obtained by closed reduction. No subsequent disturbance of growth.

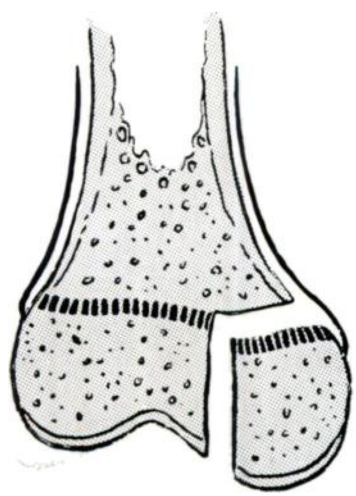


FIG. 22

FIG. 23-A

Fig. 22. Type III epiphyseal-plate injury: fracture of part of the epiphysis.
Fig. 23-A: Type III injury of anterolateral corner of the left lower tibial epiphysis, anteroposterior view.

plate is essential, for the sake not only of the epiphyseal plate but also of a smooth joint surface. Unless the fracture is undisplaced, open reduction is always necessary. The epiphyseal plate must be accurately realigned in order to prevent bone union across the plate with resultant local premature cessation of growth (Figs. 27-A and 27-B). If metal fixation is required to obtain stability, preferably it is placed across the metaphysis, although fine, smooth Kirschner wires which traverse the plate for a few weeks do not interfere with subsequent growth.

Type V (Fig. 28)

This relatively uncommon injury results from a very severe crushing force

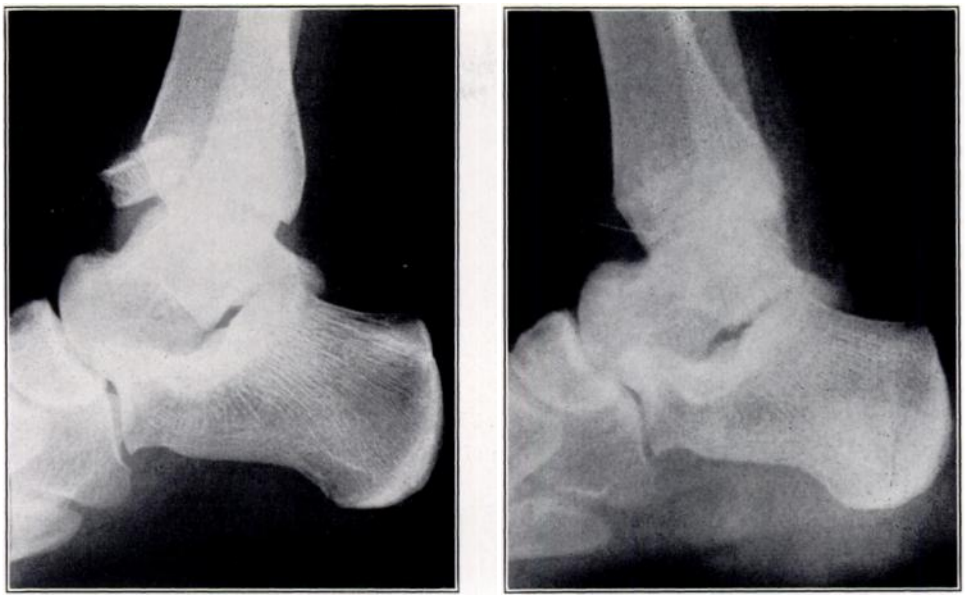


FIG. 23-B FIG. 23-C

Fig. 23-B: Lateral view.
Fig. 23-C: After open reduction. No internal fixation was necessary. (Wire is continuous intradermal wire suture in operative wound.) No subsequent disturbance of growth.

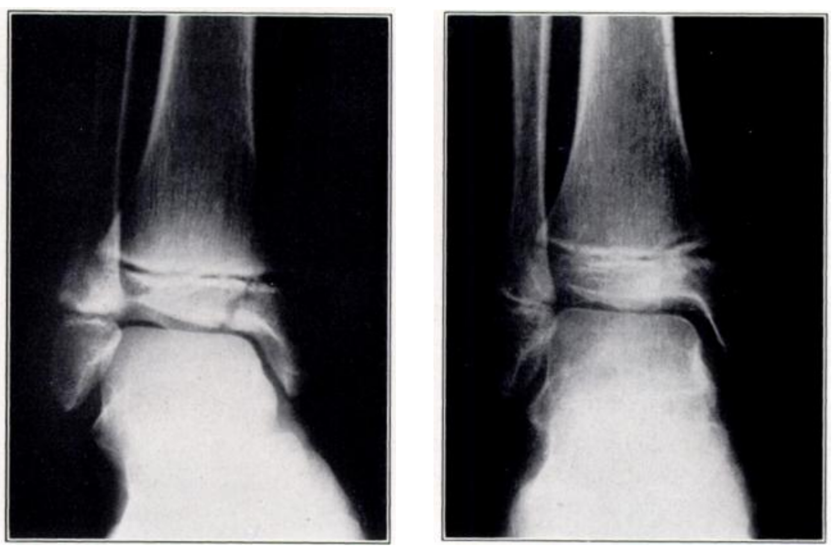
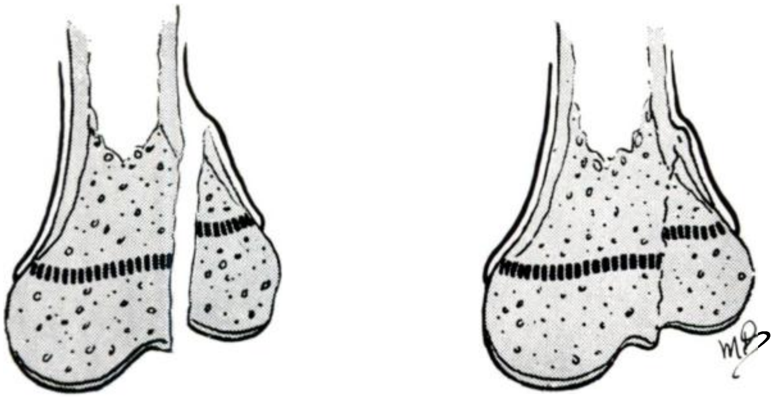


FIG. 24-A FIG. 24-B

Fig. 24-A: Type III injury of the medial portion of the right lower tibial epiphysis.
Fig. 24-B: Three months after closed reduction. Joint surface has been restored. No subsequent disturbance of growth.

applied through the epiphysis to one area of the epiphyseal plate. It occurs in joints which move in one plane only, such as the ankle or the knee. A severe abduction or adduction injury to a joint that normally only flexes or extends is likely to produce crushing of the epiphyseal plate, which may separate. Displacement of the epiphysis is unusual under these circumstances, and the first roentgenogram gives little indication of the seriousness of the injury; indeed, the injury may be dismissed as a sprain [17].

One must suspect crushing of the epiphyseal plate when such an injury is



A FIG. 25 B

Type IV epiphyseal-plate injury: *A*, fracture of the epiphysis and epiphyseal plate; *B*, bone union and premature closure.

FIG. 26-A FIG. 26-B

Fig. 26-A: Type IV injury right lateral condyle of humerus (capitellum). Injury should have been treated by open reduction.
Fig. 26-B: Premature closure of the epiphyseal plate of the lateral condyle (left) five years later.

sustained. Weight-bearing must be avoided for three weeks in the hope of preventing the almost inevitable premature cessation of growth. The prognosis in Type V epiphyseal-plate injuries is decidedly poor (Figs. 29 and 30).

PROGNOSIS CONCERNING DISTURBANCE OF GROWTH

Significant disturbance of growth follows approximately 10 per cent of epiphyseal-plate injuries, and minor growth disturbances are seen after a higher percentage of injuries [6]. Although it is not possible to make a prognosis in a given child with a particular epiphyseal-plate injury with absolute accuracy, several factors help considerably in the estimate.

Factors in Prognosis

Type of epiphyseal-plate injury: The type of injury described anatomically in the authors' classification is important prognostically. In general, Types I, II, and III injuries have a good prognosis for growth provided the blood supply of the epiphysis is intact. For instance, the blood supply is particularly vulnerable to injury in the head of the femur and the head of the radius. Type IV epiphyseal

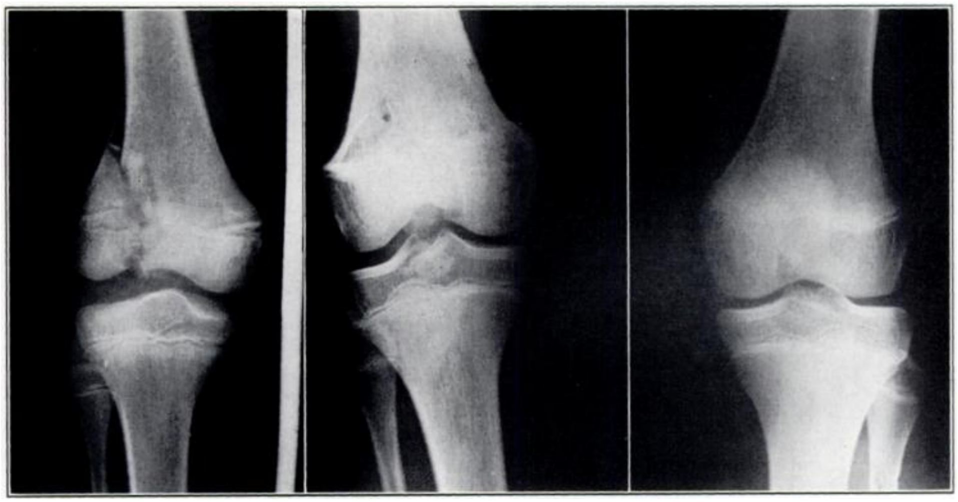
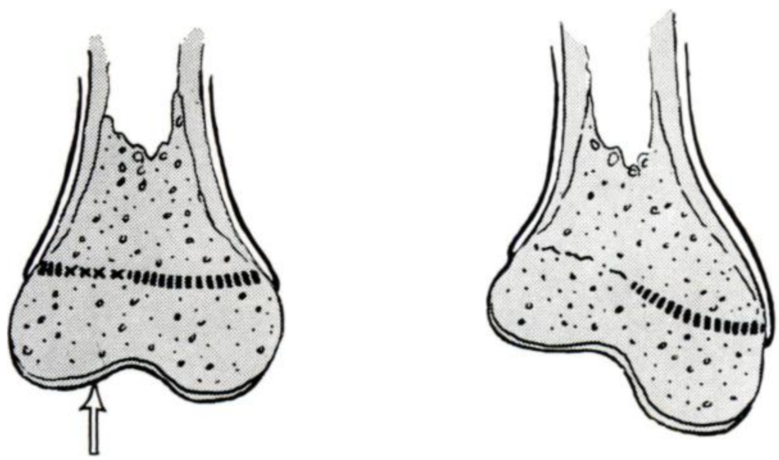


FIG. 27-A FIG. 27-B

Fig. 27-A: Type IV injury of lateral condyle of right femur. Injury should have been treated by open reduction to obtain completely accurate realignment of the epiphyseal plate and of the joint surface.

Fig. 27-B: Premature closure of the lower femoral epiphyseal plate with resultant shortening three years later.



A FIG. 28 B

Type V epiphyseal-plate injury: *A*, crushing of the epiphyseal plate; *B*, premature closure.

injuries carry a bad prognosis unless the epiphyseal plate is completely realigned. Type V injuries associated with actual crushing of the cartilaginous plate have the worst prognosis.

Age of the child at the time of injury: The age of the child is an indication of the amount of growth normally expected in the particular epiphyseal plate during the remaining years of growth. Obviously, the younger the child at the time of injury the more serious any growth disturbance will be, whereas even a serious injury incurred during the last year of growth will not produce a significant deformity since there is so little normal growth potential remaining.

Blood supply to the epiphysis: As we mentioned earlier, the epiphyseal plate is nourished by blood vessels of the epiphysis, and if this blood supply is destroyed the epiphyseal plate degenerates and growth ceases. Thus, interference with the blood supply to the epiphysis (a common complication of epiphyseal injuries of the femoral head and radial head) is associated with a poor prognosis.

Method of reduction: Unduly forceful manipulation of an epiphysis may injure

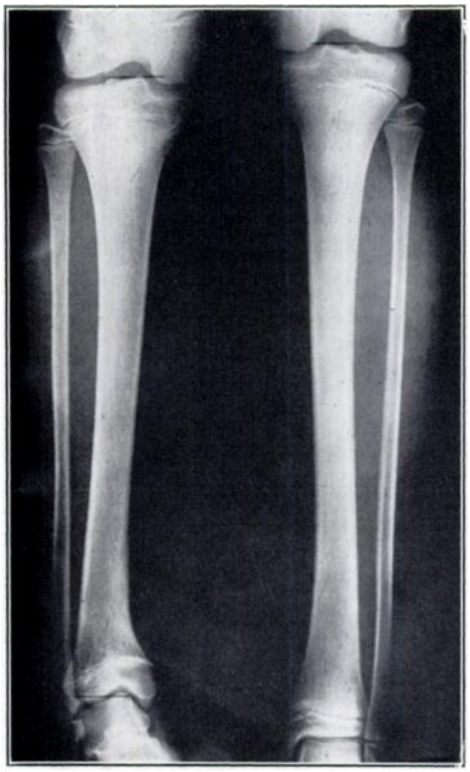


FIG. 29

FIG. 30

Fig. 29: Two years after Type V injury involving medial portion of right lower tibial epiphyseal plate. Note varus deformity of the right ankle and the discrepancy in leg length.

Fig. 30: Four years after Type V injury involving medial portion of the left upper tibial epiphyseal plate.

FIG. 31

Type II injury proximal phalanx of left ring finger. Note considerable rotational deformity at the fracture site.

the epiphyseal plate; this is particularly true if the manipulation is carried out after the tenth day following injury [13]. Likewise, the use of instruments to pry on an epiphyseal plate at time of open operation is deleterious to the plate. Screw nails or threaded wires which traverse the epiphyseal plate also increase the chances of premature cessation of growth.

Open or closed injury: Open injuries of the epiphyseal plate are uncommon. However, they have a poorer prognosis than closed injuries do because of the added factor of contamination and possible infection. If infection develops at the site of an epiphyseal-plate injury, the cartilaginous epiphyseal plate is usually destroyed by chondrolysis, and the prognosis is very poor indeed.

PRINCIPLES OF TREATMENT OF EPIPHYSEAL-PLATE INJURIES

Gentleness of reduction: In epiphyseal-plate injuries of Types I, II, and III, in contrast to fractures through bone, one of the fracture surfaces is composed of delicate, vulnerable cartilage of the epiphyseal plate. Consequently, unduly forceful manipulation of such an injury is to be avoided in order to prevent damage to the plate. This principle applies as well to surgical methods of reducing a displaced epiphysis at the time of open operation. No instrument should be used to pry a displaced epiphysis back into place.

Time of reduction: The best time to reduce an epiphyseal-plate injury is the day of the injury, since reduction becomes progressively more difficult with each day [10]. Indeed, after about ten days, the fragments, particularly in Type I and Type II, are difficult to shift without using excessive force. Under these circumstances, forceful manipulation may cause further damage to the cartilaginous plate and should be avoided; at this stage, therefore, it is wiser to accept an imperfect reduction than to risk the danger of either forceful manipulation or open operation. Corrective osteotomy can be performed later if necessary. In Type III and Type IV injuries, however, delayed reduction, although not desirable, is preferable to leaving the intra-articular fragment displaced.

Method of reduction—closed or open: The vast majority of Type I and Type II epiphyseal-plate injuries are readily reduced by closed means, and furthermore the reduction is easily maintained. Type III injuries may require open reduction to obtain a smooth joint surface, and displaced Type IV injuries nearly always require open reduction. When internal fixation is deemed necessary, it is preferable to place such fixation through the metaphysis rather than through the epiphysis. Although screws or threaded wires should never be inserted across the epiphyseal plate, fine, smooth Kirschner wires which cross the plate at right angles may be used safely, but they should be removed when the injury has healed [8]. Great care must be taken to avoid damage to the blood supply of the epiphysis.

Acceptable position of reduction: The contour of the epiphyseal plate is such that perfect reduction of Type I and Type II injuries is usually possible. If, however, there should be residual moderate displacement (anterior, posterior, medial, or lateral) or slight angulation, repeat manipulation is not necessary, since remodeling of the bone from the periosteum is adequate. The criteria for acceptable position are less rigid in the region of a multiplane joint, such as the shoulder, than in the region of a single plane joint, such as the knee or ankle. Type III and Type IV injuries must be perfectly reduced for reasons already mentioned.

Period of immobilization: Experience has shown that the three variations of epiphyseal separation (Types I, II, and III injuries) unite in approximately one-half the time required for union of a fracture through the metaphysis of the same bone in the same age group; therefore, the period of immobilization may be reduced correspondingly. This interesting phenomenon that has already been described in the experimental investigation is due to the unique process of healing in these injuries. Type IV injuries, by contrast, and because of their location, require the same period for union as metaphyseal fractures.

Indication of prognosis to the parents: In a given epiphyseal-plate injury, the prognosis concerning growth disturbance should be considered, at least in general terms, as described earlier. Part of the surgeon's responsibility in the treatment of these injuries is to provide the parents with some indication of the prognosis without causing them undue anxiety. The importance of follow-up examination needs to be stressed.

Follow-up observation: The need for regular follow-up observation of epiphyseal-plate injuries is obvious; just how long a period of observation is required is not always obvious. Since growth disturbance may be delayed, at least in its manifestations, for as long as one year, this period of observation is the minimum [11]. Six months after injury the injured bone and its opposite number in the normal uninjured extremity should be examined roentgenographically. If little growth has occurred in the normal, uninjured bone during this six-month period, a further six-month period must elapse before one can say with certainty that there is no disturbance of growth.

MANAGEMENT OF DEFORMITY DUE TO PREMATURE CESSATION OF GROWTH

After an epiphyseal-plate injury, local growth may either cease immediately or it may continue at a retarded rate for a variable period before complete cessation. Furthermore, the growth disturbance may involve either the entire epiphyseal plate or only one part of it. The resultant deformity is progressive until the end of the child's growing period. Thus, the gravity of the clinical problem depends on several factors, including the site of growth disturbance, the extent of involvement of the epiphyseal plate, and the expected amount of growth remaining in the involved plate. The main types of deformity that may develop are progressive angulation, progressive shortening, and a combination of both. Considerable judgment is required in planning the most effective management of these progressive deformities.

Progressive angulation: Retardation or cessation of growth in one area of the epiphyseal plate with continuation of growth in the remainder produces gradually increasing angulation. In this circumstance, growth in the remainder of the plate eventually ceases prematurely. Thus, the problem of shortening is added to that of angulation. It is usually preferable to deal with progressive angulation by open wedge osteotomy in order to preserve the growing potential of the undamaged portion of the epiphyseal plate and to gain some length in the extremity. Unless the entire epiphyseal plate has ceased growing, the osteotomy should overcorrect the deformity so that its inevitable recurrence may be delayed. When progressive angulation exists in a young child, it may be necessary to perform osteotomy more than once. Epiphyseal arrest by stapling may help to correct increasing angulation but only if the damaged area of the epiphyseal plate is still growing. However, this method has the disadvantage of producing further shortening of the involved extremity.

Progressive shortening: If one of two paired bones (radius or ulna, tibia or fibula) is the site of premature cessation of growth, the resultant discrepancy in length between the two bones will produce a progressive deformity (varus or valgus) of the nearest joint. For example, premature cessation of growth at the lower radial epiphyseal plate in the presence of continued growth at the lower ulnar epiphysis will produce an increasing valgus deformity or radial deviation of the hand. Therefore, it may be necessary either to lengthen the shorter bone surgically or to shorten the longer bone, and at the same time to arrest the growing epiphysis to prevent recurrence of deformity. When a single bone (femur or humerus) is the site of increasing shortening the problem is of discrepancy of limb length which is significant only in the lower extremity. Discussion of the various indications and methods for equalization of limb length is beyond the scope of this presentation.

SPECIFIC EPIPHYSEAL-PLATE INJURIES

A general knowledge of injuries to the epiphyseal plate is applicable to each specific site of injury. Nevertheless, since the specific epiphyses and their plates have various anatomical features, and since the forces applied to them differ, a few practical points concerning specific injuries merit mention.

Upper Extremity

Phalangeal Epiphyses

The epiphysis of the distal phalanx may be separated by sudden flexion injury in childhood. Clinically, the child's finger resembles a mallet or baseball finger since the flexor digitorum profundus tendon flexes the metaphysis into which it is inserted while the extensor tendon, being inserted into the epiphysis, maintains the epiphysis in the extended position. A lateral roentgenogram of the finger is needed to differentiate this type of epiphyseal-plate injury from a ruptured extensor tendon; the latter is uncommon in childhood, since the epiphyseal plate is weaker than the tendon. The epiphyseal displacement is readily reduced, and the reduction is easily maintained by a plaster splint for three weeks.

Epiphyseal-plate injury at the base of the proximal or middle phalanx is uncommon, but when it occurs it may be associated with considerable rotation at the line of separation (Fig. 31). The rotational deformity must be accurately reduced so the involved finger will be in proper relationship with its neighbors in both the flexed and extended positions.

Lower Radial Epiphysis

The lower end of the radius is by far the commonest site of epiphyseal-plate injury. The injury, almost invariably Type II, usually occurs in children more than ten years old and is comparable to the common Colles fracture in adults. In the epiphyseal-plate injury, however, there is little fracture hematoma, and local anesthesia is unsatisfactory. Reduction should be performed using general anesthesia. Reduction is readily obtained, the intact hinge of periosteum on the dorsal aspect of the radius preventing overcorrection (Figs. 20-A through 20-D). The plaster cast should extend above the elbow and be well molded, with the forearm pronated and the wrist ulnar deviated and slightly flexed. Immobilization for three weeks is adequate.

Prognosis is good, even if there is slight residual angulation, because remodeling at this site is very satisfactory; late osteotomy is seldom indicated [1]. In more severe injuries of the wrist the lower ulnar epiphyseal plate also may be separated.

Upper Radial Epiphysis

The common type of injury at this site is Type II, produced by a valgus force on the elbow, with resultant angulation of the radial head (Figs. 32-A, 32-B, and 32-C). Unless the angulation is extreme, reduction usually can be obtained by holding the extended elbow in varus and pressing directly over the radial head. If there is more than 15 degrees residual angulation after closed reduction, the radiohumeral joint will not function smoothly, and permanent limitation of supi-

FIG. 32-A

FIG. 32-B

Fig. 32-A: Type II injury left upper radial epiphysis from an abduction injury. Note the valgus deformity at the fracture site.
Fig. 32-B: Position obtained by closed reduction.

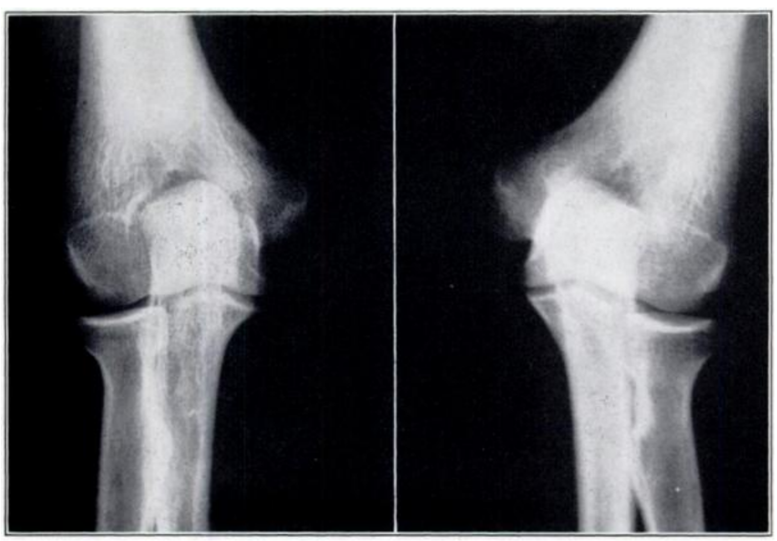


FIG. 32-C
Ten years later, there is no disturbance of growth.

nation and pronation may result. With this much angulation after manipulation, open reduction is indicated. The radial head should never be excised in children because the resultant loss of growth in the radius inevitably will produce progressive radial deviation at the wrist joint and progressive valgus deformity at the elbow.

A less common, but more serious, injury of the upper radial epiphysis is complete separation of the radial head with wide displacement and associated dislocation of the elbow joint. Open reduction is indicated, but even though the radial head is devoid of soft-tissue attachment—and therefore devoid of blood supply—it should be replaced. Premature closure of the epiphyseal plate is inevitable because of interference with blood supply, but since this type of injury usually occurs in an older child significant deformity is rare.

Lower Humeral Epiphysis (Lateral Condyle)

Fracture of the lateral condyle of the humerus (capitellum) is a Type IV injury of the epiphyseal plate, and as such it is a serious injury with potential problems related to union and growth [7]. Even when the initial displacement of the capitellum is slight, it tends to increase during the ensuing period of immobilization; weekly roentgenographic examinations are necessary to be sure that progressive displacement does not occur.

When the fracture is displaced, open reduction is clearly indicated, not only to restore a smooth joint surface but also to realign the epiphyseal plate (Fig. 33). Internal fixation may be obtained either by multiple sutures in the periosteum or

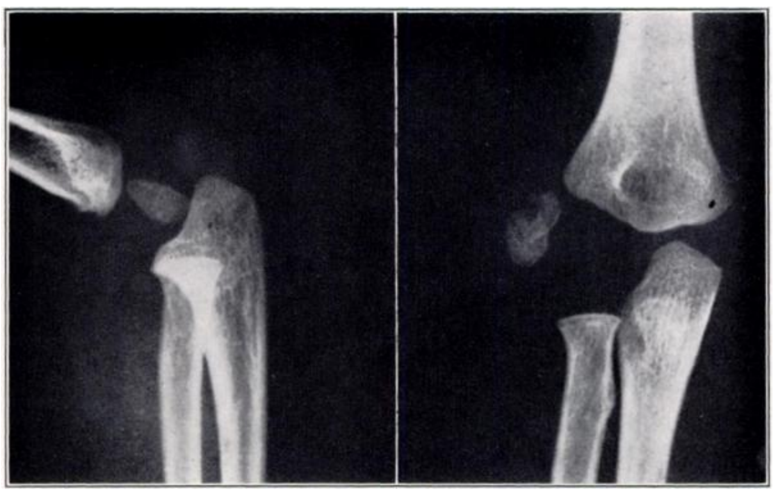


FIG. 33

Type IV injury of lateral condyle (capitellum) of right humerus with rotation and angulation of fragment. This injury must be treated by open operation.

by two fine removable Kirschner wires. The elbow should be immobilized for three weeks at 90 degrees; a more flexed position tends to displace the capitellum laterally. Failure to obtain or maintain accurate reduction of the fractured lateral condyle inevitably results either in delayed union, in non-union with secondary overgrowth of the radial head, or in premature cessation of growth with progressive valgus deformity of the elbow and tardy ulnar-nerve paralysis (Fig. 26).

Upper Humeral Epiphysis

Epiphyseal-plate injuries at the upper end of the humerus are either Type I, in young children, or Type II, in children more than ten years old (Fig. 34-A and 34-B). The wide range of circumduction at the shoulder joint probably explains the absence of Types III, IV, and V injuries at this site. Reduction may be difficult because of inability to control the mobile head of the humerus, but traction on the humerus with the arm in the overhead position usually will reduce the displacement. Perfect reduction is not necessary, since remodeling of the upper end of the humerus from the periosteal tube is very satisfactory [7]. Open reduction is almost

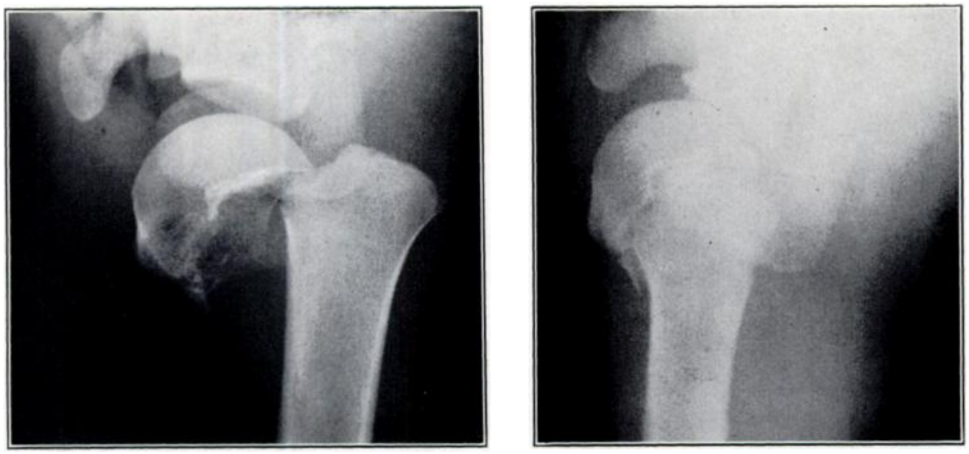


FIG. 34-A FIG. 34-B

Fig. 34-A: Type II injury of left upper humeral epiphysis, demonstrated by supero-inferior roentgenogram with arm abducted.

Fig. 34-B: Position obtained and maintained by closed reduction. No subsequent disturbance of growth.

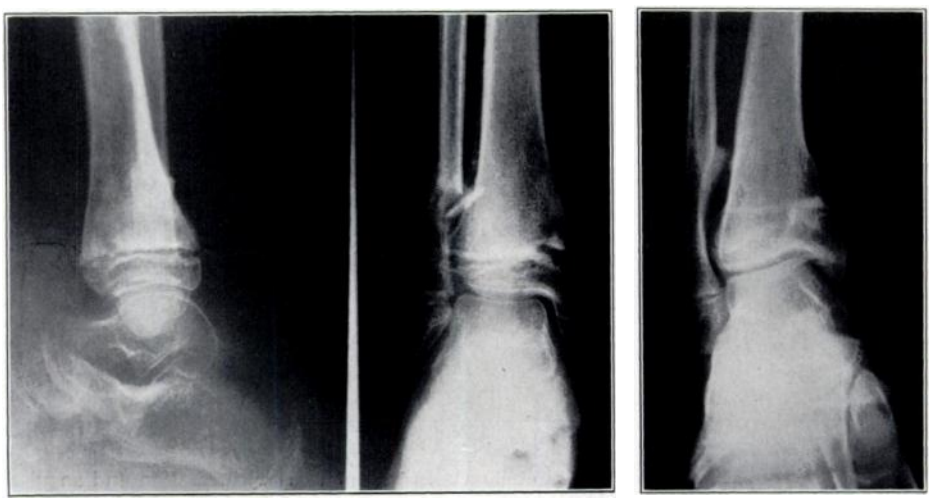


FIG. 35-A FIG. 35-B

Fig. 35-A: Type V injury involving right lower tibial epiphysis with associated fracture of the fibula. Note the relatively slight displacement of the tibial epiphysis.

Fig. 35-B: One year later, there is varus deformity of the ankle owing to premature closure of the medial portion of the lower tibial epiphyseal plate. The lateral portion of the epiphyseal plate is almost closed and fibular overgrowth is already apparent.

never necessary, except on rare occasions when the long head of the biceps becomes trapped in the fracture site [16]. After reduction, the shoulder should be immobilized for three weeks in the "salute position" in a full shoulder spica cast and protected by a sling for a further week.

Lower Extremity

Lower Tibial Epiphysis

The lower tibial epiphyseal plate is subjected to a variety of injuries, because, in contrast to the shoulder, the ankle joint moves in only one plane and is very stable in all other planes [9]. Type II injuries of the lower tibial epiphysis usually can be managed by closed reduction (Figs. 21-A and 21-B). Type III injuries, which occur more frequently at this site than elsewhere, require perfect reduction in order to restore a smooth joint surface; open operation thus may be necessary (Figs. 23-A, 23-B, and 23-C). The lower tibial epiphysis is also the commonest site of the crushing Type V injury, which in the ankle is usually the result of a severe varus force. This kind of injury consistently carries a poor prognosis for growth (Figs. 29, 35-A, and 35-B). Since there may be little or no displacement of the epiphysis in the Type V injury, the child may be considered to have simply a severe sprain of the ankle [17]; the true nature of the injury may not be suspected until premature cessation of growth is established.

Upper Tibial Epiphysis

The epiphyseal plate of the upper tibial epiphysis is quite irregular and includes the long anterior tongue of the tibial tubercle; hence, epiphyseal separa-

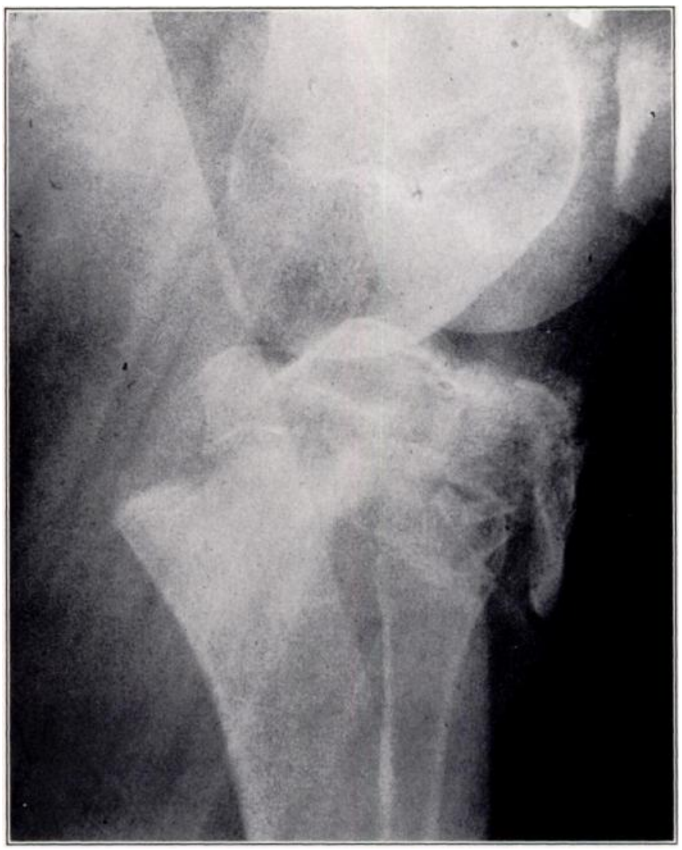


FIG. 36

Type II injury of the upper tibial epiphysis resulting from a severe automobile accident. This injury was complicated by serious damage to the popliteal artery.

tions at this site are uncommon and occur only as a result of very severe injury (Fig. 36). The popliteal vessels may be seriously damaged particularly with a hyperextension injury. Reduction sometimes can be obtained by closed means, but any coexistent major vascular injury necessitates open operation. A Type V injury of the upper tibial epiphysis may result from a severe abduction or adduction injury (Fig. 30).

Lower Femoral Epiphysis

The lower femoral epiphysis is the largest of the pressure epiphyses, and it is

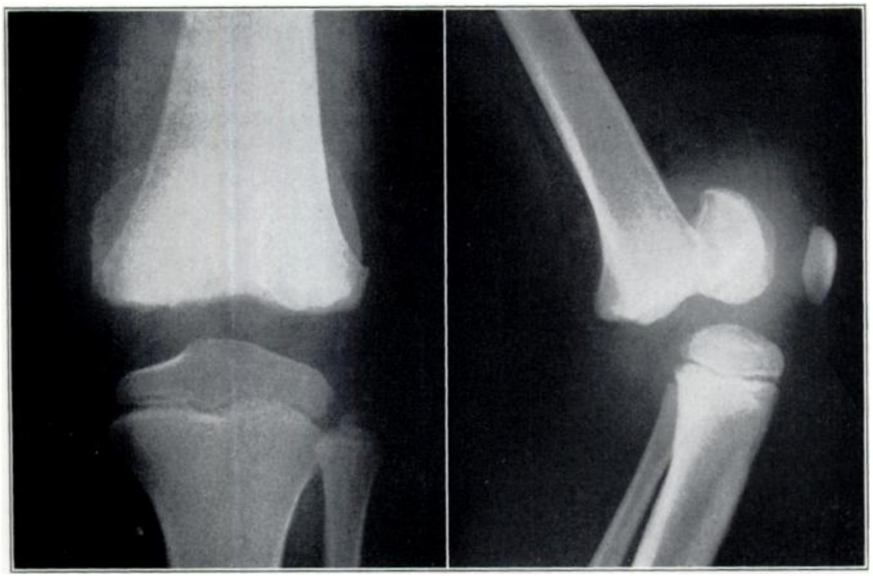


Fig. 37-A

Hyperextension Type II injury of left lower femoral epiphysis. Note the forward displacement of the femoral epiphysis.

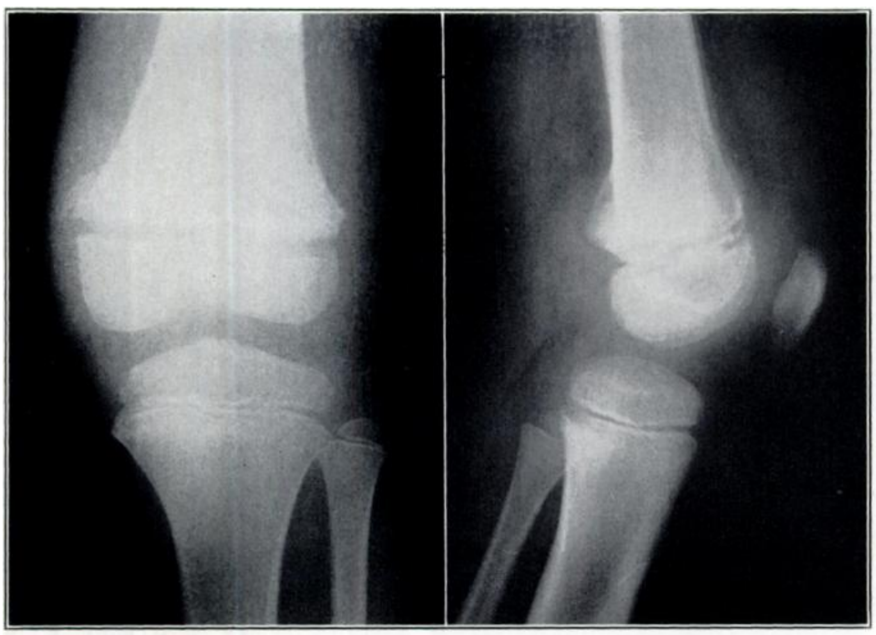


Fig. 37-B

Position obtained and maintained by closed reduction. No subsequent disturbance of growth.

the only one that exhibits an ossification center at birth [5]. Birth injuries of this epiphysis are usually associated with difficult delivery with extended breech presentation. Because this is a Type I injury there is a good prognosis (Figs. 14-A and 14-B). The lower femoral-epiphyseal plate, being a site of rapid skeletal growth, is frequently the site of Type I separation in scurvy (Figs. 16-A and 16-B).

In older children, a severe injury that would rupture a major ligament of an adult knee produces a Type II injury of the epiphyseal plate, since the plate is weaker than the ligaments. For example, the child who appears to have suffered a complete tear of the medial collateral ligament is more likely to have separation of the lower femoral epiphysis. If doubt exists and the initial roentgenogram is not helpful, a roentgenogram of the knee made in a valgus position will reveal the site of abnormal movement.

A serious injury of the lower femoral epiphysis is the hyperextension type with forward displacement of the epiphysis [18] (Figs. 37-A and 37-B). The posterior corner of the metaphysis is driven backward against the popliteal vessels. Sufficiently serious vascular injury may result that surgical exploration is indicated. This hyperextension injury is comparable in many ways to the hyperextension type of supracondylar fracture of the humerus. Reduction of the displacement is most readily obtained by placing the patient face down, applying traction on the semibent knee, pushing the proximal fragment forward, and then flexing the knee. The reduction is most stable with the knee flexed to at least 90 degrees but the circulation of the leg must be watched very closely. The flexion at the knee may be reduced after ten days. In any case, the total period of immobilization should not exceed three weeks, since flexion contracture of the knee associated with longer periods of immobilization may be very resistant to treatment.

The lower femoral epiphysis may also be the site of the serious Type IV injury which carries a poor prognosis unless perfect reduction is obtained. The joint surfaces and the epiphyseal plate must be accurately realigned in order to avoid both degenerative joint disease and premature cessation of growth; open operation and temporary internal fixation are usually required.

Upper Femoral Epiphysis

Epiphyseal-plate injuries at this site are always Type I. Traumatic separation of the femoral head may result from a birth injury, in which case the diagnosis is difficult, since at this time the entire head, being cartilaginous, is radiolucent. The clinical picture and the roentgenograms may suggest congenital dislocation of the hip, but the presence of slight crepitus indicates that epiphyseal separation has occurred. Within a week of the injury, the roentgenogram reveals new-bone formation which establishes the diagnosis with certainty.

The prognosis is poor in traumatic separation of the upper femoral epiphysis because of the frequently associated disruption of its blood supply and resultant avascular necrosis [7]. Since the epiphyseal plate receives its nutrition from the epiphyseal side, avascular necrosis of the femoral head results in death of the epiphyseal plate and consequent premature cessation of growth. Thus, the problem of progressive coxa vara is superimposed upon that of avascular necrosis of the femoral head (Figs. 18-A through 18-D). The displacement can usually be reduced by closed means. Reduction is best maintained by the insertion of removable threaded wires that pass through the neck and traverse the epiphyseal plate.

Pathological separation of the upper femoral epiphysis (slipped upper femoral epiphysis), either gradual or acute, is not within the scope of this presentation.

INJURIES INVOLVING TRACTION EPIPHYSES

The tendinous attachment of muscle origins or insertions into bone via Sharpey's fibers is so secure that when a sudden traction force is applied to the tendon it does not pull out of bone; instead, the force avulses a fragment of bone. During childhood, the weakest point at the insertion or origin of a muscle is the epiphyseal plate of the traction epiphysis; therefore, a sudden and severe traction force avulses the traction epiphysis through its plate.

Since a traction epiphysis does not contribute to longitudinal growth of the bone to which it is attached, any growth disturbance of its epiphyseal plate is not associated with deformity. If the epiphysis is accurately replaced, the epiphyseal plate becomes united to the shaft of the bone as it does after injuries to a pressure epiphysis; however, if the epiphysis remains displaced it becomes attached to the parent bone by fibrous union.

Certain of the traction epiphyses are particularly vulnerable to avulsion injuries and these will be discussed briefly.

Medial Epicondyle of the Humerus

The medial epicondyle of the humerus, being the site of origin of the common flexor muscles of the forearm, may be avulsed by a severe valgus or abduction injury of the elbow (Fig. 38). When the injury is not severe, the resultant displacement of the medial epicondyle is slight, and the elbow joint remains stable. Clinically, the diagnosis is suggested by the presence of swelling and tenderness over the medial aspect of the elbow. If the roentgenographic diagnosis is doubtful

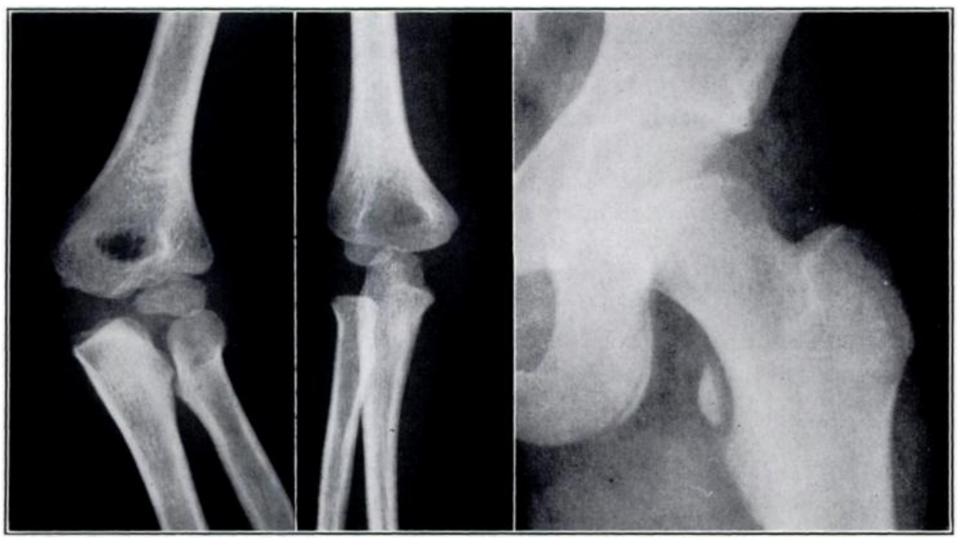


FIG. 38 FIG. 39 FIG. 40

Fig. 38: Traumatic separation (avulsion) of medial epicondyle of left humerus—a traction epiphysis.
Fig. 39: Traumatic separation of medial epicondyle of right humerus in a three-year-old child. The ossification center of the medial epicondyle has not yet appeared. Only roentgenographic evidence of injury is an increased soft-tissue shadow on the medial aspect of the elbow. The diagnosis was readily made by physical examination.
Fig. 40: Traumatic separation of the lesser trochanter of the left femur. The residual soft-tissue attachment of the iliopsoas muscle to the femur prevents marked displacement of the lesser trochanter.

a comparable view of the opposite elbow is very helpful. When this injury occurs in a child less than four years old, that is, before the cartilage of the medial epicondyle is ossified, the diagnosis must be made on clinical grounds alone (Fig. 39).

The extent of the injury, as indicated by the degree of instability of the elbow, is best determined by applying a valgus or abduction force to the extended elbow with the child under general anesthesia. If the elbow joint is stable, conservative treatment consisting of three weeks' immobilization with the elbow at slightly less than 90 degrees of flexion is indicated. In more severe injuries, the elbow joint is dislocated, and the medial epicondyle is widely displaced.

Occasionally the elbow joint will snap back into place and trap the medial epicondyle in the joint. Under these circumstances, the epicondyle can usually be pulled out of the joint by abducting the elbow joint, at the same time applying traction on the common flexor muscle origin by supinating the forearm and extending the wrist, while the child is under anesthesia. The more severe traction injuries of the medial epicondyle are associated with lateral instability of the elbow joint which is readily detectable in an anesthetized child. In marked instability, best results are obtained by open operation in which the epicondyle is either sutured securely into place by its periosteal attachments or is held in place by a removable Kirschner wire. Severe injuries frequently are associated with a traction injury of the ulnar nerve, which usually recovers completely.

Tibial Tubercle

During childhood, the downward, tongue-like projection of the upper tibial epiphysis constitutes the tibial tubercle and represents the traction epiphysis of the quadriceps muscle. Sudden contraction of the quadriceps against resistance may avulse a varying amount of this projection. When a large portion of the tibial tubercle is widely separated, open operation is indicated. More commonly, the separation is slight and immobilization of the knee in extension is adequate. Minor degrees of separation of the tibial tubercle probably account for the clinical condition commonly referred to as Osgood-Schlatter disease.

Lesser Trochanter of the Femur

The powerful iliopsoas muscle is inserted into the femur primarily via its traction epiphysis, the lesser trochanter, but it also gains attachment by an extension of the tendon into the periosteum of the shaft. Sudden abduction and extension of the hip may result in avulsion of the lesser trochanter, but the remaining periosteal attachment prevents marked displacement (Fig. 40). Clinically, relatively little disturbance is associated with this injury, and the only treatment indicated is rest in bed with the hip flexed until discomfort subsides, after which the patient may be allowed to resume activities.

Traction Epiphyses of the Pelvis

A sudden powerful contraction of the hamstring muscle group, for instance, during strenuous athletic activities, may avulse their site of origin, the epiphysis of the ischium. The displacement is seldom great, and the injury usually heals with abundant formation of bone. Weight-bearing should be avoided for three weeks.

The anterior superior spine, which is the traction epiphysis of the sartorius muscle, and the anterior inferior spine, which is the traction epiphysis of the rectus femoris muscle, may be avulsed by sudden contraction of the attached muscle. In either case, symptomatic treatment consisting in local rest for three weeks with the hip in flexion is sufficient.

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The Biological Effect of Continuous Passive Motion on the Healing of Full-Thickness Defects in Articular Cartilage

An Experimental Investigation in the Rabbit*†

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Abstract: A new concept, *continuous passive motion of a synovial joint in vivo*, was investigated to determine its biological effect on the healing of full-thickness articular cartilage defects that penetrate the subchondral bone of knee joints of adolescent and adult rabbits. The effect of continuous passive motion was compared with the effects of immobilization and of intermittent active motion. This investigation included assessment of 480 defects in the knees of 120 adolescent rabbits and assessment of 108 defects in the knees of twenty-seven adult rabbits. The continuous passive motion was well tolerated by these animals, whose general well-being was undisturbed.

The healing of the defects at weekly intervals up to four weeks was assessed by gross examination and by an analysis of two indices of healing determined by light microscopy: (1) the nature of the reparative tissue, and (2) the degree of metachromasia of the matrix as demonstrated by toluidine-blue staining.

At three weeks this assessment revealed that in the adolescent rabbits, healing of the defects by hyaline articular cartilage was present in 8 per cent of forty defects in ten animals whose knees were immobilized, in 9 per cent of forty defects in ten animals whose knees were permitted intermittent active motion, and in 52 per cent of forty defects in ten animals whose knees were managed immediately after operation by continuous passive motion. At three weeks, in the adult animals, healing of the defects by hyaline articular cartilage was present in 3 per cent of thirty-six defects in nine animals whose knees were immobilized, in 5 per cent of thirty-six defects in nine animals whose knees were permitted intermittent active motion, and in 44 per cent of thirty-six defects in nine animals whose knees were managed immediately after operation by continuous passive motion.

Thus, the metaplasia of the healing tissue within the defects from undifferentiated mesenchymal tissue to hyaline articular cartilage was not only much more rapid but also much more complete with continuous passive motion than with either immobilization or intermittent active motion.

Clinical Relevance: The results of the present investigation emphasize that neither immobilization nor intermittent active motion provides an adequate stimulus for the healing of full-thickness defects by articular cartilage. Although the biological effect of continuous passive motion on the healing of such defects was strikingly beneficial, it must be emphasized that none of the rabbits was allowed to resume normal activity after the completion of the experiment, which lasted for from one to four weeks. Thus, it remains to be determined whether or not the integrity of this newly formed reparative tissue will be maintained when it is subjected to normal weight-bearing activity for long periods.

In the current era of increasing emphasis on total joint excision and joint replacement by man-made prosthetic devices in the treatment of human arthritis, it is still important to continue basic investigations of the *preventive* aspects of degenerative arthritis, with particular emphasis on the possibility of stimulating the healing and regeneration of articular cartilage. Thus, we concur with the 1971 editorial comment of Cruess[11], who stated that: "it seems necessary to revise our approach to damaged cartilage and to attempt to provide the best conditions for repair in the hope that natural processes can be enhanced and so-called reconstructive procedures avoided."

Two considerations are relevant as background information: first, the known limited healing and regenerative power of articular cartilage, and second, the continuing controversy concerning the indications for rest and for motion in the management of disorders and traumatic le-

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sions of synovial joints. An extensive review of the literature is not within the scope of the present paper, but there are numerous publications concerning the limited healing and regenerative powers of articular cartilage[4,5,7-9,13,19,20,27-29,32,33,35,37-45,48-50,54,57,59] as well as publications concerning the indications for rest and motion, both on the basis of empiricism[1,6,12,25,29,36,47,58,64] and on the basis of scientific investigations[2,14-18,22,26,30,31,51-53,60,61]. However, the biological effect on healing of *continuous passive motion of a synovial joint in vivo* has never been investigated.

Our hypothesis was that continuous passive motion of a synovial joint *in vivo* would have a beneficial biological effect on the healing of full-thickness defects in articular cartilage. The purpose of our experimental investigation was to test the validity of this hypothesis.

Experimental Design

Adolescent (almost fully grown but epiphyseal plates still open) male New Zealand White rabbits weighing 2.3 to 3.0 kilograms were studied in the first phase of the investigation. Adult (fully grown with closed epiphyseal plates) male rabbits of the same breed weighing 4.0 to 5.0 kilograms were used in the second phase of the study.

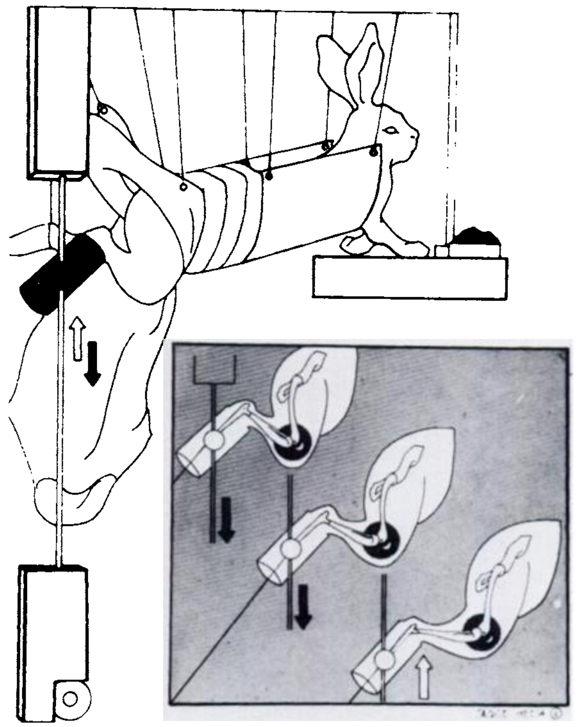

FIG. 2

Drawing of a rabbit's right hind limb in the continuous passive motion apparatus. The actual range of motion used was an arc of 70 degrees (from 40 degrees to 110 degrees of flexion).

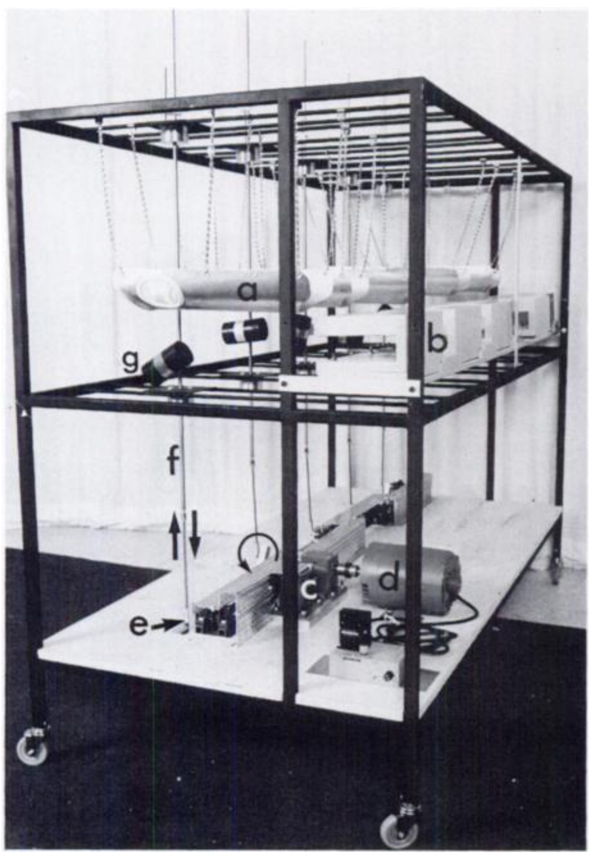

FIG. 1

Apparatus designed to suspend five rabbits and provide continuous passive motion of the right knee of each (mechanism of action described in text). *a*, Suspended padded aluminum half-shell to support body of rabbit; the two openings allow the rabbit's hind limbs to protrude. *b*, Containers for food and water. *c*, Reduction gear box. *d*, One-quarter-horsepower electric motor. *e*, Offset cam. *f*, Vertical rod linked to offset cam and to which is attached the cylindrical plastic cup (*g*) that encases the rabbit's right hind foot.

FIG. 3

The four standard sites of the one-millimeter-diameter full-thickness defects in the articular cartilage and subchondral bone of the distal end of the right femur at the time of operation: patellar groove, anterior and middle parts of the medial femoral condyle (right), and lateral femoral condyle (left). The patella has been temporarily dislocated laterally.

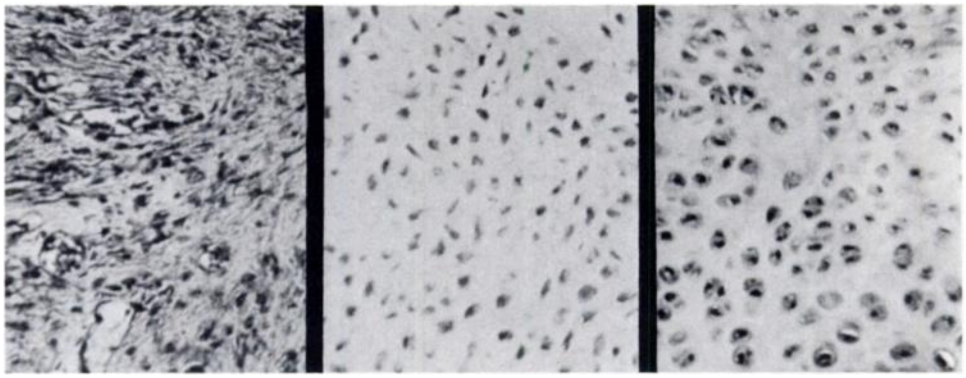

FIG. 4

Index of healing — nature of the reparative tissue (hematoxylin and eosin, × 200). Left: Vascular fibrous tissue containing spindle-shaped fibroblasts. Center: Incompletely differentiated mesenchymal tissue composed of plump cells that are beginning to differentiate toward chondrocytes. Right: Hyaline articular cartilage containing chondrocytes in lacunae.

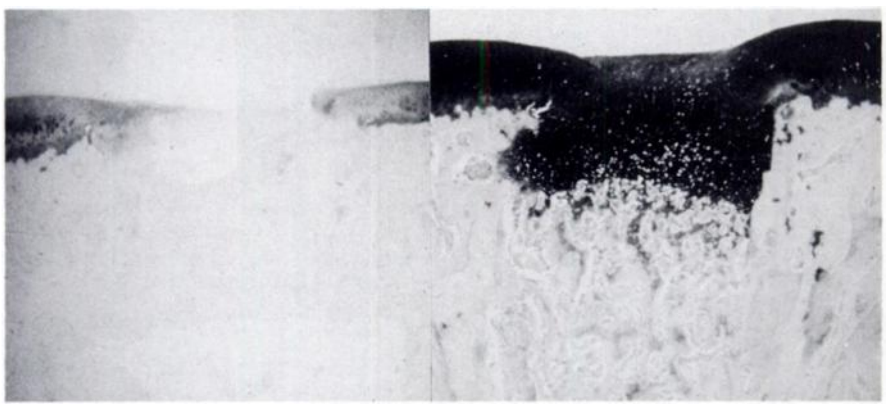

FIG. 5

Index of healing — degree of metachromasia of the matrix (toluidine blue, × 27). Left: No staining. Right: Near-normal staining compared with that of the intact articular cartilage beyond the edges of the defect.

Continuous Passive Motion Apparatus

A special apparatus was designed that would provide continuous passive motion of one knee of each of five rabbits at the same time (Fig. 1). A padded aluminum half-shell, which was suspended from the frame of the apparatus by adjustable chains, supported the body of each rabbit; the hind limbs protruded through two openings. Containers for food and water were positioned at the head end of each half-shell. A one-quarter-horsepower electric motor and reduction gear mounted on the base of the apparatus moved a horizontal chain drive which, in turn, rotated five offset cams, each linked to a movable vertical metal rod. Fixed to each vertical rod by means of a vertically adjustable swivel joint was a cylindrical plastic cup which contained the dental plaster-of-Paris cast that encased one hind foot of each rabbit. As the cams were turned by the chain drive, the five vertical rods and their attached plastic cups were moved up and down slowly and smoothly, thereby providing continuous passive motion of one knee of each of the five rabbits (Fig. 2). We arbitrarily chose the rate of one complete cycle every forty seconds and chose a range of motion of the knee joint of from 40 to 110 degrees of flexion, an arc of 70 degrees.

Feasibility Studies

To determine the feasibility of the proposed experiment in terms of the rabbits' tolerance of the restraint and the continuous passive motion of one knee as well as the effect of such motion on intact articular cartilage of this joint, we conducted a preliminary series of investigations on five adolescent rabbits. An elasticized bandage was applied to the freely hanging opposite hind limb to prevent dependent edema. The rabbits seemed to be comfortable in the apparatus for periods of as long as four weeks, as evidenced by the observations that their normal sleep patterns were undisturbed; they ate and drank well; they continued to gain weight; and in general they seemed content. When they were killed, the articular cartilage and subchondral bone in the knee joints that had been moved continuously for four weeks appeared normal compared with the articular cartilage of normal rabbit knee joints, as determined by both gross examination and assessment of histological sections stained with either hematoxylin and eosin or toluidine blue.

Experimental Model

The right knee joint of each experimental animal was subjected to the following standard operative procedure under general anesthesia (halothane, nitrous oxide, and oxygen).

After the fur in the area had been shaved and the skin had been prepared with Betadine (povidone-iodine), the knee joint was exposed through a medial parapatellar incision and the patella was dislocated laterally. The joint then was acutely flexed to provide exposure of the articular cartilage of the patellar groove and the femoral condyles. Using an electrically driven dental drill cooled by a stream of normal saline, full-thickness defects, one millimeter in diameter, were made in the articular cartilage and subchondral bone to a standard depth of four millimeters.

A full-thickness defect was made in each of four standard sites: the patellar groove, the anterior and middle parts of the medial femoral condyle, and the middle part of the lateral femoral condyle (Fig. 3). The previously dislocated patella was then reduced, the medial capsular incision and skin were sutured, and a light dressing was applied. The overlying bandage permitted free motion of the knee joint.

For animals in the continuous passive motion series, the foot of the limb operated on was immediately encased in dental plaster of Paris and firmly bonded to the plastic cylinder. These animals then were placed in the apparatus and continuous passive motion was started before the rabbits had recovered from the general anesthesia.

Experimental Protocol

After the standard operative procedure, the knees that had been operated on were subjected to one of three forms of postoperative management: Series I — immobilization; Series II — intermittent active motion (normal cage activity); and Series III — continuous passive motion. Thus, there were three series of forty adolescent rabbits (a total of 120 rabbits and 480 defects) and three series of nine adult rabbits (a total of twenty-seven rabbits and 108 defects), managed postoperatively according to one of the three regimens.

FIG. 6

Filmy intra-articular adhesions extending from the synovial membrane to full-thickness defects in the medial femoral condyle (right) and the lateral femoral condyle (left) of an adolescent rabbit's right knee after three weeks of immobilization.

Adolescent Rabbits

Series I: The knee that had been operated on was immobilized in a plaster-of-Paris cast in 140 degrees of flexion (the normal resting position of a rabbit's knee) for one, two, three, or ten weeks. Ten animals were studied at each time-period.

Series II: Activity was unrestricted in a large cage (floor dimensions, ninety by ninety centimeters and ceiling height, eighty centimeters). The periods selected for study after normal cage activity (intermittent active motion) were one, two, three, and four weeks. There were ten animals in each time-period.

Series III: Continuous passive motion of the involved knee was maintained for one, two, three, and four weeks, with ten animals studied at each time-period.

Adult Rabbits

The experimental protocol of the adult rabbits was the same as that of the adolescent animals except that all of the animals in each of the three series were studied at three weeks only. There were nine animals in each series.

Control Knee Joints

In Series I and II the left knee, which had not been operated on and was free to move, served as a control. In Series III, however, the left knee was virtually immobilized in a position of extension by the elasticized bandage during the period of continuous passive motion of the other knee. Furthermore, the left limbs in Series III were dependent during this period, and despite bandaging an effusion and intra-articular adhesions developed in all of these knees. Since these knee joints were not considered suitable controls for Series III, the control knee joints of Series I and II, as well as the continuously moved knee joints from the feasibility studies and normal rabbit knee joints, served as controls for Series III. All of the control knees were considered to be normal; they appeared so by gross examination and consequently only a few were assessed histologically.

Preparation of Specimens

Each animal was killed with an overdose of intravenous Nembutal (pentobarbital) and the involved knee joints were reopened through the original incision, which in every instance had healed well. The distal end of the femur of each animal was dissected free of all soft tissues, examined under a dissecting microscope (magnification, × 20), and photographed. The specimens were kept moist with normal saline during the gross examination and then were fixed in 10 per cent neutral buffered formalin. After decalcification for three to four weeks using equal portions of 45 per cent formic acid and 20 per cent sodium citrate, we cut blocks of tissue including the cartilage and subchondral bone in the region of each of the four defects.

These blocks were dehydrated using increasing concentrations of alcohol up to absolute alcohol, then cleared with cedar-wood oil, rinsed in chloroform, and permeated with three changes of paraffin wax in a vacuum. At least four sections, six micrometers thick, were cut through the central portion of each defect with a rotary microtome.

Two sections or more from the center of each defect were stained with hematoxylin and eosin for histological detail and at least two sections were stained

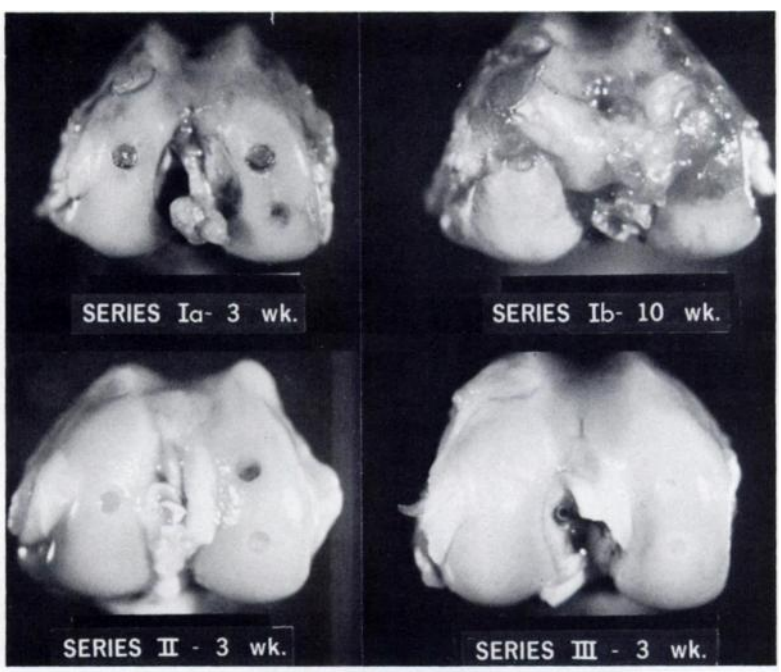

FIG. 7

Gross appearances of typical defects in the three series of experiments (adolescent rabbits).

Series Ia (immobilization for three weeks): Note the granulation-like tissue in the defects.

Series Ib (immobilization for ten weeks): Note the numerous extensive intra-articular synovial adhesions in the region of each of three defects in the femoral condyles; there are no adhesions in the region of the defect in the patellar groove.

Series II (intermittent active motion for three weeks): Healing of the defects is somewhat better in this series than in Series Ia at three weeks, but healing is still incomplete.

Series III (continuous passive motion for three weeks): Healing of the defects is by tissue grossly resembling articular cartilage. Healing in this series is considerably more complete than in either Series I or Series II.

with toluidine blue for histochemical assessment of the glycosaminoglycans of the cartilage matrix. The two sections (one from each stain group) used for final assessment of each defect were those judged to be closest to the center. Since the histological appearances were similar in each of the various sections of a given defect, those chosen for final assessment were considered to be representative of that defect.

Indices of Healing

From an extensive review of the relevant literature, we concluded that previous investigators had not established specific and separate indicators of healing of full-thickness defects in articular cartilage. Accordingly, we established two indices of healing based on distinctly separate histological features, fully recognizing the subjective and semiquantitative nature of such indices: (1) the nature of the reparative tissue, and (2) the degree of metachromasia in the matrix.

Nature of the Reparative Tissue

The sections stained with hematoxylin and eosin were analyzed and categorized according to the nature of the *predominant* tissue in each defect at the level of the surrounding articular cartilage; that is, between the tidemark and the articular surface. The tissue within the subchondral portion of each defect was excluded from this analysis.

Using this method of analysis, the composition of the *predominant* reparative tissue in each of the defects was placed in one of the following three categories: (1) *fibrous tissue* containing spindle-shaped fibroblasts; (2) *incompletely differentiated mesenchymal tissue* composed of plump cells that were beginning to differentiate toward chondrocytes (in the past this type of tissue usually has been referred to as "fibrocartilage" even though it does not resemble the fibrocartilage normally present in such structures as the menisci of the knee joint); and (3) *hyaline articular cartilage* containing chondrocytes in lacunae and appearing comparable to the mature hyaline cartilage in the control joints and in the intact areas of the same joint (Fig. 4).

Degree of Metachromasia of the Matrix

The sections stained with toluidine blue were analyzed and graded according to the degree of metachromasia of the matrix. This was done by assessing the *predominant* degree of metachromasia in each defect at the level of the adjacent articular cartilage (between the tidemark and the articular surface). As with the first index, the tissue within the subchondral portion of each defect was excluded from this analysis.

Using this method of analysis, the *predominant* degree of metachromasia of the matrix of the reparative tissue in each of the defects was assigned one of the following grades: (1) no purple staining, (2) slight purple staining, (3) moderate purple staining, and (4) normal or near-normal purple staining, comparable to that of the control normal hyaline articular cartilage (Fig. 5).

Results in Adolescent Animals

As previously noted, these animals were male New Zealand White rabbits which weighed 2.3 to 3.0 kilograms and were almost fully grown but still had open epiphyseal plates in the region of the knee as demonstrated roentgenographically.

Tolerance of the Rabbits

Series I (immobilization): The rabbits tolerated the above-the-knee plaster casts well, and after the first postoperative day they were able to use their three mobile limbs to move about freely in the cages.

Series II (intermittent active motion): During the first postoperative week these rabbits tended not to move the knee that had been operated on, presumably because motion was painful. By the end of the first postoperative week, however, they were able to use the knee relatively normally as they hopped about the cages. By the end of the second postoperative week the majority of these rabbits hopped normally.

Series III (continuous passive motion): The rabbits in this series were placed in the continuous-motion apparatus while still under anesthesia and recovered from the anesthetic with the right knee joint in continuous passive motion. They appeared to be comfortable from the beginning. Throughout the various time-periods the adolescent rabbits ate and drank well, slept well, continued to gain weight, and in general seemed content.

Gross Findings

Joint Mobility

Series I (immobilization): The degree of postoperative stiffness in the forty knees varied directly with the duration of immobilization. At three weeks all ten immobilized knees had a limited range of motion from the resting position of 140 degrees of flexion to approximately 70 degrees of flexion (about half the normal range from

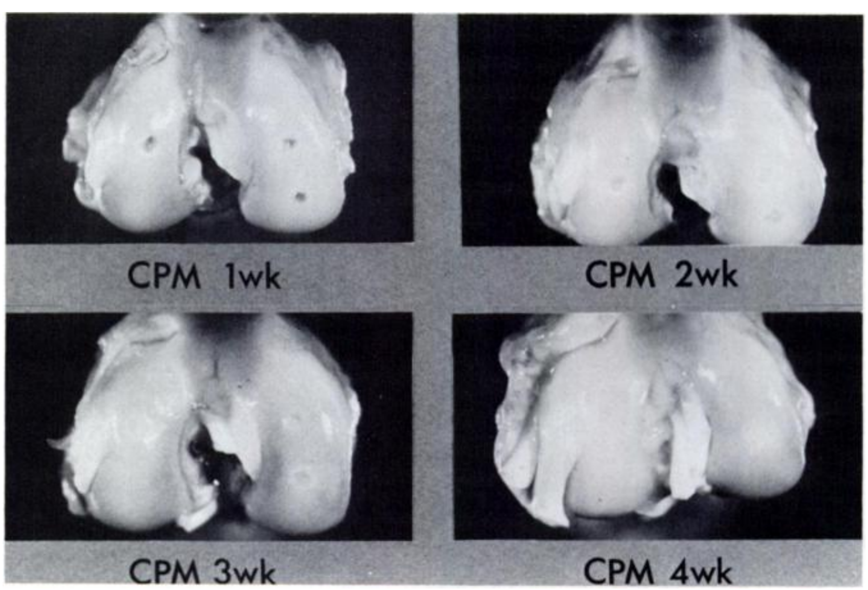

FIG. 8

Gross appearances of typical defects in Series III, continuous passive motion (CPM), at one, two, three, and four weeks. Note that the healing is both rapid and complete; by four weeks the defects are filled with firm, whitish tissue which grossly resembles articular cartilage.

140 degrees of flexion to zero degrees). After ten weeks of postoperative immobilization all ten knees in this subgroup were very stiff indeed, with only a few degrees of motion.

Series II (intermittent active motion): During the first postoperative week there was painful limitation of motion in all forty knees. By the end of the second postoperative week the joint mobility had returned to a near-normal range in the knees of the thirty surviving rabbits (ten rabbits having been killed at the end of the first week).

Series III (continuous passive motion): At one, two, three, and four weeks, the range of motion at the time of death was completely normal in all forty knees (ten rabbits in each time-period).

Healing of the Arthrotomy Wounds

At all time-periods studied in all three series of experiments, the arthrotomy wounds were well healed. Thus, neither intermittent active motion nor continuous passive motion interfered with soft-tissue healing of the wounds.

Intra-Articular Adhesions

Series I (immobilization): Up to the end of two weeks of immobilization there were no intra-articular adhesions. At three weeks the synovial membrane was connected to half of the defects in the femoral condyles by filmy adhesions (Fig. 6). After ten weeks of immobilization, however, the intra-articular adhesions involving the defects in the femoral condyles were both numerous and extensive (Fig. 7) in the ten knees of the surviving rabbits (thirty rabbits having been killed prior to ten weeks). Such adhesions accounted in large part for the aforementioned gross limitation of joint motion.

Series II (intermittent active motion): There were no intra-articular adhesions in any of the forty knees examined at one, two, three, and four weeks (Fig. 7).

Series III (continuous passive motion): No intra-articular adhesions were seen in any of the forty knees examined at one, two, three, and four weeks (Fig. 7).

Healing of the Defects

Series I (immobilization): By the end of the third week of postoperative immobilization, only six (15 per cent) of the forty defects were filled by healing tissue that resembled articular cartilage by gross examination. In the remaining thirty-four defects (85 per cent), the healing tissue consisted of either reddish granulation-like tissue or yellowish-white soft tissue (Fig. 7). After ten weeks of postoperative immobilization, all but two of the thirty defects in the femoral condyles were covered by dense adhesions (Fig. 7). The ten defects in the patellar grooves of these ten rabbits were not covered by adhesions and were filled with yellowish-white soft tissue.

Series II (intermittent active motion): At three weeks only ten (25 per cent) of the forty defects were filled by healing tissue that resembled articular cartilage by gross examination. In the remaining thirty defects (75 per cent) the healing tissue was yellowish-white in color and was soft (Fig. 7).

Series III (continuous passive motion): The gross appearance of the healing defects was definitely superior in all four time-groups of Series III compared with the appearance of the defects in Series I and II. At three weeks, thirty (75 per cent) of the forty defects were filled by tissue that resembled articular cartilage by gross examination (Fig. 7). In only ten (25 per cent) of the forty defects was the healing tissue yellowish-white and soft. By the end of four weeks of continuous passive motion, all thirty-two

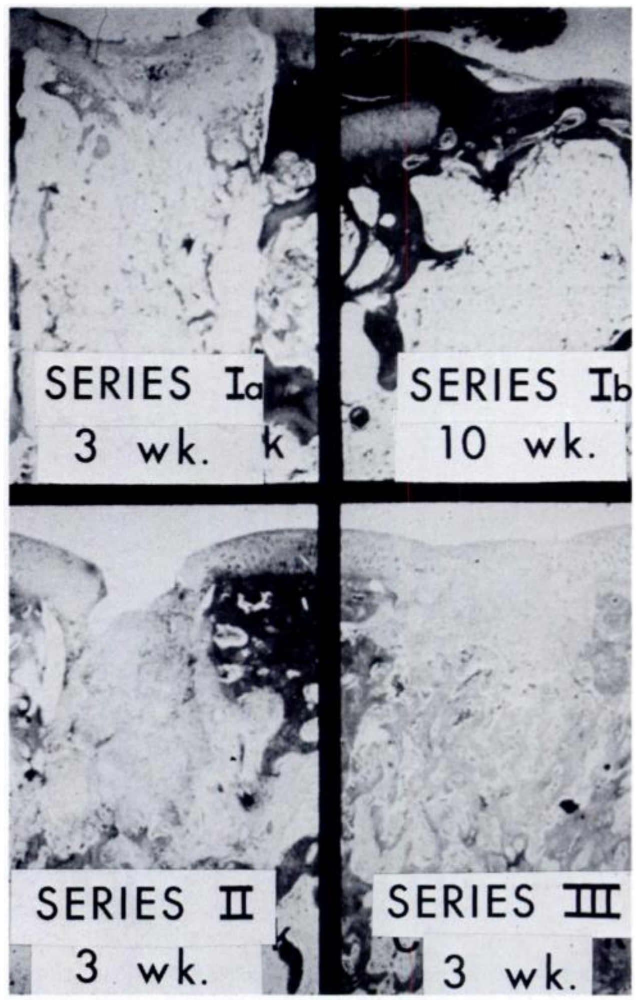

FIG. 9

The nature of the reparative tissue in typical defects in the three series of experiments in adolescent rabbits (hematoxylin and eosin, × 27).

Series Ia (immobilization for three weeks): Healing is by predominantly fibrous tissue. (For higher magnification of defects in Series Ia at three weeks see Figs. 10-A, 10-B, and 10-C.)

Series Ib (immobilization for ten weeks): Note that healing is by predominantly fibrous tissue that is continuous with the fibrous tissue of an overlying intra-articular adhesion. (For higher magnification of defects in Series Ib see Fig. 10-D.)

Series II (intermittent active motion for three weeks): Note that healing is by incompletely differentiated mesenchymal tissue and that this tissue has not reached the joint surface. (For higher magnification of defects in Series II see Figs. 11-A, 11-B, and 11-C.)

Series III (continuous passive motion for three weeks): Healing is by predominantly hyaline articular cartilage and the healing tissue has reached the level of the joint surface. Endochondral ossification may be seen in the depth of the defect. (For higher magnification of defects in Series III see Figs. 13-A, 13-B, and 13-C.)

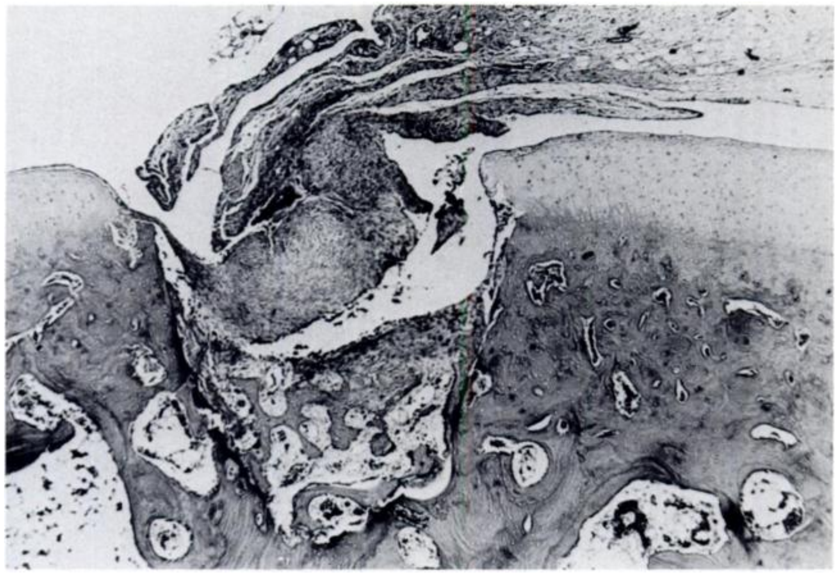

FIG. 10-A

Figs. 10-A through 10-D: Series Ia and Ib (immobilization for three and ten weeks in adolescent rabbits).
Fig. 10-A: At three weeks, the superficial portion of the defect has been filled with predominantly fibrous tissue that is continuous with the fibrous tissue of an intra-articular synovial adhesion. The deep portion of the defect has been filled with new bone (hematoxylin and eosin, × 47).

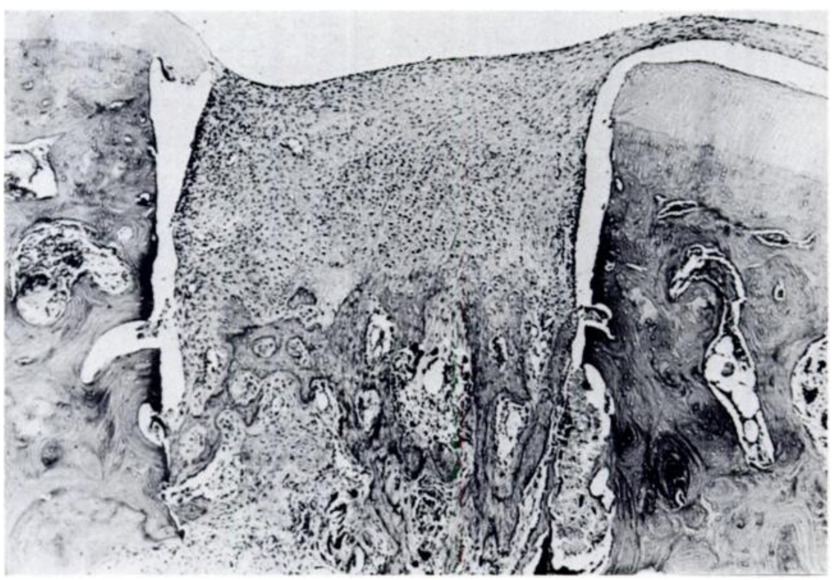

FIG. 10-B

At three weeks, the superficial portion of the defect has been filled with predominantly fibrous tissue that is continuous with the fibrous tissue of a filmy adhesion. A mixture of new bone and preosseous cartilage may be seen in the depth of the defect (hematoxylin and eosin, × 60).

(80 per cent) of the forty defects in the knees of the ten surviving rabbits (thirty rabbits having been killed previously) were filled with firm, whitish tissue that resembled articular cartilage by gross examination (Fig. 8).

Appearance by Light Microscopy

Nature of the Reparative Tissue

Series I (immobilization): All forty defects at one week and all forty defects at two weeks were filled with either granulation tissue or undifferentiated mesenchymal tissue. At three weeks the healing was by predominantly fibrous tissue in thirty-four (85 per cent) of the forty defects (Figs. 9, 10-A, 10-B, and 10-C). In the remaining six defects (15 per cent), at three weeks healing was by either poorly differentiated mesenchymal tissue or hyaline articular cartilage. After ten weeks of immobilization all but two of the thirty defects in the femoral condyles were covered by fibrous-tissue adhesions and were filled with fibrous tissue (Fig. 10-D). The ten defects in the patellar groove were not covered by adhesions and were filled with either fibrous tissue (four defects) or hyaline articular cartilage (six defects).

Series II (intermittent active motion): At one week and at two weeks all eighty defects were filled with either

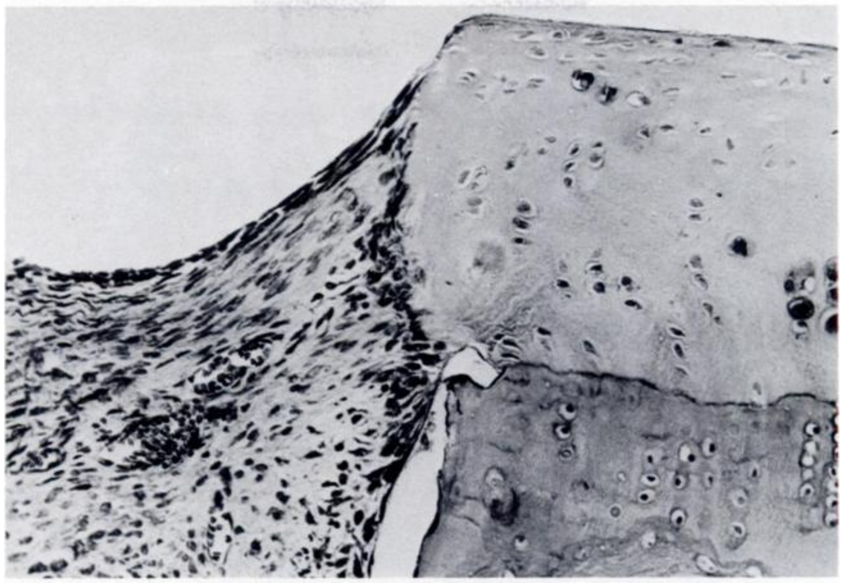

FIG. 10-C

At three weeks, the defect at the left is filled with predominantly vascular fibrous tissue that is not well bonded to the subchondral bone (hematoxylin and eosin, × 301).

FIG. 10-D

At ten weeks, the superficial portion of the defect at the right has been filled with predominantly fibrous tissue that is continuous with the fibrous tissue of an extensive overlying intra-articular synovial adhesion. The deeper portion of the defect is filled with new bone (hematoxylin and eosin, × 301).

granulation tissue or undifferentiated mesenchymal tissue. At three weeks, healing of the defects was by predominantly fibrous tissue in thirty (75 per cent) of the forty defects (Figs. 9, 11-A, 11-B, and 11-C). Of the remaining ten defects at three weeks, six were filled with incompletely differentiated mesenchymal tissue and only four (9 per cent), with hyaline articular cartilage. At four weeks, thirty-three (80 per cent) of the forty defects were filled with fibrous tissue; five, with incompletely differentiated mesenchymal tissue; and only two (5 per cent), with hyaline articular cartilage.

Series III (continuous passive motion): At the end of the first week all forty defects were filled with either granulation tissue or undifferentiated mesenchymal tissue (Fig. 12). At two weeks, eleven of the forty defects contained tissue that was still mesenchymal in nature, but was beginning to differentiate toward cartilage in that the cells were becoming more spherical (Fig. 12). At three weeks the cells at the level of the intact cartilage resembled chondrocytes in twenty-one (52 per cent) of the forty defects, except in the most superficial zone in which the cells were less well differentiated (Figs. 12, 13-A, 13-B, and 13-C).

At this time-period, of the remaining nineteen defects, eight were filled predominantly with fibrous tissue and eleven were filled predominantly with incompletely

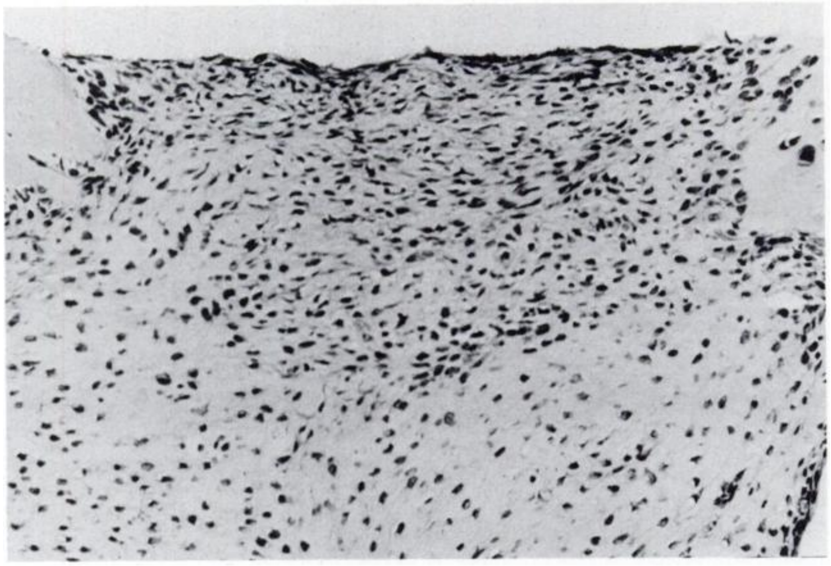

FIG. 11-A

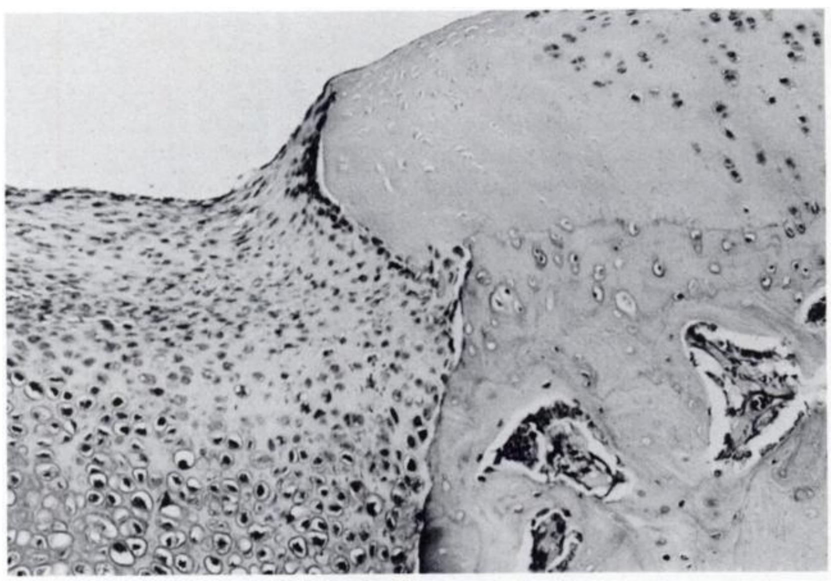

FIG. 11-B

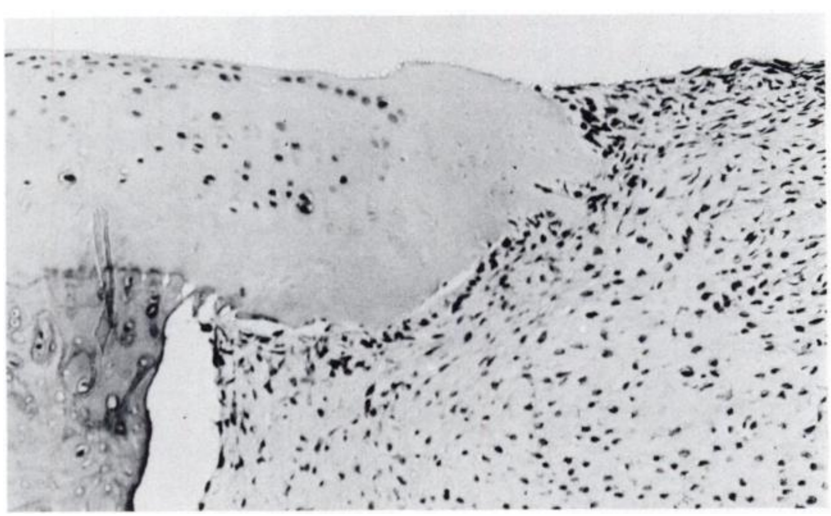

FIG. 11-C

differentiated mesenchymal tissue.

After four weeks of continuous passive motion, the cells at the level of the intact cartilage resembled chondrocytes in twenty-two (55 per cent) of the forty defects (Figs. 12 and 14-A through 14-E). Of the remaining eighteen defects, five were filled with undifferentiated mesenchymal tissue and thirteen, with fibrous tissue. Thus, the nature of the reparative process at four weeks was not significantly different from that at three weeks.

The nature of the reparative tissue in each of the three series in the adolescent animals at three weeks is presented in graphic form in Figure 15.

Metachromasia of the Matrix

Series I (immobilization): There was either slight or no toluidine-blue staining of the matrix of the reparative tissue in all but thirteen of the 160 defects in the four time-groups in this series. At three weeks, only four (10 per cent) of the forty defects exhibited normal or near-normal staining (Fig. 16). Thus, the production of glycosaminoglycans by the reparative cells was very low even though we appreciate that toluidine-blue staining is only semiquantitative and may not detect all amounts of glycosaminoglycans synthesized by the cells.

Series II (intermittent active motion): In all but nine of the 160 defects in the four time-groups in this series there was either slight or no toluidine-blue staining of the matrix of the reparative tissue. At three weeks only five (12 per cent) of the forty defects exhibited normal or near-normal staining (Fig. 16). Even after four weeks of intermittent active motion, only four of forty defects exhibited normal or near-normal staining.

Series III (continuous passive motion): Metachromatic staining of the matrix of the reparative tissue usually appeared between the second week and the third week (Fig. 17). By three weeks, normal or near-normal staining was seen in twenty-four (60 per cent) of the forty defects, and by four weeks such staining was seen in twenty-two (55 per cent) of the forty defects, indicating that in these defects the chondrocytes of the newly formed cartilage were producing glycosaminoglycans in the matrix. Thus, the degree of metachromasia of the matrix at four weeks was not significantly different from that at three weeks (Figs. 16 and 17).

The percentage of defects showing normal or near-normal metachromasia at three weeks in each of the three series of adolescent animals is shown in graphic form in Figure 18.

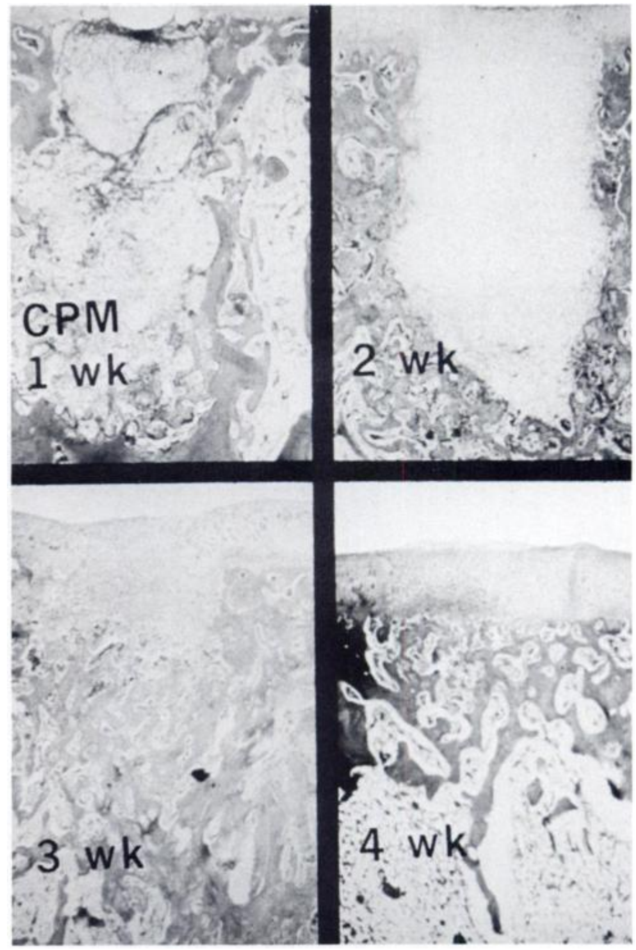

FIG. 12

Series III (continuous passive motion [CPM]) for one, two, three, and four weeks in adolescent animals (hematoxylin and eosin, × 27). At one week, granulation tissue and undifferentiated mesenchymal tissue fill the defect. At two weeks, the healing tissue has begun to differentiate toward cartilage. At three weeks, the cells in the superficial part of the defect are predominantly chondrocytes. (For higher magnifications of defects in Series III at three weeks see Figs. 13-A, 13-B, and 13-C.) By four weeks, endochondral ossification has reached the tidemark. The cells in the superficial portion of the defect — that is, at the level of the intact cartilage — are chondrocytes. (For higher magnification of defects in Series III at four weeks see Figs. 14-A through 14-E.)

Results in Adult Animals

As previously noted, these animals were male New Zealand White rabbits that weighed 4.0 to 5.0 kilograms and were fully grown, with closed epiphyseal plates in the region of the knee as demonstrated roentgenographically. Only one time-period (three weeks) was used in this second phase of the investigation.

Initially there were thirty rabbits — ten each of Series

Figs. 11-A, 11-B, and 11-C: Series II (intermittent active motion for three weeks in adolescent rabbits).

Fig. 11-A: A section through the full width of a one-millimeter defect and the intact articular cartilage at each edge shows that the healing in the superficial portion of the defect is predominantly by fibrous tissue, whereas in the deeper portion of the defect the healing tissue contains incompletely differentiated mesenchymal cells that are beginning to differentiate toward chondrocytes (hematoxylin and eosin, × 200).

Fig. 11-B: The depressed surface layers of the healing tissue at the left contain predominantly fibrous tissue. Immediately below the level of the tidemark the tissue is composed of incompletely differentiated mesenchymal cells. In the deeper layer the tissue is preosseous cartilage that will undergo endochondral ossification (hematoxylin and eosin, × 200).

Fig. 11-C: The healing in the superficial portion of the defect at the right is by predominantly incompletely differentiated mesenchymal cells. The healing tissue is not bonded to the subchondral bone (hematoxylin and eosin, × 200).

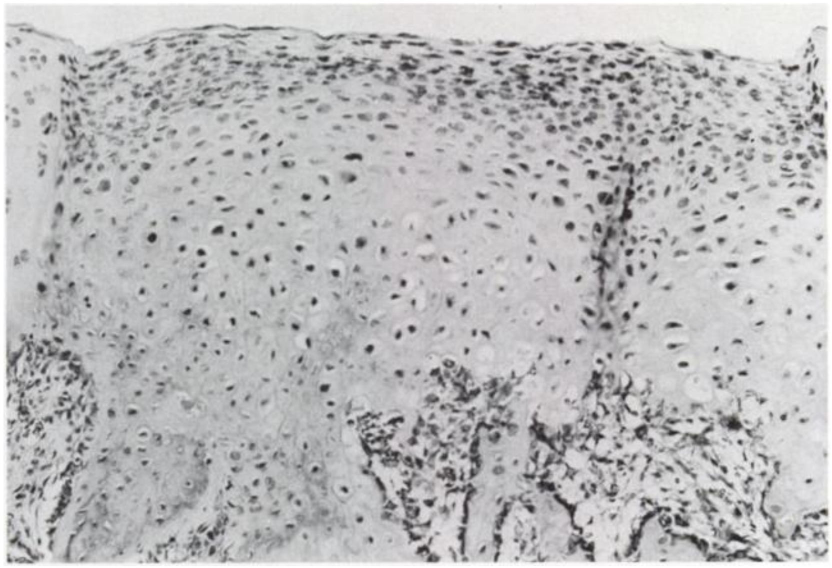

FIG. 13-A

Figs. 13-A, 13-B, and 13-C: Continuous passive motion for three weeks in adolescent animals.
Fig. 13-A: A section through the full width of a one-millimeter defect with intact cartilage at the extreme edges shows that the cells in the superficial portion of the defect at the level of the intact cartilage are chondrocytes, whereas in the most superficial portion, at the level of the joint surface, the cells are less well differentiated (hematoxylin and eosin, × 200).

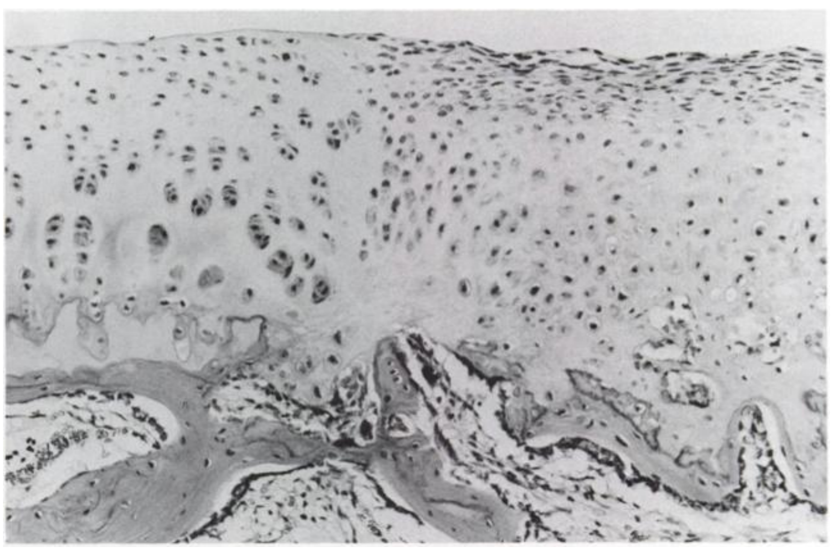

FIG. 13-B

The cells and the matrix of the reparative tissue at the right resemble those of articular cartilage. The reparative tissue is firmly bonded to the edge of the intact cartilage, and endochondral ossification has reached, but not extended beyond, the level of the tidemark of the intact cartilage (hematoxylin and eosin, × 200).

I, II, and III — with four defects in one knee of each animal, giving a total of 120 defects. During the investigation, however, one rabbit in each of the three series died of Pasteurella pneumonia, leaving twenty-seven rabbits with a total of 108 defects. The assessment and analysis of these 108 defects was done by the same methods used in the investigation of the adolescent animals.

Tolerance of the Rabbits

Observations of the tolerance of the adult animals were essentially the same as those described for adolescent animals except that the adult animals on continuous passive motion, being fully grown, did not gain weight. However, they maintained their weight, which was an indication of their general well-being.

Gross Findings

Joint Mobility

Series I (immobilization): At three weeks the nine immobilized joints had a limited range of motion from the resting position of 140 degrees of flexion to approximately 70 degrees of flexion; that is, half the normal range of from 140 degrees of flexion to zero degrees.

Series II (intermittent active motion): After three

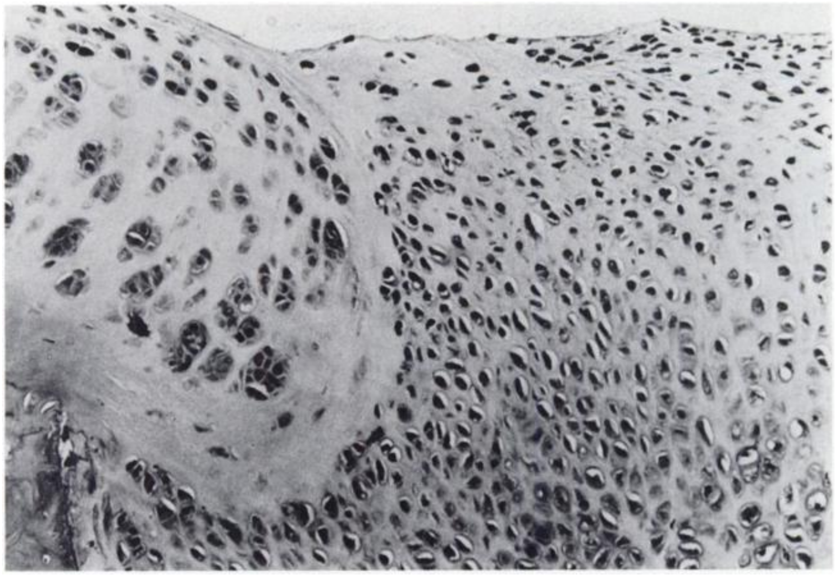

FIG. 13-C

Higher magnification of the left side of the defect shown in Fig. 12 (Series III, three weeks). The cells of the reparative tissue on the right resemble chondrocytes and the tissue is firmly bonded to the edges of the intact cartilage and the subchondral bone (hematoxylin and eosin, × 241).

weeks the mobility in the nine joints in this series had returned to nearly normal.

Series III (continuous passive motion): All nine joints maintained on continuous passive motion for three weeks exhibited a completely normal range of motion.

Intra-Articular Adhesions

Series I (immobilization): After three weeks of immobilization, filmy adhesions which were comparable to those seen in the adolescent animals were found between the synovial membrane and half of the defects in the femoral condyles (Fig. 6).

Series II (intermittent active motion): In this series no intra-articular adhesions had formed in any of the thirty-six knees examined at three weeks.

Series III (continuous passive motion): No intra-articular adhesions were found in any of the thirty-six knees that were maintained on continuous passive motion for three weeks.

Healing of the Defects

Series I (immobilization): By the end of the third week of postoperative immobilization only one (3 per cent) of the thirty-six defects was filled by healing tissue that on gross examination resembled articular cartilage. Five (14 per cent) of the defects contained yellowish-white soft tissue and the remaining thirty defects (83 per cent) were filled with reddish granulation tissue.

Series II (intermittent active motion): At three weeks only two (5 per cent) of the thirty-six defects in this group were filled with tissue that resembled articular cartilage. Of the other thirty-four defects, six (17 per cent) contained yellowish-white soft tissue and the remaining twenty-eight defects (78 per cent) were filled with reddish granulation-like tissue.

Series III (continuous passive motion): In the adult animals, as in the adolescent rabbits, the gross appearance of the healing defects after three weeks of continuous motion was definitely superior to the appearance of the defects after either three weeks of immobilization or three weeks of intermittent active motion. Considering all thirty-six defects, sixteen (44 per cent) contained tissue that resembled articular cartilage by gross examination, eight (22 per cent) were filled with yellowish-white tissue, and twelve (33 per cent) contained reddish granulation-like tissue.

Thus, in the 108 defects in adult animals assessed at three weeks by gross examination, the relative differences in the appearance of the healing tissue between the three series were comparable to those between the three series in adolescent animals, as depicted in Figure 7. In each of the three series of adult animals, however, the percentages of defects that healed by tissue resembling articular cartilage were smaller than those in the adolescent animals at three weeks.

Appearance by Light Microscopy

Nature of the Reparative Tissue

Series I (immobilization): After three weeks of immobilization, the tissue in the thirty-six defects was predominantly fibrous in thirty-one (86 per cent), incompletely differentiated mesenchymal tissue in four (11 per cent), and hyaline articular cartilage in one (3 per cent).

Series II (intermittent active motion): After three weeks of intermittent motion, the tissue in the thirty-six defects was predominantly fibrous in twenty-nine (81 per cent), incompletely differentiated mesenchymal tissue in five (14 per cent), and hyaline articular cartilage in two (5 per cent).

Series III (continuous passive motion): At three

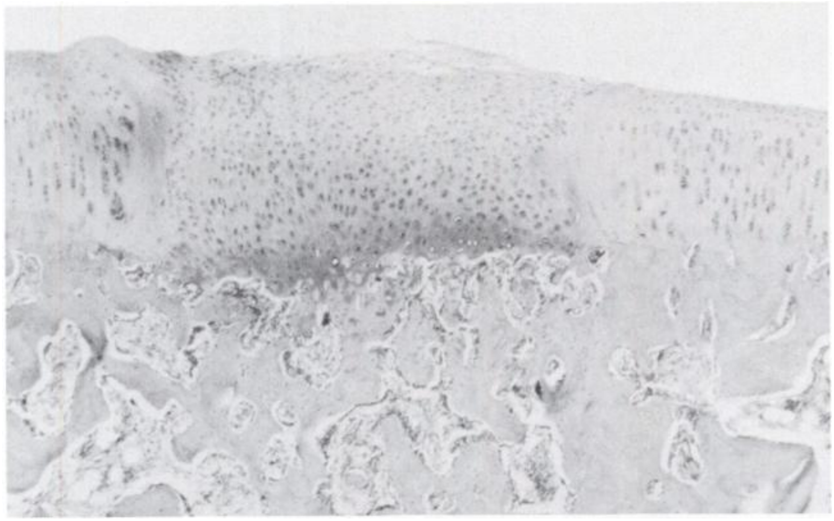

FIG. 14-A

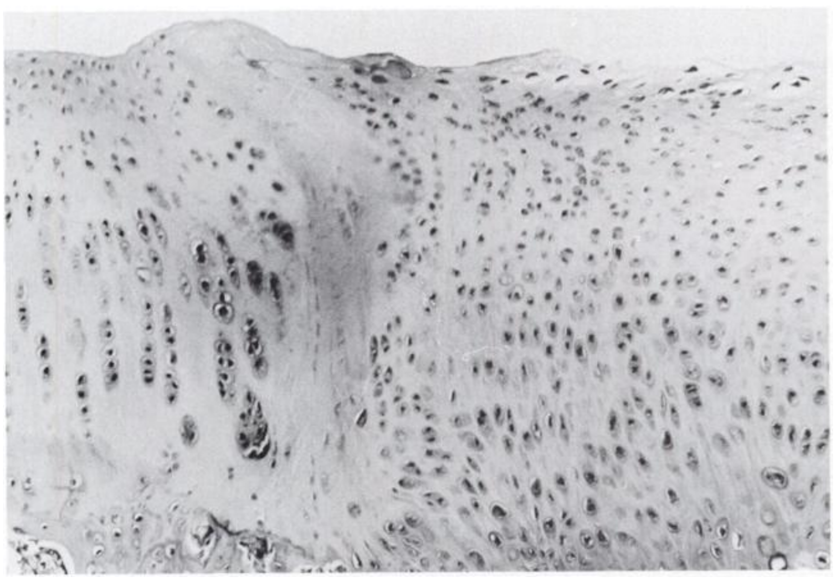

FIG. 14-B

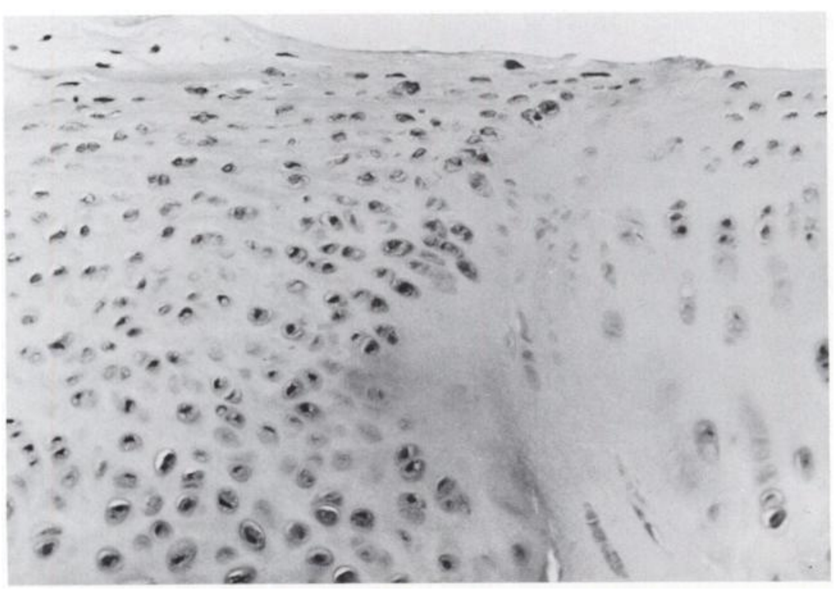

FIG. 14-C

FIG. 14-D

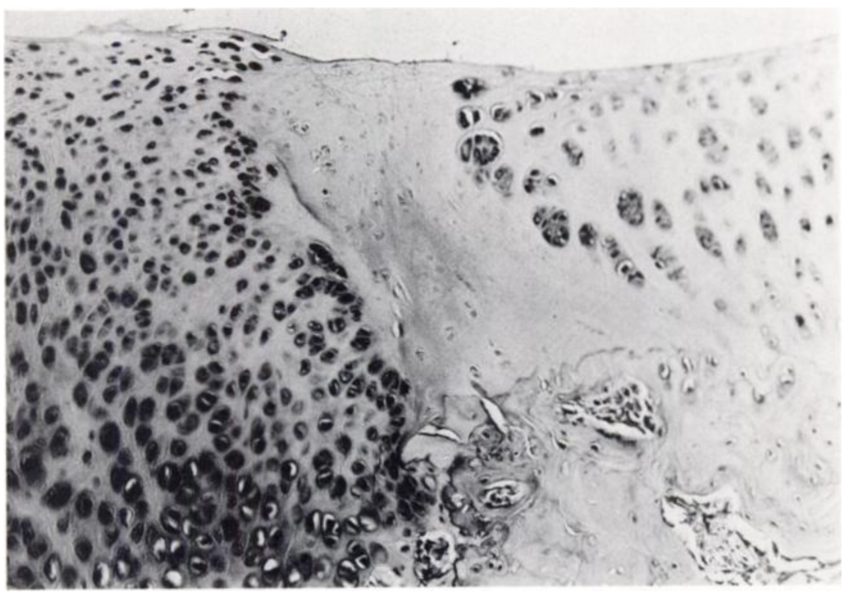

FIG. 14-E

Figs. 14-A through 14-E: Continuous passive motion for four weeks in adolescent animals.
Fig. 14-A: A section through the full width of a one-millimeter defect with intact cartilage at each edge shows that the reparative tissue resembles articular cartilage and is firmly bonded to the edges of the intact cartilage. Endochondral ossification has reached, but not extended beyond, the level of the tidemark on each side of the defect (hematoxylin and eosin, × 50).
Fig. 14-B: Higher magnification of the left side of the defect shown in Fig. 14-A reveals that the cells of the reparative tissue at the right are chondrocytes. This tissue is more cellular than the adjacent normal, mature cartilage (hematoxylin and eosin, × 200).
Fig. 14-C: Higher magnification of the right side of the defect shown in Fig. 14-A shows that the cells and matrix of the reparative tissue at the left are those of hyaline articular cartilage (hematoxylin and eosin, × 315).
Fig. 14-D: Higher magnification of the left side of the defect shown in Fig. 12 (Series III, four weeks) demonstrates that the reparative tissue at the right is predominantly hyaline articular cartilage (hematoxylin and eosin, × 301).
Fig. 14-E: The cells and matrix of the reparative tissue at the left are those of articular cartilage, although this tissue is more cellular than the adjacent normal, mature cartilage (hematoxylin and eosin, × 200).

weeks, in this series the predominant tissue in the thirty-six defects was fibrous in eleven (31 per cent), incompletely differentiated mesenchymal tissue in nine (25 per cent), and hyaline articular cartilage in sixteen (44 per cent). The hyaline articular cartilage in these sixteen defects was comparable to that seen after three weeks of continuous passive motion in the adolescent animals.

Thus, in the 108 defects assessed and analyzed in the adult animals, the relative differences in the nature of the reparative tissue seen in the three series were comparable to those seen in the three series in adolescent animals. The effect of three weeks of continuous passive motion in stimulating healing by hyaline articular cartilage in the adult animals was only slightly less than that in the adoles-

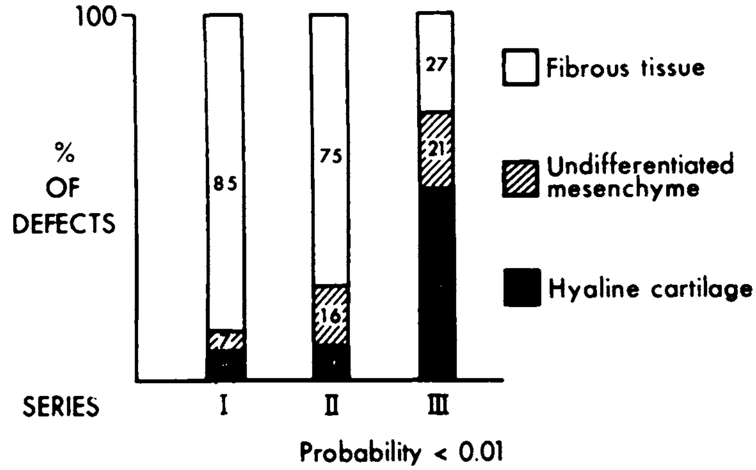

FIG. 15

First index of healing: the nature of the reparative tissue in the forty defects in adolescent animals in each of the three series at three weeks. The bars depict the percentages of the forty defects in each series that exhibited predominantly hyaline cartilage, incompletely differentiated mesenchymal tissue, or fibrous tissue. Note that the nature of the reparative tissue in the defects after continuous passive motion (Series III) is far superior to that after either immobilization (Series I) or intermittent active motion (Series II).

cent animals (44 per cent healed with articular cartilage in adults compared with 52 per cent in adolescents).

The nature of the reparative tissue in the thirty-six defects in each of the three series in the adult animals at three weeks is summarized graphically in Figure 19.

Metachromasia of the Matrix

Series I (immobilization): There was either slight or no staining of the matrix with toluidine blue in thirty-four (95 per cent) of the thirty-six defects after three weeks and normal or near-normal staining in the other two defects (5 per cent).

Series II (intermittent active motion): After three weeks there was either slight or no staining in thirty-one (86 per cent) of the thirty-six defects and normal or near-normal staining in the remaining five (14 per cent).

Series III (continuous passive motion): In twenty (56 per cent) of the thirty-six defects, after three weeks there was either slight or no staining of the matrix, while in the remaining sixteen (44 per cent) the staining of the matrix of the newly formed tissue was either normal or near-normal, comparable to that seen after three weeks of continuous passive motion in the adolescent animals.

Thus, in the 108 defects assessed and analyzed in the adult animals, the relative differences in the metachromasia of the matrix between the three series were comparable with the relative differences between the three series in the adolescent animals. The effect of three weeks of continuous passive motion in stimulating healing by tissue with normal or near-normal metachromasia was somewhat less in adult animals than in adolescent animals (44 per cent normal or near-normal in adults compared with 60 per cent in adolescents).

The percentages of the defects showing normal or near-normal metachromasia of the matrix in the thirty-six defects in each of the three series of adult animals at three weeks is shown graphically in Figure 20.

Discussion

As demonstrated by the data presented here, the biological effect of continuous passive motion on the healing of full-thickness defects in the articular cartilage of the knee joints of both adolescent and adult rabbits is strikingly beneficial compared with the effect of either immobilization or intermittent active motion. Indeed, in these defects continuous passive motion increased both the rate and the completeness of healing by articular cartilage to a degree not attained previously.

Of particular importance in the discussion of these findings and their significance are the limitations inherent in the experiments (the indices of healing and the duration of the experiments), the origin and differentiation of the reparative cells, the biological factors involved in such cellular differentiation, the rabbits' tolerance of postoperative continuous passive motion, and the potential relevance of this investigation to clinical orthopaedic problems in the human.

Limitations of the Present Investigation

Indices of Healing

There is a definite need for truly quantitative histological indicators of the healing of full-thickness defects in articular cartilage. We have established two specific indices of the completeness of such healing based on separate histological features (the nature of the reparative tissue and the degree of metachromasia of the matrix) and have attempted objectively to quantify these indices for the purpose of analysis. We recognize, however, that the assessment of such indices is, by their very nature, inherently somewhat arbitrary and subjective. Nevertheless, these two separate indices of the completeness of healing correlated well in the three series of experiments both in adoles-

FIG. 16

Appearances by light microscopy, depicting the degree of metachromasia of the matrix in typical defects of the three series in adolescent animals (toluidine blue, × 27).

Series Ia (immobilization for three weeks): There is no metachromatic staining of the matrix.

Series Ib (immobilization for ten weeks): There is still no metachromatic staining of the matrix.

Series II (intermittent active motion for three weeks): The matrix of the reparative tissue exhibits only slight metachromatic staining.

Series III (continuous passive motion for three weeks): The matrix of the reparative tissue exhibits near-normal metachromatic staining compared with that of the intact articular cartilage beyond the edges of the defect.

cent and in adult rabbits, as shown graphically in Figures 15, 18, 19, and 20. This correlation would seem to indicate that these indices are of analytical value.

Duration of the Experiments

The experiments reported in the present investigation were terminated at four weeks from the time that the full-thickness defects were created. An essential question, of course, is whether or not the newly formed hyaline articular cartilage produced by continuous passive motion will be maintained when it is subjected to normal weight-bearing activity for prolonged periods.

A partial answer to this question has been provided by research currently in progress, in which we have assessed the state of healing of defects in the knees of rabbits that were managed by continuous passive motion for three weeks after the defects were created in their knees and then were allowed to resume normal activity. At six months the regenerated articular cartilage was found to be intact in approximately one-half of these defects. These preliminary results, when compared with those reported in the present investigation (healing by hyaline articular cartilage in 52 per cent of defects at three weeks and in 55 per cent at four weeks), suggest that the regenerated cartilage stimulated by continuous passive motion will withstand normal weight-bearing function for at least six months. The results of this continuing research will be reported when we have completed the assessment of the state of the regenerated cartilage after longer intervals.

Origin and Differentiation of the Reparative Cells

In all three series of experiments (480 defects in 120 adolescent rabbits and 108 defects in thirty-six adult rabbits), the cells that participated in the healing process seemed to arise from the pluripotential mesenchymal cells or primitive fibroblasts of the subchondral region. The chondrocytes in the intact edges of the defect exhibited relatively little change during the four weeks under study and did not appear to contribute in any way to the healing

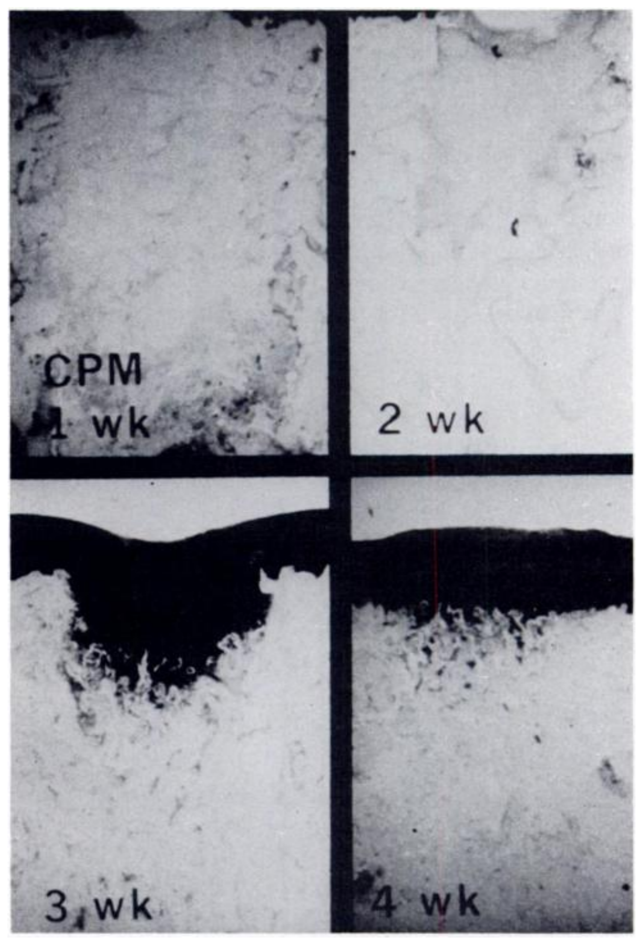

FIG. 17

Series III (continuous passive motion [CPM]) for one, two, three, and four weeks in adolescent animals (toluidine blue, × 27). Metachromatic staining of the matrix of the reparative tissue first appears between the second and third weeks, and by the end of four weeks it is comparable to that of the intact cartilage beyond the edges of the defect.

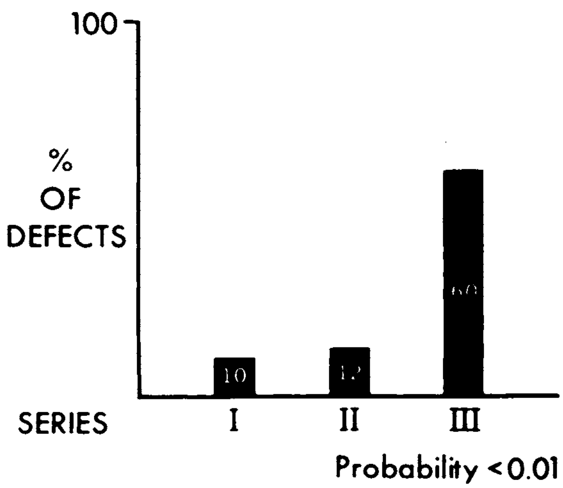

FIG. 18

Second index of healing: the degree of metachromasia of the matrix at three weeks in the forty defects in each of the three series in adolescent animals. The bars depict the percentages of the forty defects in each series that exhibited normal or near-normal metachromatic staining of the matrix of the reparative tissue by toluidine blue. Note that the degree of metachromasia of the matrix after continuous passive motion (Series III) is far superior to that after either immobilization (Series I) or intermittent active motion (Series II).

process. Furthermore, in a separate study yet to be reported, we found that partial-thickness defects in articular cartilage that did not penetrate the subchondral bone exhibited no evidence of healing even with continuous passive motion. Thus, it must be assumed that the cells responsible for the reparative tissue originate from the undifferentiated but pluripotential mesenchymal cells in the endosteum of the subchondral bone and similar cells in the bone marrow, including pericytes associated with blood vessels.

In 1949, Collins[10] stated that a less differentiated

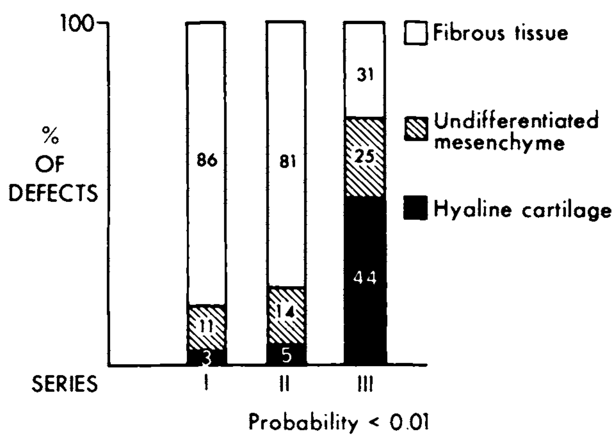

FIG. 19

First index of healing: the nature of the reparative tissue at three weeks in the thirty-six defects in each of the three series in adult animals. The bars depict the percentages of the thirty-six defects in each series that exhibited predominantly hyaline cartilage, incompletely differentiated mesenchymal tissue, and fibrous tissue. The nature of the reparative tissue in the defects treated with continuous passive motion (Series III) is far superior to that after either immobilization (Series I) or intermittent active motion (Series II).

mesenchymal tissue can always produce a more differentiated variety to meet the requirements of a particular situation and that fibrocartilage, or even hyaline cartilage, in time can grow where there was none before. Sokolof[56], in 1969, noted that the pluripotentiality of articular granu-

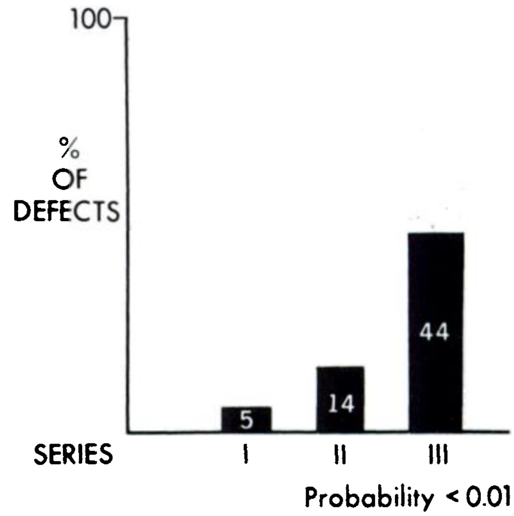

FIG. 20

Second index of healing: the degree of metachromasia of the matrix at three weeks in the thirty-six defects in each of the three series in adult animals. The bars depict the percentages of the thirty-six defects in each series that exhibited normal or near-normal metachromatic staining of the matrix of the reparative tissue by toluidine blue. The degree of metachromasia of the matrix in the defects treated with continuous passive motion (Series III) is far superior to that after either immobilization (Series I) or intermittent active motion (Series II).

lation tissue for maturation into several sorts of skeletal structure, analogous to callus in a fractured bone, is well recognized, but that little is known of the biological factors that govern the particular paths of differentiation.

Biological Factors Involved in the Differentiation of Reparative Cells

That intermittent active motion is a factor in neochondrogenesis by cells from the subchondral bone was suggested by Smith-Petersen's observations[55] in 1939 that a new joint surface of cartilage-like tissue formed under the mobile cup-shaped "mould" used in the hip arthroplasty he developed. In 1958, Urist[62] reported long-term investigations of hips in which such an arthroplasty had been performed previously; he found that the hyaline-like cartilage formed in the repair of the joint surface was like articular cartilage but it was not true articular cartilage. Pauwels[46], from his long clinical experience in treating degenerative joint disease, has proposed the concept that cartilaginous articular surfaces and fracture callus are hyaline in regions where the tissue is subjected to compressive loading but become progressively more fibrous where there are tensile forces. Similarly, Collins[10] wrote that movement and pressure especially seem to favour differentiation toward hyaline cartilage. The experimental investigations of Hohl and Luck[26], Kettunen[30], and Kettunen and Rokkanen[31] also showed that intermittent motion stimulates the healing process of full-thickness defects in articular cartilage.

In tissue-culture experiments employing primitive fibroblasts — that is, pluripotential mesenchymal cells — Bassett[3], in 1962, demonstrated that these cells differentiate along different lines depending on both physical factors and oxygen tension. Thus, compaction and a high oxygen tension caused the primitive cells to form bone; compaction and a low oxygen tension caused them to produce cartilage; and tensile force and a high oxygen tension influenced them to produce fibrous tissue. The concept that the type of force applied affects chondrogenesis was also supported by the *in vitro* studies of organ cultures reported by Glücksmann[21].

In 1965, Krompecker and Toth[34] proposed that mechanical compressive stress favors the formation of hyaline cartilage in the granulation tissue of regenerating joint surfaces in dogs by reducing the blood flow in its vessels, so that the resulting hypoxia provides the stimulus for the chondroid metaplasia. Similarly, Ham and Harris[24] suggested that if the osteogenic cell (called by some the "osteoprogenitor" cell) differentiates in a non-vascular environment, it follows the pathway into cartilage.

Ham[23] has suggested that in the present investigation the improved regeneration of articular cartilage associated with continuous passive motion may be due to enhancement of the circulation of synovial fluid. We believe that compared with intermittent active motion, continuous passive motion provides a much greater stimulus for neochondrogenesis through the differentiation of pluripotential mesenchymal cells toward chondrocytes, especially during the first few weeks of the healing process. Of interest in the present investigation was the observation that intermittent active motion provided only a slightly greater stimulus toward neochondrogenesis than did immobilization, whereas continuous passive motion provided a markedly greater stimulus toward neochondrogenesis compared with these other two forms of postoperative management.

Rabbits' Tolerance of Postoperative Continuous Passive Motion

A consistent observation in the present experiments was that the rabbits subjected to continuous passive motion of the knee started immediately after operation (while still under general anesthesia) seemed to be comfortable from the beginning and throughout the duration of the experiments. It is, of course, not possible to assess with accuracy the presence or absence of pain in a rabbit. Nevertheless, these rabbits ate and drank well, slept well, and in general seemed content; the adolescent rabbits continued to gain weight and the adult rabbits maintained their weight. These indicators of the general well-being of the rabbits suggest that they were not having a significant amount of pain.

A theoretical explanation of the rabbits' tolerance of postoperative continuous passive motion is that the proprioceptive impulses from the continuously moving joint may in some way block the perception of pain from the involved knee at the level of the spinal cord, in keeping with the so-called gate-control theory of pain proposed by Wall[63].

It is well known by orthopaedic surgeons and patients alike that either active or passive *intermittent* motion of a diseased or injured joint is painful, particularly at the start of such motion. Once the joint has been moving for a short while, however, the motion becomes less painful — only to become painful again after a period of rest when motion is resumed. A possible explanation for this phenomenon is that during the intervening periods of immobilization, between the periods of intermittent motion, the abnormal joint becomes relatively stiff due to so-called articular gelling, intra-articular adhesions, and the adaptive shortening of the capsule. Given this premise, it would not be surprising that initiation of the next period of intermittent motion would be painful.

With continuous passive motion and no intervening periods of immobilization, these deleterious changes would not occur and at least one source of pain would thereby be eliminated. Furthermore, it is conceivable that the pain-sensitive periarticular soft tissues quickly become adapted to the constant range and rate of continuous passive motion provided by the apparatus.

Potential Relevance of the Present Investigation to Clinical Orthopaedic Problems

Neither immobilization nor intermittent active motion stimulated adequate healing of full-thickness defects in articular cartilage. Nevertheless, intermittent active motion was definitely preferable to immobilization, since it is clear from the experimental results that after injury to the articular surface, prolonged immobilization promotes the formation of intra-articular adhesions. Therefore, at present we recommend that in the management of such injuries, early intermittent active motion should be encouraged whenever feasible to prevent adhesions.

Although the potential applications of continuous passive motion to the management of diseased and injured synovial joints in humans are exciting to contemplate, it would be premature to apply this concept to the clinical care of patients at present. Such application should await the completion and reporting of continuing investigations, currently in progress, to assess the durability of the newly formed hyaline articular cartilage after long periods of normal weight-bearing function.

Conclusions

On the basis of the results of this investigation, we believe that our hypothesis (that continuous passive motion of a synovial joint *in vivo* would have a beneficial biological effect on the healing of full-thickness defects in articular cartilage) is valid, and we offer the following conclusions.

1. Continuous passive motion of a knee joint during the first four weeks after operation is well tolerated by both

adolescent and adult rabbits and does not seem to disturb their general well-being.

2. Continuous passive motion does no harm to the intact, normal living articular cartilage in rabbits' knees as determined by gross and microscopic examinations.

3. Intra-articular adhesions complicate the process of repair of full-thickness defects in the articular cartilage of rabbits' knees that have been immobilized postoperatively for longer than three weeks. Such adhesions are prevented both by intermittent active motion and by continuous passive motion.

4. Continuous passive motion stimulates much more rapid and more complete healing of full-thickness defects in the articular cartilage of rabbits' knees than does either immobilization or intermittent active motion. At three weeks, continuous passive motion of the knee joints had stimulated healing by hyaline articular cartilage in 52 per cent of the forty defects in adolescent rabbits and in 44 per cent of the thirty-six defects in adult rabbits. The neochondrogenesis in the healing of these defects seemed to occur through differentiation of the pluripotential cells of the subchondral tissues to chondrocytes as a result of the stimulation provided by continuous passive motion of the joint.

5. The long-term durability of this newly formed hyaline articular cartilage after the resumption of normal weight-bearing function must be determined by continuing investigation of the biological effect of continuous passive motion on the healing of full-thickness defects of articular cartilage.

NOTE: The authors are grateful to Arthur W. Ham, Professor Emeritus, Department of Anatomy, Division of Histology, Faculty of Medicine, University of Toronto, for his continuing interest and encouragement in this investigation from the time of its inception.

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Periprosthetic bone loss in total hip arthroplasty. Polyethylene wear debris and the concept of the effective joint space

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Periprosthetic Bone Loss in Total Hip Arthroplasty

Polyethylene Wear Debris and the Concept of the Effective Joint Space*

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ABSTRACT: Thirty-four hips in which there had been prosthetic replacement were selected for study because of the presence of linear (diffuse) or lytic (localized) areas of periprosthetic bone loss. In all hips, there was careful documentation of the anatomical location of the material that had been obtained for histological analysis, and the specific purpose of the removal of the tissue was for examination to determine the cause of the resorption of bone. Specimens from twenty-three hips were retrieved during an operation and from eleven hips, at autopsy. The area of bone loss was linear only in sixteen hips, lytic only in thirteen, and both linear and lytic in five.

In all thirty-four hips, intracellular particulate debris was found in the macrophages that were present in the area of bone resorption. All thirty-four had intracellular particles of polyethylene, many of which were less than one micrometer in size. Thirty-one hips had extracellular particles of polyethylene as well. Twenty-two of the thirty-four hips had intracellular metallic debris; in ten, metallic debris was found extracellularly as well. Ten of the sixteen cemented specimens had intracellular and extracellular polymethylmethacrylate debris.

In the mechanically stable prostheses — cemented and uncemented — polyethylene wear debris was identified in areas of bone resorption far from the articular surfaces. The number of macrophages in a microscopic field was directly related to the amount of particulate polyethylene debris that was visible by light microscopy.

Although the gross radiographic appearances of linear bone loss and lytic bone loss were different, the histological appearance of the regions in which there was active bone resorption was similar. Regardless of the radiographic appearance and anatomical origin of the specimen, bone resorption was found to occur in association with macrophages that were laden with polyethylene debris. In general, the number of macrophages present had a direct relationship to the degree of bone resorption that was seen.

We believe that these findings indicate that joint fluid penetrates far more extensively than previously thought, even in a well fixed component, along the interface between the prosthesis and bone and in the periprosthetic tissues; it is often more extensive than is shown by arthrography.

We therefore suggest the concept of the effective joint space to include all periprosthetic regions that are accessible to joint fluid and thus accessible to particulate debris. We also suggest that the difference between lytic (localized) bone loss and linear (diffuse) bone loss may be related to the local concentration or distribution of particulate wear debris; this may in turn depend on patterns of the flow of joint fluid (preferential flow) within the effective joint space.

Before total hip arthroplasty became common, localized bone destruction was almost always secondary to tumor, infection, or metabolic disease and was rarely seen with endoprostheses[40]. When periprosthetic bone loss appears localized or scalloped, it has been called osteolysis or lysis[11], to distinguish it from bone loss that is linear or more evenly distributed around the implant.

Osteolysis was observed by Charnley early in the development of low-friction arthroplasty, but because of the frequent occurrence of infection early in his series, he attributed the osteolysis to the infection[8]. The discovery of particulate polymethylmethacrylate in specimens from focal areas of lysis around both stable and loose prostheses, as well as from areas of more linear and uniform bone resorption, gave rise to the concept of so-called cement disease[25,27]. One of the proposed advantages of fixation without cement is avoidance of this complication. However, lysis has been reported in association with both stable and loose uncemented femoral components, indicating that the problem is broader in scope and is far from solved[21,29].

The observation of particulate metallic debris in histological sections from localized regions of aggressive lysis around uncemented implants has generated additional controversy about the best alloy for joint replace-

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TABLE I

DATA ON THE THIRTY-FIVE HIPS*

Case†	Sex, Age (Yrs.)	Diagnosis	Type of Fixation, Prosthesis‡	Duration *in Situ* (Mos.)	Symptoms	Source	Location	Bone Loss	Mechanical Stability
1	M, 68	Post-traumat. arthritis	Uncemented, H-G	20	Pain in thigh	Operation	Femur	Linear	Loose
2	M, 65	Osteoarth.	Uncemented, H-G	17	Pain in thigh	Operation	Femur	Linear	Loose
3	M, 56	Osteoarth.	Uncemented, H-G	36	Pain in thigh	Operation	Femur	Linear	Well fixed
4	M, 59	Osteoarth.	Uncemented, H-G	27	Pain	Operation	Femur	Linear	Loose
5	M, 57	Osteoarth.	Uncemented, H-G	21	Pain	Operation	Femur	Linear	Loose
6	M, 61	Osteoarth.	Uncemented, H-G	36	Pain in thigh	Operation	Femur	Lytic	Loose
7	M, 40	Slipped cap. femoral epiphysis	Uncemented, H-G	35	Pain in thigh	Operation	Femur	Linear/ lytic	Well fixed
8	F, 59	Avascular necrosis	Uncemented, H-G	44	Pain in thigh	Operation	Femur	Lytic	Loose
	F, 59	Avascular necrosis	Uncemented, H-G	44	Pain in thigh	Operation	Acetab.	Linear	Well fixed
9	M, 41	Post-traumat. arthritis	Uncemented, H-G	50	Pain in thigh	Operation	Femur	Lytic	Loose
10	M, 68	Osteoarth.	Uncemented, H-G	72	Pain	Operation	Femur	Linear/ lytic	Loose
	M, 68	Osteoarth.	Uncemented, H-G	72	Pain	Operation	Acetab.	Lytic	Well fixed
11	F, 55	Post-traumat. arthritis	Uncemented, AML	16	Pain	Operation	Femur	Linear	Loose
12	M, 57	Osteoarth.	Uncemented, PCA	36	Pain in thigh	Operation	Acetab.	Linear	Loose
13	M, 39	Slipped cap. femoral epiphysis	Uncemented, H-G	57	Pain in thigh	Operation	Femur	Linear	Loose
14	F, 62	Fracture	Uncemented, H-G	6	Pain in groin	Operation	Femur	None	Well fixed
15	M, 56	Osteoarth.	Uncemented, PSR	52	Asymptomatic	Operation	Femur	Lytic	Well fixed
16	M, 53	Osteoarth.	Uncemented, PSR	30	Asymptomatic	Operation	Femur	Lytic	Well fixed
17	F, 57	Osteoarth.	Uncemented, PSR	39	Asymptomatic	Operation	Femur	Lytic	Well fixed
18	M, 62	Osteoarth.	Cemented, Mueller	38	Pain	Operation	Femur	Lytic	Loose
19	M, 63	Osteoarth.	Cemented, Mueller	60	Pain	Operation	Femur	Lytic	Loose
20	F, 62	Congen. disloc. of hip	Cemented, Harris	72	Pain	Operation	Femur	Lytic	Well fixed
21	F, 58	Congen. disloc. of hip	Cemented, Harris	93	Pain in groin	Operation	Femur	Lytic	Well fixed
22	F, 60	Osteoarth.	Cemented, T-28	86	Asymptomatic	Operation	Femur	Lytic	Well fixed
23	F, 42	Post-traumat. arthritis	Cemented, Harris	156	Pain in groin	Operation	Femur	Lytic	Well fixed
24	M, 66	Osteoarth.	Uncemented, AML	60	Asymptomatic	Autopsy	Femur	Lytic	Well fixed
25	M, 70	Osteoarth.	Cemented, Mueller	156	Asymptomatic	Autopsy	Acetab.	Linear	Well fixed
26	M, 73	Osteoarth.	Cemented, HD-2	114	Asymptomatic	Autopsy	Acetab.	Linear	Well fixed
27	F, 94	Osteoarth.	Cemented, HD-2	NA	Asymptomatic	Autopsy	Acetab.	Linear	Well fixed
28	F, 97	Osteoarth.	Cemented, A-T	118	Asymptomatic	Autopsy	Acetab.	Linear	Well fixed
29	F, 93	Osteoarth.	Cemented, Mueller	209	Asymptomatic	Autopsy	Acetab.	Linear	Loose
30	F, 91	Osteoarth.	Cemented, HD-2	129	Asymptomatic	Autopsy	Acetab.	Linear	Loose
31	F, 79	Osteoarth.	Cemented, Mueller	180	Asymptomatic	Autopsy	Femur	Linear	Well fixed
32	F, 73	Osteoarth.	Cemented, A-T	102	Asymptomatic	Autopsy	Femur	Linear	Well fixed
33	M, 82	Osteoarth.	Cemented, Mueller	82	Pain	Autopsy	Femur	Linear/ lytic	Loose
34	F, 82	Osteoarth.	Cemented, HD-2	137	Asymptomatic	Autopsy	Femur	Linear/ lytic	Well fixed
35	M, 52	Osteoarth.	Uncemented, H-G	82	Pain	Operation	Greater troch.	Lytic	Well fixed
	M, 52	Osteoarth.	Uncemented, H-G	82	Pain	Operation	Acetab.	Lytic	Well fixed

*One hip (Case 14) that had no bone loss was included for comparison.

†Cases 7, 18 and 19, 20 and 21, 22 and 23, 25 through 30, and 31 and 32 have been reported on previously[11,22,28,30,43].

‡H-G = Harris-Galante prosthesis, AML = Engh prosthesis, PCA = porous-coated anatomic prosthesis, PSR = porous-surface replacement, HD-2 = Harris Design 2 prosthesis, T-28 = Trapezoidal-28 prosthesis, and A-T = Aufranc-Turner prosthesis.

ment. Both particulate cobalt-chromium and particulate titanium alloy have been observed in association with loosening and with loss of bone stock in total hip arthroplasty without cement[2,6,16,29,35].

Immunohistological comparison of tissue from areas of aggressive localized bone resorption (osteolysis) with tissue from areas of linear bone loss led Santavirta and associates to propose that the aggressive localized lesions are a distinct pathological entity[38-40,43,44].

We undertook the present study in an attempt to define further the mechanisms of periprosthetic bone resorption.

Materials and Methods

Twenty-three carefully documented operative cases and eleven autopsy cases were included; for each, the exact anatomical origin of the specimen of tissue was known, and every specimen had been obtained specifically to study the pathology of bone loss. The collection included examples of both diffuse (linear) and lytic (localized) bone loss around well fixed and loose implants, cemented and uncemented, from the femur and acetabulum (Table I).

Bone loss was strictly linear in sixteen hips, lytic in thirteen, and both linear and lytic in five. The prosthesis had been cemented in sixteen hips (in eight of these the bone resorption was lytic), and no cement had been used in nineteen (ten had lysis). The area of bone loss that was studied was in the femur in twenty-four cases, in the acetabulum in seven, and in both the femur and acetabulum in three.

We included two hips that had been analyzed in our original report on osteolysis after total hip replacement[11], two from our study of osteolysis in mechanically stable cemented total hip replacements[22], two from the follow-up report on bone lysis in well fixed cemented femoral components[28], and one from the study of osteolysis in association with stable uncemented femoral components[29]. Two femoral specimens retrieved at autopsy[30] and six acetabular components retrieved at autopsy also had been reported on previously[43]. All specimens that had been reported on previously were re-examined.

In three of the hips from our present study, the prostheses were porous-surface replacement implants with a femoral bearing surface of titanium alloy. These have been shown to have a high rate of wear and are associated with rapidly progressive destruction of bone in the femoral neck and head, leading to early clinical failure[35].

In addition to the thirty-four hips in which there was periprosthetic bone resorption, one hip (Case 14) was included for comparison. This hip was mechanically stable, had uncemented implants, and had no bone loss as demonstrated on radiographs. Revision had been done at six months because the patient had substantial limb-length inequality and pain in the groin secondary to an incorrectly sized biarticular component.

TABLE II

LOOSENING, AS DEMONSTRATED ON PLAIN RADIOGRAPHS AND ON ARTHROGRAMS

	Plain Radiographs		Arthrograms	
Case	Femoral Component	Acetabular Component	Femoral Component	Acetabular Component
1	Loose	Well fixed	Not done	Not done
2	Loose	Loose	Negative	Negative
3	Well fixed	Well fixed	Negative	Negative
4	Loose	Well fixed	Positive	Negative
5	Well fixed	Well fixed	Positive	Negative
6	Loose	Well fixed	Positive	Negative
7	Loose	Well fixed	Positive	Negative
8	Loose	Well fixed	Positive	Negative
9	Loose	Well fixed	Positive	Negative
10	Loose	Well fixed	Not done	Not done
11	Loose	Bipolar	Negative	Bipolar
12	Well fixed	Loose	Negative	Negative
13	Loose	Well fixed	Not done	Not done
14*	Well fixed	Bipolar	Positive	Bipolar
15	Well fixed	Well fixed	Not done	Not done
16	Well fixed	Well fixed	Not done	Not done
17	Well fixed	Well fixed	Not done	Not done
18	Loose	Loose	Not done	Not done
19	Loose	Loose	Not done	Not done
20	Well fixed	Well fixed	Not done	Not done
21	Well fixed	Loose	Negative	Positive
22	Well fixed	Well fixed	Negative	Negative
23	Well fixed	Loose	Negative	Positive
24	Well fixed	Well fixed	Not done	Not done
25	Not applic.	Well fixed	Not done	Not done
26	Not applic.	Well fixed	Not done	Not done
27	Not applic.	Well fixed	Not done	Not done
28	Not applic.	Well fixed	Not done	Not done
29	Not applic.	Well fixed	Not done	Not done
30	Not applic.	Well fixed	Not done	Not done
31	Well fixed	Not applic.	Not done	Not done
32	Well fixed	Not applic.	Not done	Not done
33	Loose	Not applic.	Not done	Not done
34	Well fixed	Not applic.	Not done	Not done
35	Well fixed	Well fixed	Negative	Negative

*No bone loss was seen on radiographs.

The radiographs were assessed for the stability of the components as well as for the type and the location of the bone loss. The radiographic criteria for loosening of the femoral component were subsidence or any other change in the position of the component or development of a radiolucency at the interface between the metal and the cement[32]. The radiographic criteria for a loose acetabular component were migration of the component, fracture of the cement, or a complete radiolucency of any width about the entire cement-bone interface on any radiograph[14,32,43]. Arthrography was done before the operation in fifteen hips (Table II). The arthrographic criteria for loosening of either the femoral or the acetabular component have been published[36].

All implants were tested mechanically for stability with the exception of Case 22, in which there were no symptoms or radiographic signs of loosening; only a biopsy and grafting of the lytic lesion in the lateral portion of the mid-femur were performed.

Fig. 1

Case 17. Transmission electron micrograph (× 30,000) showing tissue taken from an area of aggressive bone resorption in the proximal part of the femur after an uncemented surface replacement arthroplasty. The macrophage contains intracytoplasmic, oval, granular, electron-lucent, membrane-bound structures that are considered to be phagocytized polyethylene particles. In this field, the large particle (arrowhead) measures approximately 1.2 by 0.4 micrometers and the small particle (below the arrowhead) measures approximately 0.2 by 0.1 micrometer. N = nucleus.

For the specimens that were retrieved at an operation, conventional (stemmed) femoral components were tested intraoperatively by application of a 22.6-newton-meter torque load in retroversion and measurement of the amount of displacement relative to bone[7]. Surface-replacement components were only loaded manually and assessed qualitatively. Acetabular components were evaluated at the operation by the surgeon, who applied a load manually to the rim of the component in both tension and compression and watched for motion and for evidence of blood or other fluid arising from the interface. Visible motion or any fluid expressed from the interface indicated lack of rigid fixation of the acetabular component to bone[14].

For specimens that were retrieved at autopsy, stability of the femoral component was also assessed by application of a torque load in retroversion. Additionally, axial and transverse motions of the stem were measured under conditions of simulated stance and stair-climbing with methods that have been described[7,30]. Acetabular components that were retrieved at autopsy were evaluated for mechanical stability in simulated stance with the use of a method described previously[10]. In another loading test, torque was applied parallel to the mouth of the unloaded socket, and the displacement of the polyethylene component relative to the bone was recorded for torques of as much as 11.3 newton-meters[43].

Specimens obtained for histological analysis were fixed in formalin, decalcified in EDTA, embedded in paraffin, cut into five-micrometer sections, stained with hematoxylin and eosin, and examined under both plain and polarized light. Due to the small size of some prosthetic particulate debris, cells in all sections were examined meticulously with a magnification factor of as much as 2000 and with the use of oil immersion and very high-quality optics. All sections were studied blindly and were graded in a semiquantitative fashion for cellular constituents and particulate debris (Table III) by two of us (T. P. S. and M. J.). Grade 0 indicated that the particles in question were not seen in that section; Grade 1, that the particles were present in a limited amount or distribution and were not readily apparent; Grade 2, that the particles were a general feature of the section; and Grade 3, that the amount of particles was striking and dominated the histological picture. A qualitative estimation of the ratio of macrophages to fibroblasts in a histological section was also recorded. In regions of active bone resorption, the cellular constituents and predominant species of particle in the immediate vicinity of the bone resorption were specifically recorded in an attempt to define the pathogenesis of the bone resorption more clearly.

Particulate metal was identified as oval particles that did not transmit light or take up stain and therefore appeared dark or black with plain-light illumination. Particles of metal were also identified by light diffraction around their edges, which was enhanced with polarized light.

Because particulate polyethylene transmits light and is not stained by hematoxylin and eosin, it is usually not visible with plain-light illumination, an important criterion for the correct identification of polyethylene. When viewed under polarized light, however, polyethylene is birefringent and appears as needles or filaments within the area that appears unoccupied when plain-light examination is used. Particulate polymethylmethacrylate may be difficult to identify with certainty on standard sections that have been stained with hematoxylin and eosin. The processing of specimens in xylene (used for all specimens in this study) dissolves out lipids and most, if not all, of the particulate polymethylmethacrylate; sites previously occupied by these particles then appear as empty spaces. These spaces may be within a macrophage or may be extracellular and surrounded by inflammatory cells. They may contain granules of barium sulfate if it was added to the polymethylmethacrylate for radiographic contrast.

Further confirmation of the presence of very small

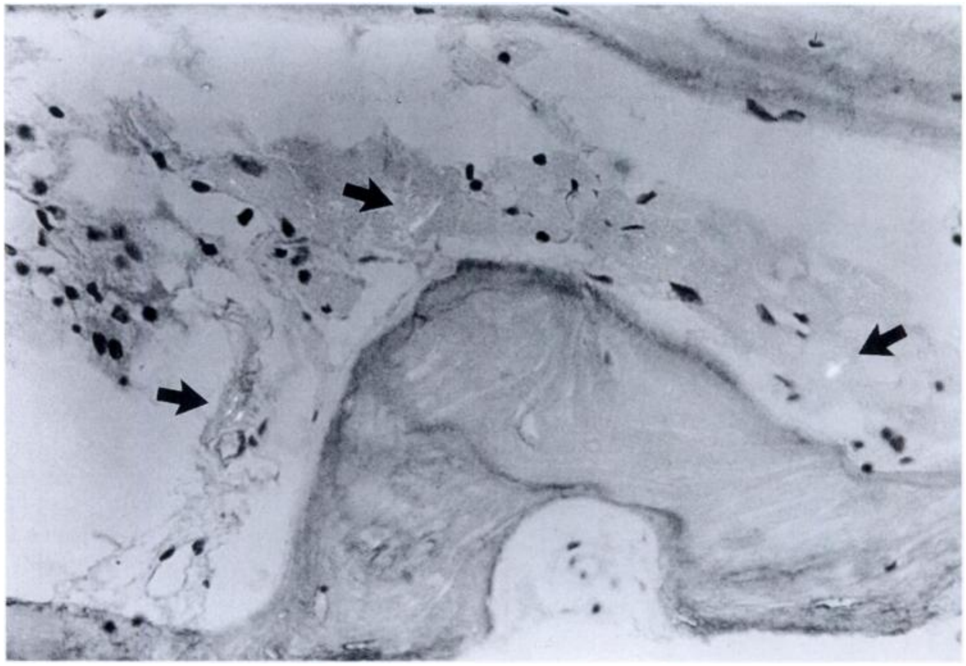

FIG. 2

Case 22. Photomicrograph (hematoxylin and eosin, ×250) showing tissue obtained from the area of bone resorption, containing numerous foamy macrophages. The cytoplasm of these macrophages is filled with particulate polyethylene. The larger particles appear as bright needles (arrows) under polarized light.

particulate polyethylene debris was obtained by examination of several representative sections with transmission electron microscopy. These specimens were fixed in glutaraldehyde and were processed with standard techniques. The specimens chosen for transmission electron microscopy had shown a predominance of macrophages on light microscopy; when examined with polarized light, these macrophages were full of birefringent polyethylene particles of various sizes.

Results

Both linear and lytic bone loss were found in associ-

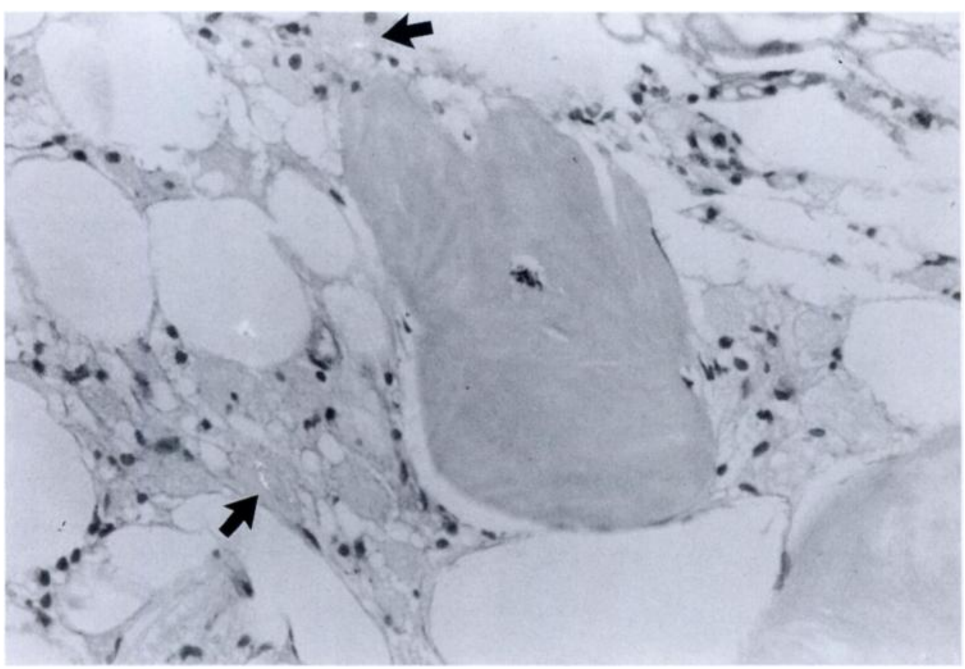

FIG. 3

Case 21. Tissue obtained from the area of osteolysis reveals numerous foamy macrophages that infiltrate the marrow (hematoxylin and eosin, ×250). The cytoplasm of these macrophages is filled with particulate polyethylene. Under polarized light, the larger particles appear as bright needles (arrows).

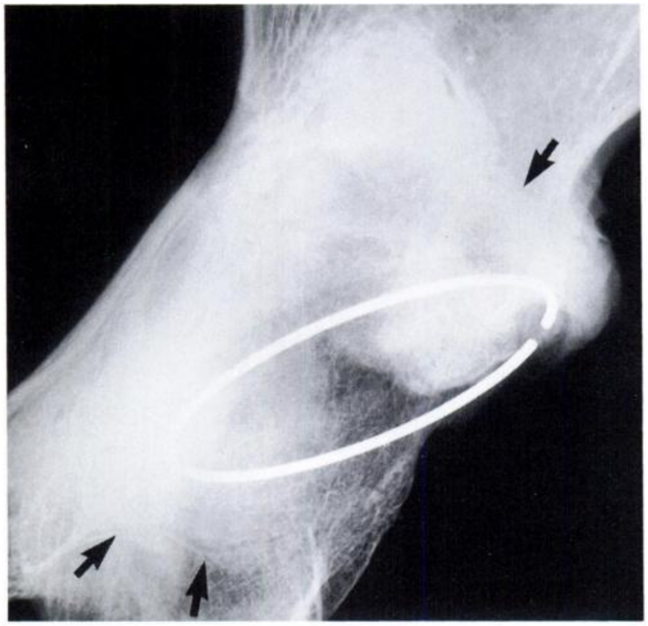

FIG. 4-A

Figs. 4-A through 4-D: Case 28. Linear (diffuse) bone loss.

Fig. 4-A: Anteroposterior radiograph of an acetabular specimen that was retrieved at autopsy, displaying diffuse narrow, linear radiolucencies (arrows). The acetabular component was shown to be well fixed by mechanical testing.

ation with cemented and uncemented implants, whether or not the prosthesis was stable (Table I).

Particles of polyethylene were found in macrophages in all thirty-four hips, and extracellular particles of polyethylene were found in thirty-one. Many of the particles of polyethylene were less than one micrometer in length. Giant cells were also identified, but they were relatively rare; larger particles were seen in giant cells more often than in macrophages. The lengths of the polyethylene particles ranged from less than one micrometer to more than 100 micrometers; most of the particles were intracellular and were less than ten micrometers long.

Particulate polyethylene was found at great distances from the articular surfaces in association with both linear and lytic bone loss and in both stable and unstable implants. In hips with or without cement, particulate polyethylene was found in areas of bone resorption that were distal to the tip of the femoral component.

A finding that was common to all specimens, with and without cement, was a very fine diffuse birefringence in the cytoplasm of the macrophages and giant cells under polarized light. This diffuse birefringence was not seen in any other cells and was similar to the birefringence characteristic of needle-like or filamentous polyethylene particles that are several micrometers long. Such diffuse birefringence was seen in phagocytic cells, both with or without intracellular particles that were several micrometers long, which were easily identified as polyethylene on the basis of their characteristic morphology and birefringence. Analysis of selected sections by transmission electron microscopy confirmed the presence of particles that were less than one micrometer in length within the macrophages. The appearance of these small particles on electron microscopy supported the proposal that these particles were composed of polyethylene (Fig. 1).

Twenty-two of the thirty-four hips had intracellu-

FIG. 4-B

A portion of the cement-bone interface from the area of linear radiolucency shown in Figure 4-A. Polymethylmethacrylate was dissolved out of the section during processing, but it had occupied the space at the top of the section (hematoxylin and eosin, × 100). A layer of predominantly fibrous tissue is interposed between the cement and the bone (small arrows); it contains only scattered macrophages. This region corresponds to the linear radiolucent line. Deep to the layer of fibrous tissue, however, there is a focal excavation into the bone (large arrow).

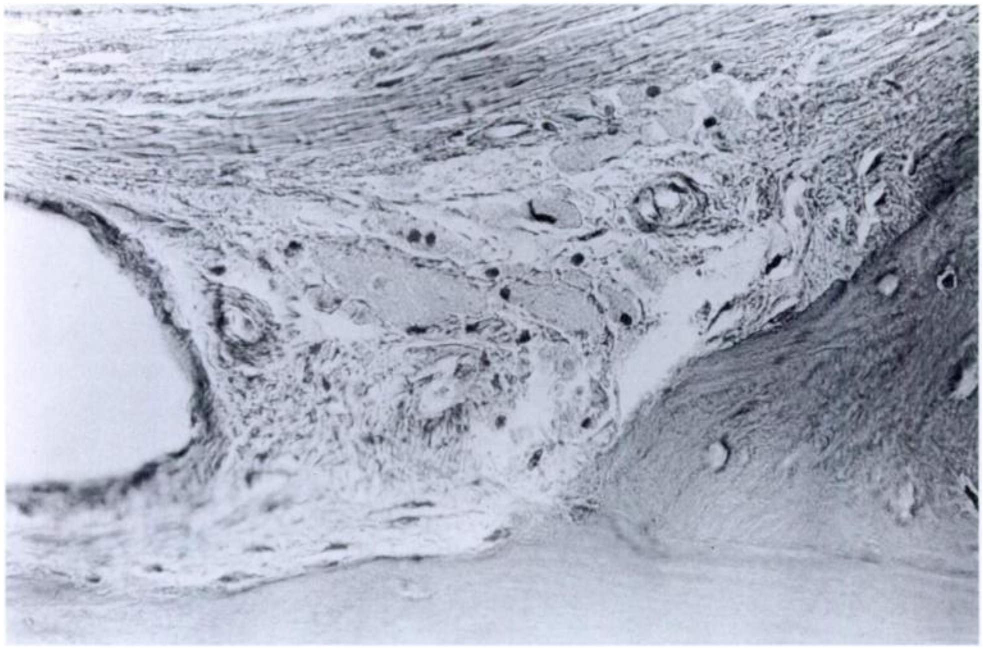

FIG. 4-C

The tissue eroding the bone is distinctly different in composition, containing a small collection of macrophages (hematoxylin and eosin, × 250).

lar metallic debris, and extracellular metallic debris was found in ten hips. The range in the size of particulate metal that was detectable within the spectrum of visible light was quite narrow (from less than one to five micrometers).

Both particulate polyethylene and metal were identified in specimens from all hips with no cement. Metallic debris was predominant and impressive in some (such as Cases 1, 2, and 3). However, particulate polyethylene always was present when particulate metal was found. In general, the particulate polyethylene was dispersed more widely throughout the specimens; particulate metal often was limited to the side of the specimen that faced the implant.

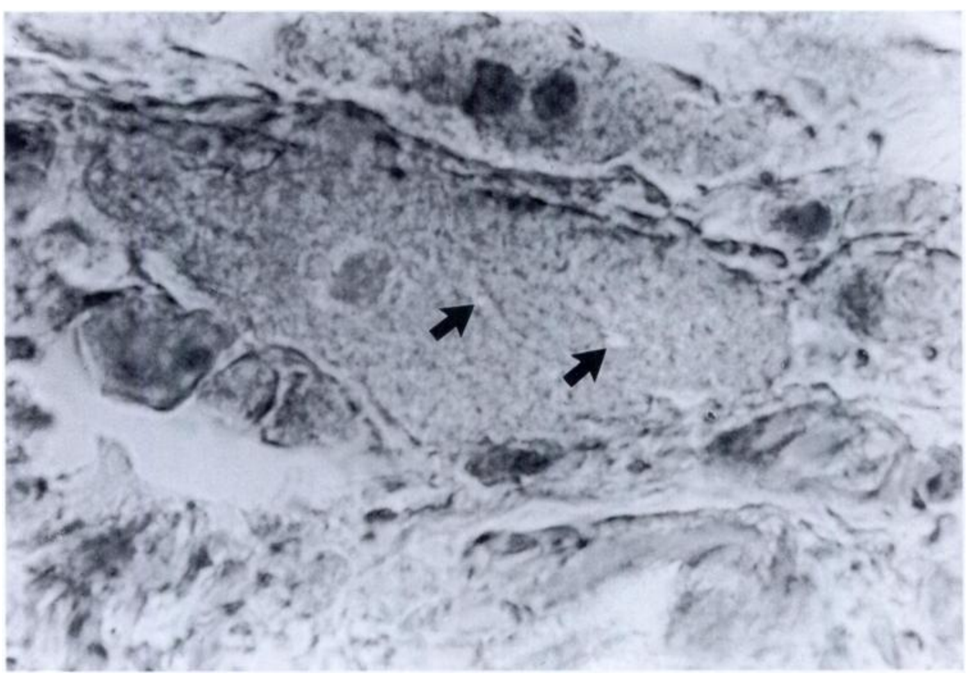

FIG. 4-D

In this photomicrograph viewed under polarized light and with oil immersion and high magnification (hematoxylin and eosin, × 1000), the macrophages are shown to be filled with multiple small polyethylene particles. Only a few of the larger intracellular particles (arrows) are visible on this black-and-white reproduction.

TABLE III
HISTOLOGICAL FINDINGS

Case	Location of Section	Bone Loss	Particulate (Extracellular/Intracellular)*			Ratio of Macrophages to Fibroblasts†	Active Bone Resorption
			Metal	Polyethylene	Polymethyl-methacrylate		
1	Femur	Linear	2/3	0/1	—	Low	No
2	Femur	Linear	0/2	1/2	—	Low	No
3	Femur	Linear	1/2	2/2	—	Low	No
4	Femur	Linear	0/1	1/2	—	Intermed.	No
5	Femur	Linear	0/2	1/2	—	High	No
6	Prox. femur	Lytic	3/2	1/2	—	Intermed.	Yes
	Dist. femur	Lytic	0/1	1/2	—	Intermed.	Yes
7	Dist. femur	Linear/lytic	0/1	0/2	—	Intermed.	No
	Dist. femur	Lytic	2/0	0/2	—	Intermed.	No
8	Dist. femur	Lytic	0/1	1/2	—	High	No
	Acetab. rim	Linear	0/0	1/1	—	High	No
9	Dist. femur	Lytic	0/1	1/2	—	High	No
	Dist. femur	Lytic	0/1	0/1	—	Intermed.	No
	Prox. femur	Lytic	0/1	1/2	—	Intermed.	No
	Calcar	Lytic	0/1	1/2	—	Intermed.	No
10	Dist. femur	Linear/lytic	0/1	1/3	—	Intermed.	No
	Dist. femur	Linear/lytic	1/2	1/3	—	Intermed.	No
	Prox. femur	Linear/lytic	0/1	0/3	—	Intermed.	No
	Calcar	Lytic	0/1	2/3	—	High	No
	Mid. femur	Linear/lytic	0/1	1/2	—	High	Yes
	Fem. shoulder	Linear/lytic	0/1	2/2	—	Intermed.	No
	Acetab. lysis	Lytic	1/2	1/3	—	High	Yes
	Screw-hole	Lytic	0/1	2/2	—	High	No
	Acetab. rim	Linear	0/1	1/2	—	Low	Yes
11	Femur	Linear	0/1	1/3	—	Low	No
12	Med. acetab.	Linear	0/1	0/1	—	Low	No
	Med. acetab.	Linear	0/1	0/1	—	Low	No
	Acetab. lining	Linear	0/1	0/2	—	Low	No
	Acetab. lining	Linear	0/0	0/1	—	Low	No
	Acetab. lining	Linear	0/0	2/2	—	Intermed.	No
13	Mid. femur	Linear	0/2	1/2	—	Intermed.	No
14	Femur	None	1/1	0/0	—	Very low	No
15	Femur	Lytic	1/2	1/2	—	High	Yes
16	Femur	Lytic	1/2	1/2	—	High	Yes
17	Femur	Lytic	1/2	1/2	—	High	Yes
18	Femur	Lytic	1/1	1/1	2/2	High	Yes
19	Femur	Lytic	1/1	1/1	2/2	High	Yes
20	Femur	Lytic	0/1	1/2	2/2	High	Yes
21	Dist. femur	Lytic	0/1	1/2	2/2	Intermed.	Yes
22	Femur	Lytic	0/0	1/2	1/1	High	Yes
23	Femur	Lytic	0/0	0/1	1/1	High	Yes
24	Calcar	Lytic	0/1	1/2	—	High	Yes
25	Acetab.	Linear	0/0	1/2	0/0	Low	Yes
26	Acetab.	Linear	0/0	1/2	0/0	Low	Yes
27	Acetab.	Linear	0/0	1/2	0/0	Low	Yes
28	Acetab.	Linear	0/0	1/2	1/1	Low	Yes
29	Acetab.	Linear	0/0	1/2	1/1	Low	Yes
30	Acetab.	Linear	0/0	1/2	1/1	Low	Yes
31	Prox. femur	Linear	0/0	1/2	0/0	High	Yes
32	Prox. femur	Linear	0/0	1/2	0/0	High	Yes
33	Prox. femur	Linear	0/0	1/2	1/1	High	Yes
	Prox. femur	Lytic	0/0	1/2	1/1	High	Yes
34	Prox. femur	Linear	0/0	1/2	0/0	High	Yes
	Femur	Lytic	0/0	1/2	0/0	High	Yes
35	Greater troch.	Lytic	0/1	2/2	—	High	Yes
	Acetab.	Lytic	0/1	1/2	—	High	Yes

*0 = no particles were seen, 1 = particles were present in a limited amount or distribution and were not readily apparent, 2 = particles were a general feature, and 3 = the amount of particles was striking and dominated.
†Low = 1:20, intermediate = 20:20, and high = 20:1.

Particulate polymethylmethacrylate could be identified in specimens from ten of the sixteen hips with cement. Even here, particulate polyethylene was found far from the articular surfaces, in association with bone loss next to both loose and mechanically stable implants (Fig. 2). In one striking example, particulate polyethylene was found in an area of bone resorption that extended ten centimeters inferior to the distal tip of the solidly fixed cement-plug (Fig. 3).

Particulate debris invariably was accompanied by macrophages. Most particles were intracellular in macrophages, and different species of particles (polyethylene, metal, and polymethylmethacrylate) could be seen within the same macrophage. Within the range of sizes of

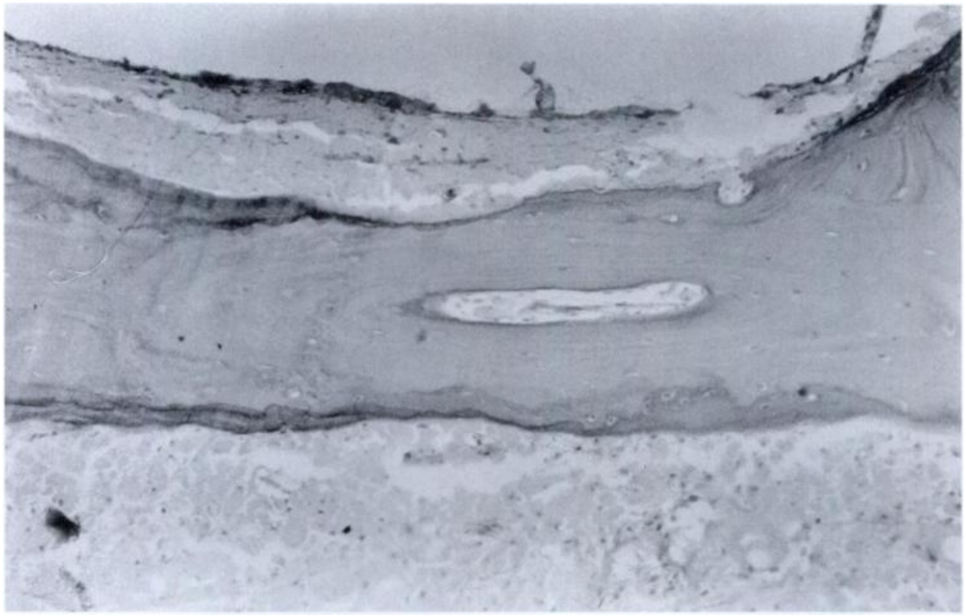

FIG. 5

Area of bone resorption in the region of the femoral neck from a mechanically stable specimen that was obtained at autopsy. There is a high concentration of foamy macrophages (hematoxylin and eosin, × 100).

FIG. 6-A

FIG. 6-B

Figs. 6-A and 6-B: Case 14. Demonstration of the effective joint space. The patient complained of pain in the groin and lengthening of the extremity on the side that had been operated on.

Fig. 6-A: Anteroposterior radiograph of the hip five months after bipolar arthroplasty. There is no radiographic evidence of bone loss.

Fig. 6-B: Anteroposterior projection of an arthrogram made five months after bipolar arthroplasty. There is tracking of the contrast medium along the stem, with pooling at the tip of the stem (arrow). At the operation, the femoral component was found to be well fixed by extensive ingrowth of bone; this was confirmed histologically.

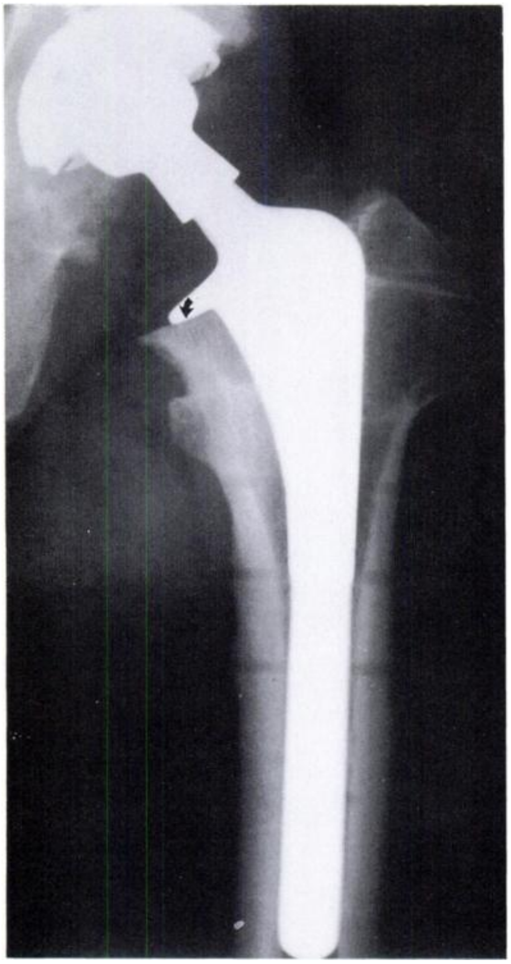

FIG. 7-A

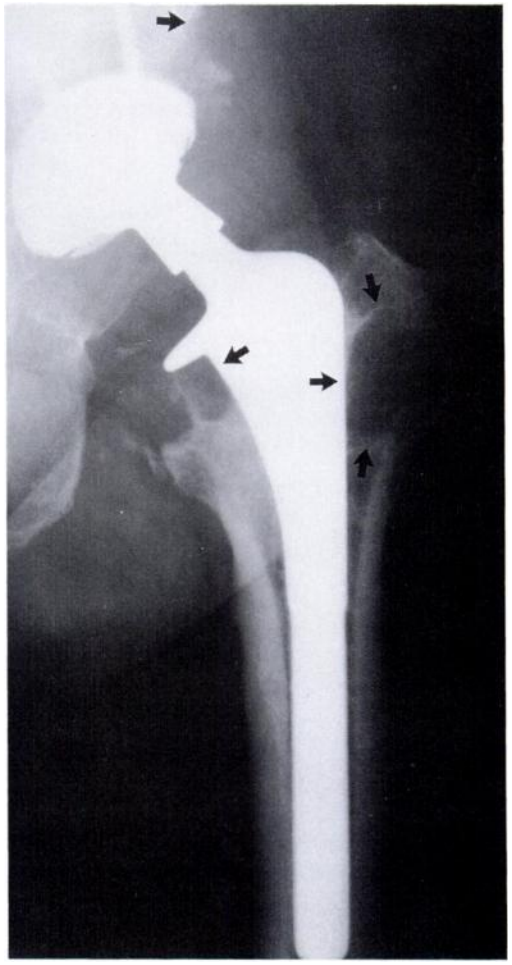

FIG. 7-B

Figs. 7-A, 7-B, and 7-C: Case 35. Anteroposterior radiographs of the hip of a fifty-two-year-old man who had a primary uncemented total hip replacement after an intertrochanteric osteotomy for osteoarthrosis.

Fig. 7-A: There is excellent contact between the collar of the prosthesis and the femoral neck (arrow) and good filling of the diaphysis by the prosthesis on this radiograph, made soon after the operation.

Fig. 7-B: After eighty-two months, there was extensive resorption of the femoral neck and evidence of osteolysis in the greater trochanter and superolateral acetabulum (arrows). The channel left by the removed blade-plate probably created a route for preferential flow of joint fluid and wear debris into the greater trochanter. The position of the femoral head within the acetabulum is eccentric, indicating extensive wear of the polyethylene liner.

particles that could be detected by light microscopy, there was a strong and direct relationship between the number of macrophages in a field and the number of particles.

We observed a spectrum in the concentration of macrophages: from a relative paucity (ratio of macrophages to fibroblasts, 1:20) to sheets of macrophages (ratio of 20:1). When present, giant cells contained the same species of particles as did the macrophages in that same region. Lymphocytes were present focally in several specimens; the meaning of this sporadic finding was unclear. Acute inflammation was not seen[31].

Particulate debris and macrophages were present not only in the interface between bone and metal or between bone and cement; they frequently invaded marrow and the intertrabecular spaces of cancellous bone. Particulate debris also was found in the periprosthetic soft tissues. Linear aggregates of macrophages that were filled with particulate polyethylene often were seen in a well developed connective-tissue stroma of numerous fibroblasts and organized collagen. These aggregates of debris-laden phagocytic cells were not readily identified within the predominantly fibrous stroma and could easily be overlooked; the region would then be interpreted as being purely fibrous tissue.

Specimens in which the over-all concentration of macrophages was high were usually in areas where aggressive localized bone resorption was visible on radiographs; the sections in which there were relatively few macrophages and a predominance of fibroblasts generally showed a linear or more diffuse pattern of resorption (Figs. 4-A through 4-D).

The specimens in which the histological sections included bone that was being actively resorbed were particularly valuable. In all twenty-nine such sections, there were histological similarities regardless of the

FIG. 7-C

An arthrogram reveals contrast medium in the region of loss of bone from the femoral neck, around the shoulder of the prosthesis into the greater trochanter, and proximally into the superolateral acetabulum (arrows). Histological examination of tissue from all three sites was similar: concentrations of foamy macrophages and rare giant cells were found in association with active bone resorption. These inflammatory cells were filled with various-sized particles of polyethylene; particles of metal were rare.

type of fixation, the gross radiographic appearance of the bone loss, or the anatomical origin of the specimen. Regardless of the predominant stroma of the specimen, focal concentrations of macrophages were observed in direct association with the areas of bone resorption (Fig. 5). The cytoplasm of these macrophages was always filled with particulate debris. Although several species of particulate debris could be identified in nearly every such specimen, particulate polyethylene was identified in association with the bone resorption in every specimen, regardless of the type of fixation or the presence or absence of mechanical stability; in some regions of resorption, polyethylene was the only type of particle that was seen. Although in some specimens the bone destruction was clearly mediated by osteoclasts, in other specimens relatively few osteoclasts were identified. Occasionally, bone formation was also observed in areas adjacent to the resorptive areas.

Among the twelve arthrograms of hips that had no cement (Table II), the most striking finding was that in two hips (Cases 7 and 14) in which torque-testing had shown that the prosthesis was rigidly fixed and histological examination revealed ingrowth of bone, the contrast medium flowed rapidly and extensively in the bone-metal interface. In Case 7, there was both linear and lytic bone loss, and in Case 14, in which the bipolar component was revised after only six months, there was no apparent bone loss on radiographs (Figs. 6-A and 6-B).

Discussion

Now that technical advances have reduced the rates of infection and loosening of components after total hip replacement[9,32], the problem of periprosthetic loss of bone has become the major focus of attention. Although periprosthetic loss of bone and loss of mechanical stability often are associated, such bone loss clearly can occur without loosening of an implant[21,22,28,29].

Two fundamental questions remain unanswered: what initiates the loss of bone, and what factors determine whether the loss of bone is diffuse or more localized? Our findings prompted us to propose the following sequence of events in response to these questions.

Polyethylene wear debris and other particles are dispersed in the joint fluid. The true limits of the effective joint space are determined by how intimate the contact is between the prosthesis and bone and how this contact varies within a given reconstruction. This variability determines the access routes for the joint fluid and particulate debris, to and along the prosthetic-bone interfaces and through the soft tissues and bone as well. Joint fluid flows according to pressure gradients and simply follows the path of least resistance. In this sense, these areas that the joint fluid reaches become part of the joint space — hence our term effective joint space. The linear aggregates of macrophages that we saw running like a stream through connective-tissue stroma may also represent channels or routes through the periprosthetic soft tissues for particulate debris.

When small particles are present in sufficient numbers, phagocytosis can result in the activation of macrophages and in the direct resorption of the bone by macrophages[1,4,15,33,34,38]. In this manner, the local concentration of particles determines the degree of the inflammatory response and hence, the degree of resorption. As bone is resorbed, a bigger sink is produced, encouraging even more flow (preferential flow) into that area, delivering more particles and causing more bone resorption. When sufficient bone has been resorbed, an osteolytic area can be seen on radiographs (Figs. 7-A, 7-B, and 7-C). We postulate that if the joint fluid and its particles are distributed more evenly in an interface, there will be slower resorption of bone, accompanied by a fibroblastic response, resulting in the radiographic appearance of linear (diffuse) bone loss.

An intact barrier at the interface of metal and cement or of cement and bone may retard periprosthetic bone loss; the integrity of such a barrier may depend to some extent on the design of the component. Anthony et al.[3] published a report on four cases of localized femoral endosteal lysis of bone in which the area of lysis was shown, at revision, to be directly related to a region in which there was a local defect in the cement-mantle. In a prosthesis such as the one in that study (Exeter; Howmedica International, Shannon, Ireland), which was specifically designed to prevent bonding between the metal implant and the cement-mantle, debris can migrate in this space and reach the endosteal surface through defects in the mantle. A similar mechanism may be at work about stems that have been designed to be bonded to the cement-mantle but in which the bonding either is incomplete or has broken down after years of service and exposure to joint fluid.

The mechanisms by which joint fluid and particulate debris are transported around the effective joint space are under investigation. Accumulating evidence suggests a role for variations in pressure of joint fluid. Hendrix et al.[13] reported large variations in the pressure of intracapsular fluid around total hip replacements during activities of daily living. Anthony et al.[3] reported fluid pressures in an area of osteolysis of as much as 198 millimeters of mercury (26.4 kilopascals). Our studies indicated that pressures of intracapsular fluid are a function of contractions of muscle and position of the joint. Additionally, the peak intracapsular pressures do not coincide with loading of the joint. We believe that this non-phasic relationship is an important force that actively drives joint fluid and particulate debris through the effective joint space and fuels progressive bone loss[42].

The concept of preferential flow may also explain why uncemented femoral implants in which the porous coating is limited to the proximal part of the prosthesis more often have osteolysis around the distal part of the stem compared with implants in which the porous coating is more extensive[29].

Joint fluid and particulate debris may flow in both directions: not only can wear debris migrate into the periprosthetic space, but particles of metal and cement from the implant can be transported to the articular surfaces. The implications of this concept for hips that have accelerated wear from three-body mechanisms are profound.

Because they are completely intra-articular, the femoral sides of surface replacements are important clinical models of the effective joint space[5,12,17-19,35]. Howie et al.[19], reporting the histological findings in a large series of femoral resurfacing components retrieved at operation, found small particles of polyethylene in association with macrophages and active bone resorption adjacent to regions of intimate cement-bone contact before there was gross evidence of loosening. They concluded that wear particles migrate along cement-bone interfaces of implants that are both macroscopically and microscopically solid, and they emphasized the role of wear particles in this type of prosthetic loosening. Nasser et al.[35] reported aggressive cavitary osteolysis in the femoral neck and head in the presence of stable uncemented femoral surface replacements. These lesions contained sheets of macrophages filled with particulate debris from both the metal alloy and the polyethylene bearing surfaces. Bone was resorbed along a front in contact with the granulomatous tissue that filled the cystic lesions. The results of our analysis of surface replacement specimens are in complete agreement with the findings of Howie et al.[19] and Nasser et al.[35].

Additional evidence for the important role of the effective joint space in periprosthetic bone loss is provided by the analysis of the acetabular specimens that were retrieved at autopsy[43]. This study demonstrated that the process of late aseptic loosening of a cemented acetabular component is the result of progressive, three-dimensional resorption of the bone that is immediately adjacent to the cement, beginning circumferentially at the intra-articular margin and progressing toward the dome of the implant. The process appears to be caused by small particles of polyethylene migrating along the cement-bone interface; bone resorption occurs as a result of the inflammatory macrophage response to the particulate polyethylene. This suggests that the initiating mechanism of late aseptic loosening of a cemented acetabular component can be biological rather than mechanical. Similar histological findings have been described in the membranes from around loose uncemented acetabular components[38].

It was previously reported that the mechanism of loosening of cemented femoral components is mechanical in nature and that the initial events involve the loss of apposition between the prosthesis and cement (debonding) and fractures of the cement[30]. In the present study, we analyzed regions of the proximal part of the femoral cement-bone interface around several of these same cemented femoral components that had been retrieved at autopsy and compared the histological findings with those involved in the mechanism of loosening of cemented acetabular components. The histological appearance was identical: debris-laden macrophages were seen in association with regions of active bone resorption. This suggests that a similar biological process of periprosthetic bone resorption does occur in a roughly centrifugal fashion on both sides of the joint[24]. Because of the difference in the shape of the femoral and acetabular components, the effect of this type of resorption on the mechanical stability of these components is different. Two centimeters of circumferential bone resorption in the proximal part of the femoral cement-bone interface adjacent to the articulation of the hip does not generally result in loosening of a femoral implant because of the extent of the femoral cement-bone interface that remains intact. If two centimeters of the acetabular cement-bone interface adjacent to the articulation is disrupted by bone resorption, however, so much of the acetabular interface will be disrupted that stability will be jeopardized.

The deleterious effects of polyethylene wear debris in cemented hip implants have been extensively documented[16,18,24,31,37,43,45,46]. Willert and Semlitsch[45] suggested that the foreign-body reaction to particulate debris may result in loosening due to deterioration of contiguous bone anchors by the soft-tissue membrane. In an experimental animal model, resorption of bone around the perimeter of an intra-articular plug of polymethylmethacrylate has been demonstrated in the presence of particulate polyethylene and in the absence of mechanical load[20].

There were obvious differences, in the specimens in our study, in the relative amounts of macrophages, fibroblasts, and connective-tissue stroma. The most important difference between specimens from areas of localized lysis and those from areas of more diffuse linear resorption was in the proportions of the cellular constituents and matrix. In specimens from radiographically identified areas of osteolysis there was usually a predominance of macrophages throughout, with little connective-tissue stroma, but in specimens from areas of diffuse and linear loss, there was usually a predominance of fibroblasts and a variable amount of organized collagenous stroma with relatively few macrophages. There were distinct similarities, however, in the regions of active bone resorption, regardless of the radiographic distinction between diffuse and localized bone loss; localized collections of debris-laden macrophages were always seen in association with localized areas of bone resorption.

We noted a diffuse intracellular birefringence in the cytoplasm of the phagocytic cells when they were viewed at high magnification under polarized light. This observation has been made in specimens only when there were highly conforming bearing surfaces of polyethylene[41]. We have examined tissues from a broad range of other implants, including femoral intramedullary rods, titanium-alloy intercalary prostheses, cemented and uncemented Moore hemiarthroplasty components, titanium-alloy uncemented hemiresurfacing components, uncemented total hip implants that had ceramic femoral and acetabular bearing surfaces, McKee-Farrar total hip replacements, and total knee replacements, but the fine diffuse birefringence appears to be unique to systems with a highly conforming polyethylene bearing surface. We postulate that this background birefringence is caused by particles of polyethylene that are too small to be resolved clearly by light microscopy. The analysis of selected sections by transmission electron microscopy confirmed the presence of particles less than one micrometer in size within the macrophages, and these small particles appeared to be polyethylene (Fig. 1). Quantitative analysis by photon correlation spectroscopy has shown that most of the particulates in tissue that has been retrieved from total hip replacements in which there are bearing surfaces of polyethylene are less than one micrometer in size[26].

Activation of macrophages is a function of both the number and the type of particles[34]. This concept has important implications for wear-testing: the spectrum of sizes and the total number of debris particles that are generated may be at least as important as the total volume of material that is lost from the bearing surfaces over a given number of cycles. Regardless of the relative biological activity of a specific material in particulate form, if particles of that material are present in sufficient numbers and are phagocytized in sufficient amounts, macrophages will be activated. Small-particle disease therefore appears to be especially problematic, because of the high numbers and tremendous migratory potential of small particles. As has been demonstrated, particulate polyethylene can migrate in the effective joint space far from the articular surfaces.

Several of the cases of osteolysis in this comparative review have been previously reported[21,22,28,29,43]. In the early analysis of osteolysis around the cemented components, particulate polymethylmethacrylate was identified but the presence of the very small, submicrometer particles of polyethylene was not appreciated[11,22]. The identification of submicrometer particulate polyethylene in specimens from areas of bone resorption around uncemented implants led us to re-examine our specimens from cemented implants in hips that had aggressive localized bone loss. With this new perspective, submicrometer particles of polyethylene were identified as a common denominator in osteolysis associated with both cemented and uncemented implants.

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The Treatment of Certain Cervical-Spine Disorders by Anterior Removal of the Intervertebral Disc and Interbody Fusion

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The Treatment of Certain Cervical-Spine Disorders by Anterior Removal of the Intervertebral Disc and Interbody Fusion *

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INTRODUCTION

The purpose of this paper is threefold: to describe a surgical procedure for removal of cervical intervertebral discs and for fusion of the cervical spine by the anterior approach [16], to outline some indications for this procedure, and to report the results in the first fourteen patients in whom this surgical procedure was employed.

Disc degeneration, with or without accompanying osteophyte formation, subluxation, instability of one cervical vertebra on another, or intervertebral-disc protrusion is the pathological change usually associated with neck, suprascapular, interscapular, occipital, arm, hand, and chest pain stemming from the cervical spine.

In the authors' experience intervertebral-disc degeneration with accompanying osteophyte formation (osteo-arthritis or spondylosis of the cervical spine) is the most common pathological change associated with neck, shoulder, arm, and hand pain [5,6,7,9,13]. Of the fourteen patients reported here, ten had these changes associated with cervical-nerve-root irritation or compression. Three patients had disc degeneration alone [8]. This degeneration, not yet accompanied by visible osteophyte formation or significant disc narrowing, was demonstrated by discography. One patient had cervical subluxation and, in addition to pain in the neck, shoulder, and left arm, also had long-tract signs due to spinal-cord involvement secondary to the spine instability.

The position and size of osteophytes are important in the cervical spine. Those arising from the posterolateral vertebral-body joints (joints of Luschka) may impinge on cervical-nerve roots, on the vertebral artery, or on both [7,10,12]. Those protruding posteriorly from the margin of a vertebral body may impinge on the spinal cord and the anterior spinal artery. However, even when osteophytes obvious by roentgenogram protrude into the intervertebral foramina, symptoms may not be present. Therefore, although the position and the size of these osteo-arthritic spurs are important, even more important in our opinion is the mobility of the neck at the level where the osteophytes occur.

Non-operative therapy is often effective in relieving head, neck, shoulder, and arm pain in the majority of patients [9,15]. This may require permanent reduction in daily activity and frequent use of traction, or of a stabilizing collar device. If conservative treatment fails to relieve the pain, or if the pain becomes excessively burdensome to the patient, then surgery is indicated.

The results of laminectomy are usually satisfying when used for relief of pressure due to posterior osteophytes impinging on the spinal cord [2,18,23] or due to acute cervical-disc protrusion [3,4,14,20,21,22].

Laminectomy is not so satisfying when posterior osteophytes compress nerve roots in an intervertebral foramen. Enlargement posteriorly of the intervertebral foramen, by removing the articular facet, as well as laminectomy may be necessary to relieve nerve-root pressure in the foramen. Unilateral excision of a posterior articulation may not cause spine instability, but when pain is bilateral adequate decompression of both intervertebral foramina at the same level may lead to instability.

* Read at the Annual Meeting of The American Academy of Orthopaedic Surgeons, Chicago, Illinois, January 28, 1957.

If the source of trouble is a degenerated disc with or without osteophytes one would like to remove that disc, but in the neck the removal of a degenerated but non-prolapsed disc is not feasible or desirable by means of posterior laminectomy.

If enlargement posteriorly of the intervertebral foramen has been extensive and is followed by symptoms of cervical-spine instability or if pain has not been relieved by enlargement of the foramen and laminectomy, then fusion of the cervical spine is desirable. After an extensive laminectomy this is often difficult by the posterior approach since the usual anchor points for the bone grafts have been removed at the time of laminectomy.

If the symptoms are due to osteo-arthritic spurs impinging on nerve roots in the intervertebral foramina, particularly if the symptoms are bilateral or if due to disc degeneration or subluxation with or without missing posterior articulations, then in our opinion, disc removal and fusion of the cervical spine by the anterior approach is indicated. We therefore present our results with an operation that appears to achieve this goal. In our hands this operation (1) has less morbidity than laminectomy and foramen decompression or posterior fusion of the cervical spine; (2) allows one to remove a degenerated disc without disturbing the spinal canal; and (3) permits interbody fusion of the cervical spine at the specific intervertebral level from which symptoms arise.

Employing eight dogs, the authors found that the anterior surgical exposure of the cervical vertebral bodies and disc spaces is a reasonably safe procedure and that it is feasible. The intervertebral-disc material could be extensively removed from between the vertebral bodies through the anterior approach without damage to the spinal cord. Bone plugs from the ilium could be placed between the vertebral bodies in the interspace from which the disc material had been removed. This procedure was used by the authors on a patient for the first time in February 1954. A surgical exposure similar to that worked out on dogs by the authors was used by Lahey [11]. However, he used it as a method of exposing esophageal diverticula and did not suggest this approach for exposing the bodies of the cervical vertebrae.

LOCALIZATION OF THE OPERATIVE LEVEL

The level at which the operation is to be carried out should be precisely localized preoperatively; the first step is the physical examination. There may be sensory deficits in a single nerve-root distribution. Specific muscle weakness in the arm and hand or reflex changes at the tendons of the biceps and triceps brachii or at the radial styloid process may point to the level of nerve-root compression. Occasionally involuntary twitching will be observed in some group of muscles referable to a particular nerve root.

Irritation or compression of the nerve roots emerging between the fourth and fifth and fifth and sixth cervical vertebrae commonly produces tenderness of the radial nerve and pain radiating to the thumb and index finger. A lesion between the sixth and seventh cervical vertebrae may refer pain to the middle finger, while lesions between the seventh cervical and first thoracic (and occasionally between the sixth and seventh cervical vertebrae) refer pain to the little finger. Prolonged hyperextension of the neck (one minute by the clock) may aggravate the pain in the neck, shoulder, and arm and even cause a clear radiation to one of the digits. With the patient sitting, downward compression applied to the head with the neck tilted to either side may cause a clear pain-radiation pattern which will facilitate localization of the lesion in the neck [4].

The second step is trying to localize the involved cervical-spine level by simple roentgenography. Sometimes anteroposterior, lateral and right and left oblique roentgenograms of the cervical spine will enable one to localize definitely one isolated level (Fig. 1-B). For instance, between the fifth and sixth cervical vertebrae isolated disc degeneration and osteophyte formation may be obvious. Lateral roentgenograms made with the patient sitting or standing while he first flexes and then extends the neck may show a level of excess or limited motion between two vertebral bodies or an interruption at one level of the normally smooth curve of vertebral alignment.

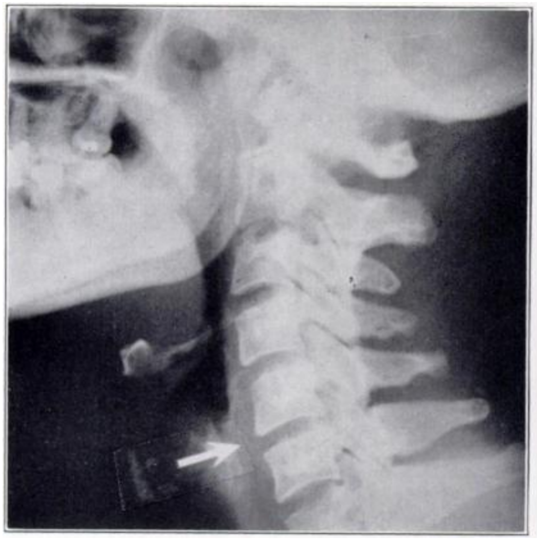

FIG. 1-A

FIG. 1-B

Figs. 1-A through 1-D: Roentgenograms showing the sequence of events during cervical-disc degeneration.

Fig. 1-A: Lateral roentgenogram of the cervical spine made in 1950, three years after the onset of symptoms, shows what appears to be a practically normal intervertebral disc between the fifth and sixth cervical vertebrae. At that time, the patient complained of pain in the neck, some right occipital headache, and tenderness and spontaneous pain over the medial superior corner of the scapula with some general aching in the right shoulder.

Fig. 1-B: Roentgenogram made in 1955 shows narrowing of the fifth and sixth cervical intervertebral-disc space with anterior and posterior bone-spur formations.

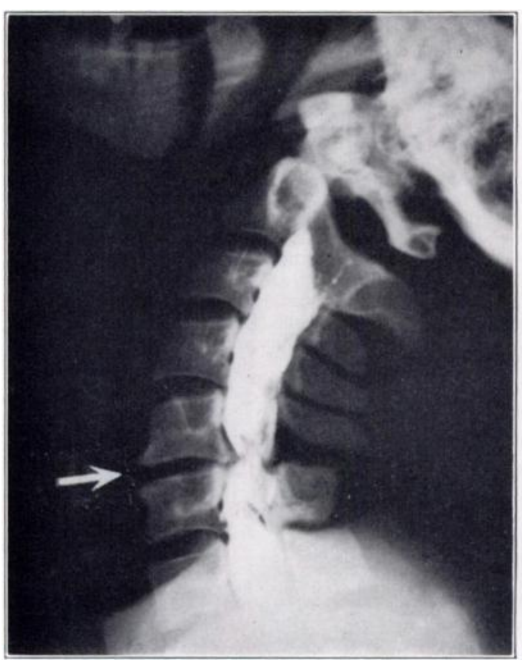

FIG. 1-C

FIG. 1-D

Fig. 1-C: A myelogram, made at the time of the roentgenogram seen in Fig. 1-B, shows the encroachment of the posterior spurs and overlying soft tissues on the dural sac which has been outlined with pantopaque.

Fig. 1-D: The bridge of bone is shown which has formed between the fifth and sixth cervical vertebral bodies following anterior removal of the intervertebral disc and interbody fusion. No motion could be seen in the cervical spine in lateral roentgenograms made while the patient flexed or extended his neck and a bone bridge between the two vertebral bodies was obvious. This is considered a solid bone fusion.

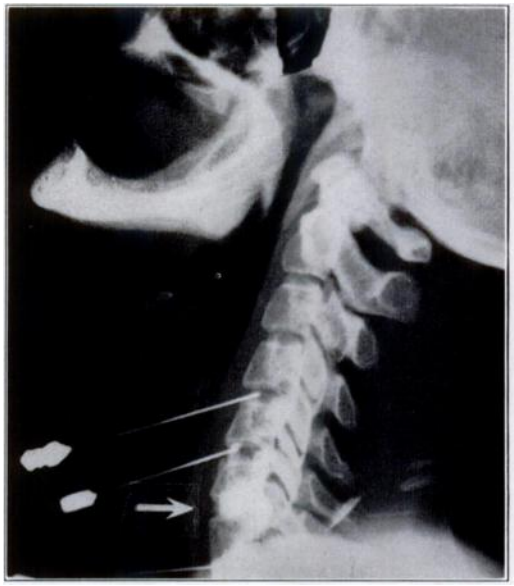

Fig. 2-A

Fig. 2-B

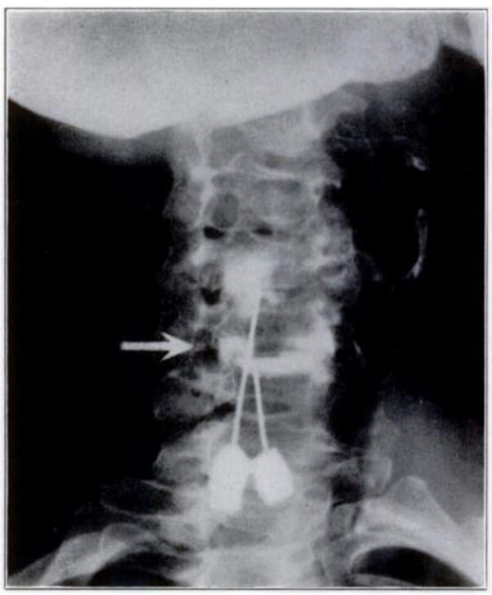

Fig. 2-C

Fig. 2-A: Case 3. Lateral view showing the extravasation of the contrast medium posteriorly under the posterior longitudinal ligament at the sixth and seventh cervical vertebral interspace.

Fig. 2-B: Case 3. Anteroposterior view of the same cervical spine showing irregular spread of the contrast medium throughout the disc space bilaterally, and through the joints of Luschka into the region of the intervertebral foramina.

Fig. 2-C: Case 14. A slightly oblique view made to show the spread of the contrast medium through the joint of Luschka into the intervertebral-foramen area. One may note that on the side of the neck, opposite to that of the arrow, a previous foraminotomy had caused removal of an articular-facet joint at the fifth and sixth cervical vertebral interspace. Symptoms had recurred subsequently on the side opposite the foraminotomy site. Foraminotomy on the side of recent symptoms would have probably necessitated partial or complete removal of the one remaining articular-facet joint at this level. Therefore, disc removal and fusion was performed to avoid instability at this level.

If such an isolated level by roentgenographic and physical findings corresponds (within anatomical limits of variability), one can be fairly certain that the level for surgery has been located.

However, plain roentgenograms and physical examination may show no well developed disc degeneration (Fig. 1-A) or the physical findings may suggest that, although one level appears abnormal by roentgenogram, physical signs and symptoms are arising from another level. Therefore, as a third step to localize precisely the involved level, special diagnostic methods may be necessary. Discograms (Figs. 2-A, 2-B, and 2-C) were made preoperatively in all of our group of fourteen patients. Myelography was done on only two patients and then only because of questionable long-tract signs (Fig. 1-C). Contrast material was injected by means of a needle inserted anterolaterally approximating the route of the anterior surgical approach to the cervical intervertebral discs. In most cases

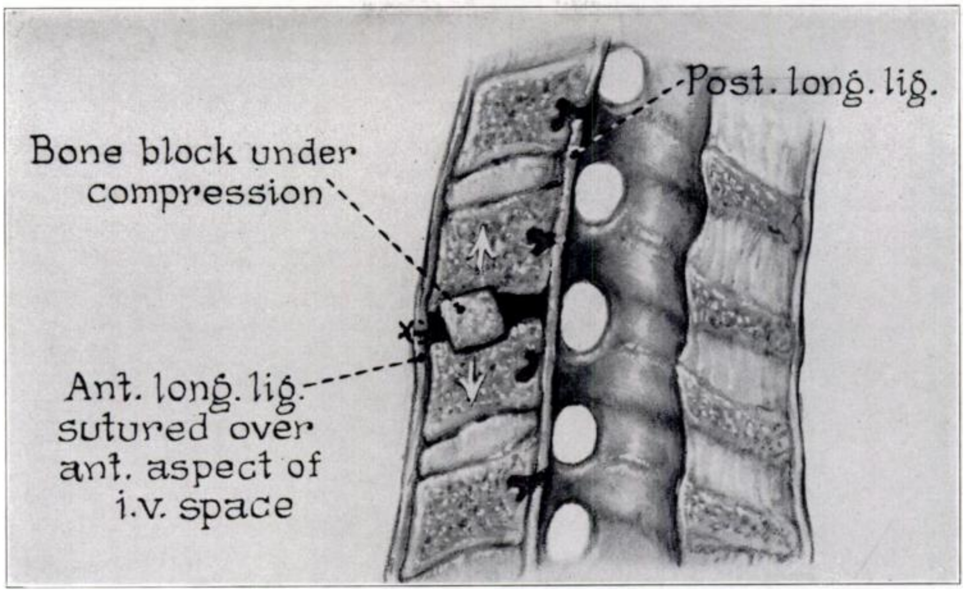

FIG. 3

Diagram showing the block of bone in place between two cervical vertebral bodies. One will note that the bone block is countersunk below the anterior longitudinal ligament so that the ligament may be resutured over it.

FIG. 4-A

FIG. 4-B

Roentgenograms made in flexion (Fig. 4-A) and in slight extension (Fig. 4-B) six months postoperatively of patient in Case 13. There is a bone bridge between the fifth and sixth and between the sixth and seventh cervical vertebral interspaces. There was no demonstrable motion. However, at the sixth and seventh cervical interspace the bone graft was not as well countersunk as that at the fifth and sixth. Although there was complete relief of symptoms at that time, there was no increase in the height of the intervertebral space secondary to operation at the sixth and seventh interspace and the interspace between the fifth and sixth cervical vertebrae showed only the preoperative height.

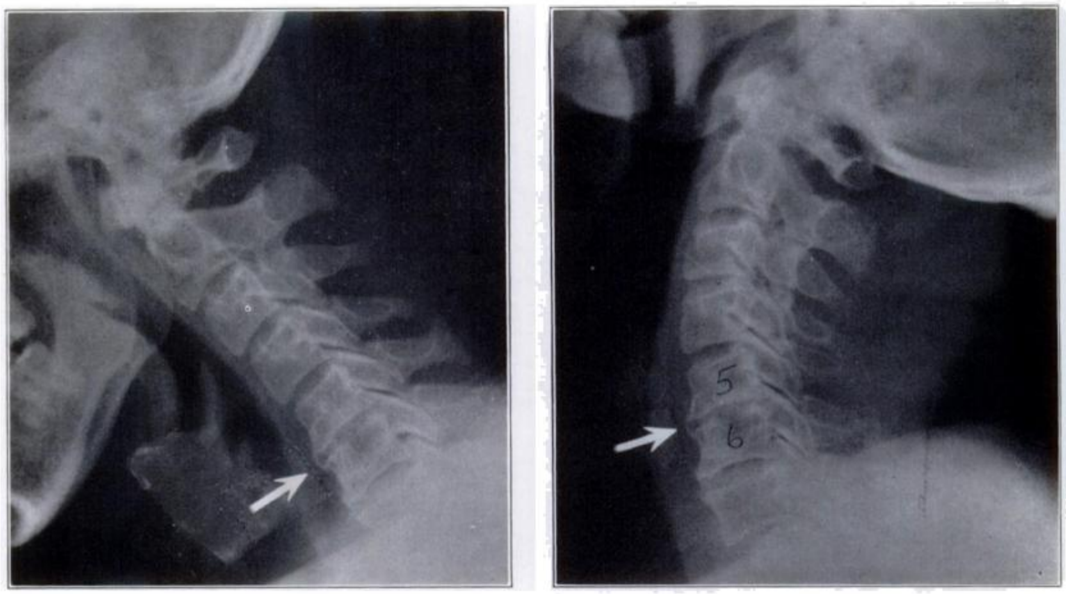

FIG. 5-A FIG. 5-B

Lateral roentgenograms of the cervical spine made in flexion and extension in the patient in Case 7 fourteen months after surgery when all the symptoms had been relieved. It will be noted that there is a bone bridge between the fifth and sixth and sixth and seventh vertebral bodies, most apparent between the fifth and sixth vertebrae. Comparison of these two roentgenograms showed no evidence of motion at these two levels and the fusion was considered solid.

the injection of contrast medium at the involved level reduplicated or exaggerated the typical pain pattern. Discography was therefore useful in those patients in whom there were multiple disc narrowings and in whom it was not clear which of the multiple levels was the source of the major complaint. In some cases the discogram showed only a slightly abnormal pattern at a level where nerve-root signs suggested the probable location of trouble, whereas a discogram made at another possible pain-producing level demonstrated the site of election for surgery by an extremely abnormal roentgenographic pattern in addition to clear reduplication of the pain. This procedure was also useful in those patients with disc degeneration in whom both narrowing of the disc and spur formation were not remarkable by roentgenogram (Figs. 2-A, 2-B, and 2-C).

OPERATION

The patient is under general anaesthesia and should be intubated. Intubation *via* the mouth often requires a degree of neck extension which may be dangerous in the presence of extensive hypertrophic changes on the posterior edges of the vertebral bodies because of possible spinal-cord injury. Therefore, intranasal intubation is recommended in such situations. The patient is placed on the operating table in a supine position. A small pad is placed between the scapulae just caudad to the neck allowing slight head and neck extension. The chin is turned about 10 degrees to the right. Traction of twenty pounds may be applied to the head by means of a halter.* The skin over the left anterior portion of the neck and the right iliac crest is prepared for surgery and the areas draped. A transverse incision is made along a skin crease at about the level of the fifth cervical vertebral body, to the left of the mid-line and about three finger-breadths above the clavicle. If the incision is made high on the neck one must be careful to avoid perforating the pharynx above the glottis. If the spine is not too heavily encased in soft tissue the carotid tubercle on the sixth cervical vertebra can be palpated before the incision is made. If the operation is to be at the fourth, fifth, sixth, and seventh cervical vertebral levels, the incision should be just at or a little above this deep osseous identifying structure.

* This has become routine practice at the Johns Hopkins Hospital.

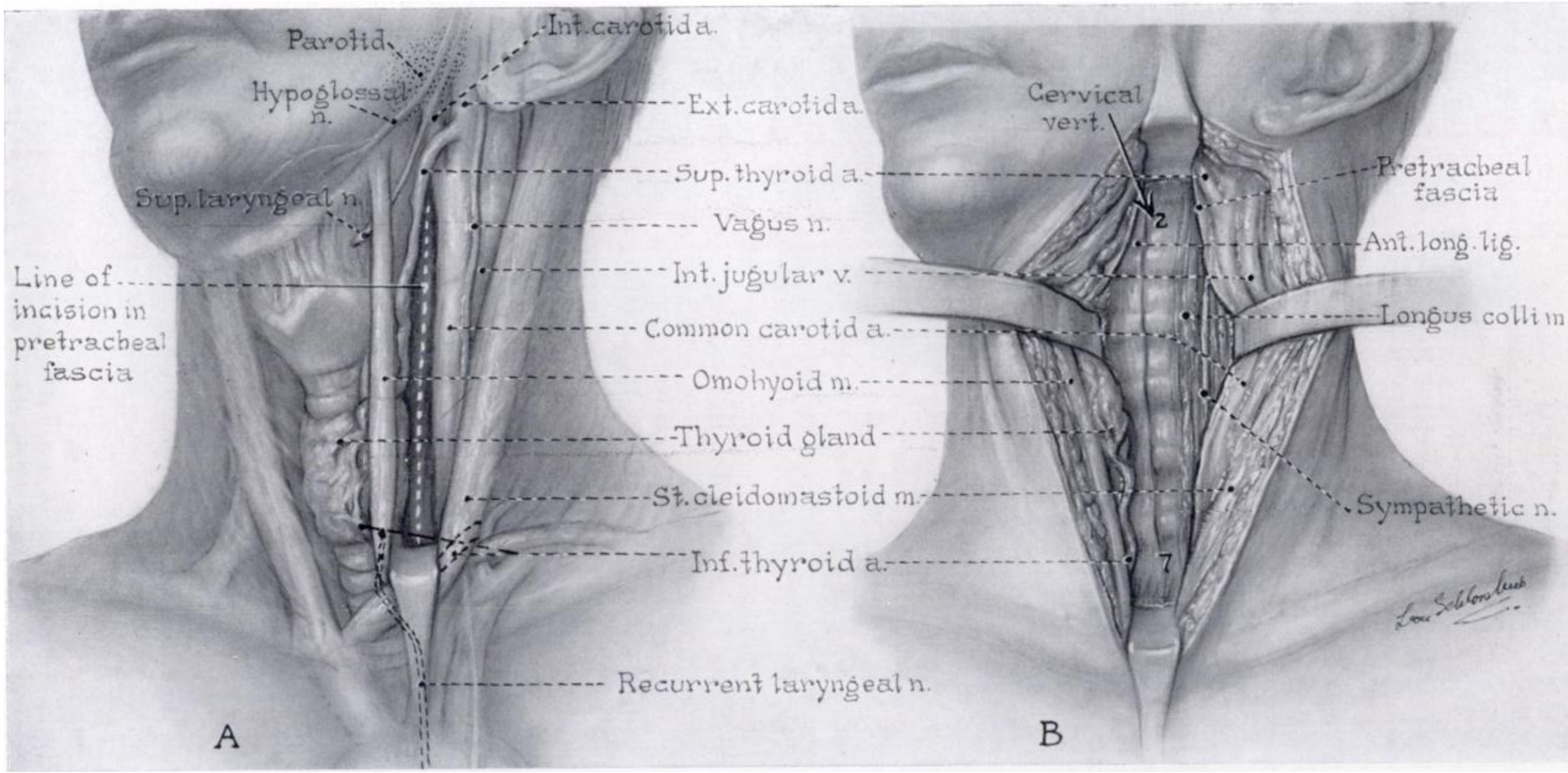

Fig. 6

Drawing showing the operative approach to the cervical spine. The flexibility of the anterolateral approach to the cervical spine depends on several factors. First, if several vertebral bodies are to be exposed between the second cervical and first thoracic levels, a slightly oblique vertical incision following the anterior border of the sternocleidomastoid muscle may be used. If only one or two vertebral bodies are to be exposed, a short transverse incision at the appropriate level may be used. (Detailed descriptions of the transverse and vertical incisions may be found on page 635 of the June 1957 issue of *The Journal.*) Second, the omohyoid and sternocleidomastoid muscles may be retracted freely, thus exposing the pretracheal fascia that covers the entrance to the interval between the structures in the carotid sheath and those in the mid-line compartment of the neck. Third, by incising the pretracheal fascia parallel to the carotid artery, one passes through the areolar tissue directly to the thin prevertebral fascia. Fourth, one can pass freely between the mid-line structures of the neck and the carotid sheath since there is a long interval between the origin of the superior thyroid artery and the origin of the inferior thyroid artery where no important nerves or arteries pass. Finally, the prevertebral fascia on the floor of the interval between the mid-line and lateral structures of the neck forms a thin transparent cover over the anterior longitudinal ligament, the anterolateral portion of the vertebral bodies, the longus colli muscles, and the sympathetic nervous system. The fascia can be incised vertically over the vertebral bodies and retracted to either side so that the operative site is directly exposed for intervertebral-disc removal and interbody fusion.

The incision is made on the left since the possibility of traction on the recurrent laryngeal nerve appears less than if the right side is used. The incision should be about eight to ten centimeters in length. It is carried through the skin, subcutaneous tissue, and platysma muscle. A vertical incision along the medial border of the sternocleidomastoid permits one to retract that muscle laterally and to retract the sternohyoid, sternothyroid, and omohyoid muscles medially and inferiorly. The carotid sheath is then seen in the center of the wound and the carotid-artery pulse should be palpated. If neck extension makes this difficult the anaesthetist may flex the patient's head and neck slightly until a good pulse is definitely palpated. A second vertical incision is then made through the pretracheal fascia just medial to and parallel with the carotid artery. The areolar soft tissue beneath this incised fascia is then spread with the fingers between the structures in the center of the neck (the thyroid gland, trachea, and esophagus) and the carotid sheath laterally. With impunity a superior or inferior thyroid artery and vein may be ligated and divided to give better exposure although in our experience this was rarely necessary unless the first thoracic or second cervical vertebra was exposed. The danger of perforating the esophagus is avoided by confining the exposure to the area between the medial and lateral structures of the neck. The carotid sheath and the sternocleidomastoid muscle are retracted laterally with a thyroid retractor. The sternohyoid, sternothyroid, and omohyoid muscles, the esophagus, trachea, and thyroid gland are retracted medially with a medium-sized Richardson retractor. Thus are exposed the prevertebral muscles and the anterior longitudinal ligament behind the esophagus. The two retractors are relaxed at ten-minute intervals to avoid prolonged tracheal or carotid-sheath pressure (Fig. 6).

The surgeon should palpate the underlying bone structures at this point from one side to the other of the neck to locate the mid-line. Thus the possibility of mistaking the irregular transverse processes for osteo-arthritic vertebral bodies is avoided and perforation of the vertebral artery is thereby obviated. The transparent prevertebral fascia is then vertically incised over the vertebral bodies. The cervical sympathetic trunk lies under this fascia over the longus colli muscles just lateral to the vertebral bodies. The longus colli muscles lie over the transverse processes of the cervical vertebrae.

The anterior longitudinal ligament glistens over the mid-line of the vertebral bodies even through the prevertebral fascia. It clearly marks the mid-line when the prevertebral fascia is drawn aside. By cleaving to the mid-line and making sure that the tip of the lateral retractor does not press on the region of the ascending sympathetic-nerve fibrils, the surgeon avoids a postoperative Horner's syndrome.

When osteo-arthritic spurs are present at only one or two intervertebral levels they can be palpated through the anterior longitudinal ligament. At this point a metal object such as a spinal needle is placed in the suspected disc space and a lateral roentgenogram is made in the operating room to confirm the position of the involved intervertebral level. (If one desires, a discogram may be made at this time.)* A fairly reliable identifying structure is the carotid tubercle which may be palpated through the wound and is usually part of the sixth cervical vertebra. Occasionally, it is found on the seventh cervical vertebra but if there is doubt about this anatomical variant its presence may be noted in the lateral roentgenogram as a shadow overlying the cervical body, usually the sixth.

A flap of the anterior longitudinal ligament is then turned back over the indicated disc space. The middle of the flap directly over the disc is intimately attached to the pellicle and the annulus. Thus the middle of the flap must be raised by sharp dissection. This flap is then laid back from the front of the disc space but remains attached to the right side of the anterior longitudinal ligament. Through this aperture the intervertebral-disc material, including the nucleus pulposus and the cartilage plates which separate the intervertebral-disc material from the bone of the vertebral bodies above and below the

* Discograms made during surgery rather than before have become the more common practice. This avoids the pain associated with the procedure, but gives only objective evidence of disc degeneration.

disc, is removed with pituitary rongeurs and curettes. If the anterior osteophytes are large and overhang the disc space they may have to be pared back a little to expose the disc space and to permit insertion of a curette and pituitary rongeur, but an effort is made to preserve the anterior cortical edges of the vertebral bodies adjacent to this disc space. In this way there remains, after the removal of the soft tissues in the disc space, a superior and inferior cortical-bone edge posterior to which the bone graft may be countersunk. Thus these cortical edges of the adjacent vertebrae are preserved to hold the bone block in place when the neck is brought to a normal neutral position, between flexion and extension, after surgery. The bone should be exposed by removal of the cartilage plate and subchondral bone at the top and at the bottom of the intervertebral-disc space if osseous union is to be subsequently expected between the adjacent vertebral bodies. The space is then measured. The space usually accepts a block of bone ten to fifteen millimeters high, ten to fifteen millimeters wide, and ten to fifteen millimeters deep.

A short incision is then made over the crest of the ilium and a suitable piece of iliac bone is obtained with a sharp osteotome to fill the space between the two cervical vertebral bodies. The size of the bone plug removed from the ilium should be greater than the final size of the trimmed block. Two vertical cuts, two centimeters deep, are made about two centimeters apart along the top of the iliac crest. The rough bone plug then measures about two by two by two centimeters, a full thickness of the crest. The iliac wound is closed and the bone graft is shaped. As cut from the ilium it is horseshoe-shaped and consists of cancellous bone surrounded on three sides by cortical bone. The top, bottom, and one end of the bone graft, as it is to be used in the intervertebral space, are cancellous. The cancellous end is inserted into the disc space. The cancellous top and bottom surfaces of the graft lie against the previously exposed cancellous surfaces of the superior and inferior vertebral bodies while the cortical exterior of the graft assumes a vertical position in the intervertebral space.

The prepared intervertebral space is then widened as much as possible by extending the patient's neck. The vertebral-body edges may be further spread apart with bone hooks or wedging devices. The head-neck traction helps to widen the intervertebral space when the disc material has been removed. The bone graft, when inserted into the intervertebral aperture, is tapped into position with a tamper and is countersunk in relation to the anterior cortical edges of the intervertebral aperture (Figs. 4-A and 4-B). When it has been seated it should be very stable. After hemostasis is complete, the flap of anterior longitudinal ligament is repositioned over the intervertebral aperture by two or more sutures.

The soft tissues are allowed to fall together. Sutures are placed in the fascial sheath of the platysma, the subcutaneous tissue, and the skin. A dry sterile dressing may be placed over the wound. No immobilization of the neck is used at this time.

POSTOPERATIVE COURSE

The arm pain may not disappear at once although the preoperative neck and suboccipital pain are usually absent immediately following surgery. One or two days postoperatively the patient is permitted to be up and walk. At four days the skin sutures are removed. The patient is allowed to go home about five to seven days after operation. When one space has been fused it has not been customary to immobilize the neck externally, but if some pain returns postoperatively a removable head-neck-shoulder splint made of plaster of Paris or a well fitted neck brace is used for one to three months. When multiple levels have been fused it has become routine to immobilize the neck for three to six months. The more spaces fused, the longer and more complete the postoperative immobilization.

A continuous bone bridge from one vertebral body to another is seldom apparent by roentgenogram for six to nine months after surgery.

TABLE I

RESULTS OF ANTERIOR REMOVAL OF INTERVERTEBRAL DISCS AND FUSION IN THE CERVICAL SPINE

Case	Age (*Years*)	Sex	Bilateral Signs	Bilateral Symptoms	Discs Removed	Relief of Preoperative Complaints	Months After Surgery at Follow-Up
1. B. R.	39	M	×	×	1	Excellent	36
2. F. L.	43	M	×	×	1	Excellent	31
3. E. M.	35	F	×	×	2	Poor	28
4. M. H.	46	F	×		2	Excellent	27
5. L. P.	35	F		×	1	Fair	27
6. V. E.	38	F			2	Excellent	27
7. C. S.	50	M			2	Excellent	26
8. T. F.	35	F		×	3	Fair	25
9. W. L.	25	M		×	1	Excellent	24
10. C. N.	38	F			1	Excellent	20
11. M. G.	36	F			1	Excellent	20
12. J. R.	33	M	×	×	2	Good	16
13. C. S.	34	F			2	Good	16
14. B.W.	43	F	×	×	1	Excellent	15

RESULTS

The results are summarized in Tables I and II. The oldest patient in the series was fifty and the youngest was twenty-five years of age, the average age being thirty-eight years. All of the patients were white. Five of the patients were men and nine were women. Eight had bilateral symptoms and six had definite bilateral physical signs. The remainder had unilateral symptoms and signs.

Twenty-two intervertebral spaces were cleaned out anteriorly and filled with a bone graft by the anterior approach. Each disc removed was grossly degenerated. The levels operated on are shown for each patient in Table II; the fifth and sixth and sixth and seventh cervical intervertebral levels were most frequently involved.

The criteria for solid fusion were a solid bridge of bone visible roentgenographically between two vertebral bodies and lack of measurable motion in the two vertebral bodies on lateral roentgenograms made during flexion and extension of the cervical spine. Although motion might have been observable at the operative site, no fusion was considered solid until a continuous bone bridge could be seen on a lateral roentgenogram (Fig. 1-D). Thus of the twenty-two intervertebral discs operated upon, eighteen eventually showed a bone bridge, and twenty-one showed no motion on roentgenograms made at follow-up examinations. In other words, in three of twenty-one disc spaces a fibrous instead of an osseous union had occurred as seen on follow-up roentgenograms. The average period of follow-up was twenty-four months.

Two patients had a fair final result. One patient (Case 3, E. M.) had no apparent relief from the disc removal and interbody fusion; subsequently due to persistent bilateral symptoms and signs, foraminotomy at two levels was performed. These procedures were extensive; most of four facet joints at the levels of the fifth and sixth and sixth and seventh cervical vertebrae were removed. The results in this patient are fair since the final procedure, but the result of the anterior fusion alone was poor. However, extensive foraminotomy could not have been done as safely, in our opinion, unless there had been stability of the spine by the anterior fusion performed several months prior to laminectomy and excision of the posterior articulations. The other patient had a fair result after anterior fusion was repeated (Figs. 7-A and 7-B).

One patient had a good and not an excellent result although all of the arm and hand pain disappeared. A little discomfort in the neck was occasionally noted and the medial

TABLE II

CERVICAL INTERVERTEBRAL DISCS REMOVED IN FOURTEEN PATIENTS

Case	Third and Fourth	Fourth and Fifth	Fifth and Sixth	Sixth and Seventh	Seventh Cervical and First Thoracic	Total
1					×	1
2				×		1
3				×	×	2
4			×	×		2
5			×			1
6			×	×		2
7			×	×		2
8	×		×	×		3
9			×			1
10			×			1
11			×			1
12		×	×			2
13			×	×		2
14			×			1
Total	1	1	11	7	2	22

FIG. 7-A

FIG. 7-B

Fig. 7-A: Case 8. Lateral roentgenogram of the cervical spine made nine days after removal of intervertebral-disc material between the third and fourth, the fifth and sixth, and sixth and seventh cervical vertebrae. One can see that the interspace between the third and fourth vertebral bodies is blocked apart by a bone graft.

Fig. 7-B: Lateral roentgenogram of the cervical spine of the same patient made nine months after operation. A good bone bridge had formed between the third and fourth cervical vertebrae. However, the disc space had returned to its preoperative height and showed no widening as a result of surgery. There was a good bone bridge between the sixth and seventh cervical vertebrae with calcification under the anterior longitudinal ligament extending up in front of the sixth cervical vertebra. The interspace between the fifth and sixth cervical vertebrae failed to show any evidence of fusion. Re-operation was done at this level resulting in symptomatic improvement.

superior scapular tip was tender. Another patient has a good result, but in view of his preoperative problem, a few residual symptoms are not of great importance.

Nine of the fourteen patients were completely relieved of their preoperative pain by this operation alone and are considered to have excellent results. Thirteen of the fourteen were improved. One was not improved by this operation alone.

An interesting observation was that the neck and occipital pain was usually relieved immediately and that the arm pain disappeared within a few days following surgery and did not return. However, one patient continued to complain for nine months until the fusion at two levels became solid as seen by roentgenogram after which he was pain-free for two years. No external immobilization was used postoperatively for this patient.

COMPLICATIONS

Two patients had Horner's syndrome, one lasting about one week and the other about six months; two had paralysis of a vocal cord, one clearing in about three weeks and the other between the sixth and ninth postoperative month; one patient had postoperative tracheitis requiring steam inhalations for five days; and in one patient the vertebral artery was perforated without sequelae.

After this series was finished the pharynx of one patient was perforated just above the glottis. In that instance the pharynx was repaired and operation on the cervical spine was delayed six weeks. The esophagus healed properly without sequelae.

No wound infections occurred. In the description of the operation the technical modification which we have found best for avoiding each of these technical complications has been noted.

CASE HISTORIES

CASE 3. E. M., a white housewife and secretary, thirty-five years old, reported no trauma in connection with the neck. Previous spine surgery had consisted in an exploration at the lumbosacral joint with disc removal and fusion in 1949. Cervical symptoms began two years prior to hospital admission during which time the patient had had non-surgical treatment for the cervical pain. Prior to operation she had numbness of the right ring finger and weakness of the grip in the right hand. She had noticed intermittent muscle twitching in the upper and lower portions of both arms, and complained of interscapular pain with the recurrent episodes of pain in the neck and arms. Prior to the intervertebral-disc removal and fusion there was hypaesthesia over the distribution of the eighth cervical-nerve root and diminished reflex of the biceps and triceps brachii on the right as compared with that on the left. There was interspinous tenderness between the sixth and seventh cervical vertebrae posteriorly and on prolonged extension of the neck, pain in both arms and hands was reproduced.

Lateral roentgenograms showed that the interspace between the fifth and sixth cervical vertebrae was very slightly narrowed. The fifth, sixth, and seventh cervical vertebrae and the first thoracic vertebra tended to remain in a neutral fixed position during flexion or attempted flexion of the neck. At the same time, above the fifth cervical vertebra flexion occurred. No remarkable spurs were seen in the oblique roentgenograms of the cervical spine. Discogram showed an abnormal pattern of a filling defect and degeneration at the fifth and sixth, and sixth and seventh cervical vertebral interspaces and at that between the seventh cervical and first thoracic vertebrae. However, the patient's pain was reproduced only at the lower two interspaces. Therefore, on October 8, 1954, intervertebral-disc removal and interbody fusion was performed from the right side at the sixth and seventh cervical vertebral interspace and at that between the seventh cervical and first thoracic vertebrae, in view of the fact that her clinical symptoms and signs were best correlated with nerve-root compression or irritation at these two levels. Postoperatively the patient was improved and muscle fibrillations that she had noted disappeared, but she still had pain into both shoulder areas and into the right hand upon extension of the neck. She continued to complain that she had pain in the neck and arms running to the ring and little fingers of both hands. The consensus of several examiners was that there was no improvement after the disc removal and fusion and the result was classified as *poor*, twenty-eight months after surgery.

Stabilization of the neck at the sixth and seventh cervical and the seventh cervical and first thoracic interspaces resulted, however, from the anterior-fusion procedure. On July 16, 1955, after this stability had been gained, a multiple foraminotomy including partial bilateral excision of the posterior articulations at the sixth and seventh cervical and seventh cervical and first thoracic levels was performed, ten months after the first operation. Following the second operation there were no complications. Neck extension was not accompanied by severe pain into the shoulders and arms as before the second procedure. The patient returned to work for the first time in several years and when re-examined twenty-eight months after the original procedure and eighteen months after the secondary laminectomy and foraminotomy, her symptoms and signs involving the right arm were relieved, and she complained only of "aching muscle tiredness" in the left shoulder and arm. The over-all result from both procedures was classified *fair*. She not only returned to doing her own housework but was working as a part-time secretary (Figs. 2-A and 2-B).

Case 4. M. H., a white housewife, forty-six years old, reported no trauma specifically related to the neck. One year prior to disc removal and interbody fusion the patient had had a foraminotomy on the left side at the fifth and sixth cervical vertebral interspace which involved complete excision of the posterior articulations. The patient had severe recurrence of her symptoms four months prior to the second procedure which had not been relieved by non-surgical treatment.

The patient had had a gradual onset of pain, first in the left shoulder and arm, about 1952. Four months prior to surgery she had had a severe recurrence of pain which had not responded to extensive non-surgical therapy. Preoperatively her symptoms consisted of pain in the neck and right shoulder, pain in the right arm and hand, and numbness in the right arm and in the thumb, index, and middle fingers. The neck pain included interscapular pain. There was a positive extension test of the neck reproducing pain into the right arm and hand. When in extension the neck was rotated, acute pain in the right arm was produced. The periosteal radial reflex was diminished on the right. There was weakness of the extensor tendons of the right hand and elbow.

Roentgenograms showed that at a previous operation on the cervical spine excision of the posterior articulations on the left had been performed at the fifth and sixth cervical vertebral interspace. There was disc narrowing and spur formation at the interspaces between the fifth and sixth and sixth and seventh cervical vertebrae bilaterally. The spurs were both posterior and posterolateral. Discogram showed abnormal outline and injection of the contrast medium produced pain at both the fifth and sixth and sixth and seventh cervical vertebral interspaces. On November 4, 1954, intervertebral-disc removal and interbody fusion was performed from the right side at the fifth and sixth and sixth and seventh cervical vertebral interspaces. Postoperatively, the abnormal physical findings rapidly disappeared and there were no residual complaints four months postoperatively. The patient was working without complaints twenty-seven months postoperatively. The result is considered *excellent*.

Case 7. C. S., a white contractor and builder, fifty years old, stated that he had been severely mauled in a labor dispute in 1939. For twelve years the neck, shoulder, and arm pain was intermittent but the attacks became more frequent and more prolonged until they were almost constant by 1952. Various forms of non-operative treatment had been employed by various physicians for one and one-half years prior to surgery without any relief of symptoms.

On physical examination prior to surgery there was obvious spontaneous muscle twitching in the right forearm in the region of the extensor muscles of the hand and fingers which could be increased by prolonged extension of the neck. Extension of the neck also produced pain at a point behind the medial superior tip of the right scapula which proceeded down the posterior edge of the deltoideus muscle, then along the radial groove to the elbow, and along the extensor surface of the elbow to the thumb and index finger. There was tenderness of the radial nerve. There was pain and tenderness on the anterior aspect of the elbow and over the extensor muscles on the right arm down to the wrist. There was paraesthesia over the thumb and index finger. There was partial paralysis of the sixth cervical-nerve root noted by absence of the periosteal radial reflex and the reflex of the left biceps brachii with partial loss of pain and touch sensation over the thumb and index finger and the lower radial side of the forearm.

Roentgenograms showed moderate narrowing of the fifth and sixth cervical intervertebral space and slight narrowing at the sixth and seventh cervical vertebral interspace with spur formation posterolaterally into the intervertebral foramen on the right side at the fifth and sixth cervical vertebral interspace. Injection of contrast medium at both the fifth and sixth and sixth and seventh cervical vertebral interspaces produced pain and the discogram showed an abnormal pattern.

On December 3, 1954, intervertebral-disc removal and interbody fusion at the fifth and sixth and sixth and seventh cervical vertebral interspaces was performed from the right side. Postoperatively there was a Horner's syndrome and temporary paralysis of the right vocal cord. These complications completely disappeared in nine months. When reviewed twenty-six months postoperatively, the patient showed only a slight residual weakness of the triceps brachii muscle but all other symptoms and signs had gradually regressed in the one year following surgery. The result was considered *excellent* (Figs. 5-A and 5-B).

Case 8. T. F., a white female nurse, thirty-five years old, reported that a fall on a hard floor in a sitting position in 1947 caused neck symptoms. The patient stated that symptoms in the neck, shoulders, and arm continued despite two operations on the neck on the left side which had consisted of seven foraminotomies. Prior to surgery in January 1955 she complained of pain in the left shoulder, index finger of the left hand,

and weakness in the grip of the left hand. There was pain in the neck, particularly on the left side. All of these symptoms had failed to respond to non-operative therapy and surgery over the previous five years.

On physical examination the patient showed hypaesthesia over the left thumb, the index and middle finger. The extension test of the neck was positive and reproduced pain into the left shoulder and down the left arm into the left index finger. Flexion of the neck reproduced the pain in the left shoulder.

Discograms were made at each interspace between the third and the seventh cervical vertebrae. It was difficult in this patient to interpret the pain distribution with the injection of contrast medium but the pain seemed to be duplicated when injection was done at the third and fourth, the fifth and sixth, and the sixth and seventh cervical vertebral interspaces. The spine was straighter than normal in the lateral view. There was roentgenographic evidence on the plain films of foraminotomy at each interspace between the third and the seventh cervical vertebrae. At three of these levels the foraminotomy was bilateral and at one level, unilateral. No large spur formation was seen. There seemed to be some narrowing at the interspaces between the fifth and sixth and the sixth and seventh cervical vertebrae.

On January 11, 1955, intervertebral-disc removal and interbody fusion at the third and fourth, the fifth and sixth, and the sixth and seventh cervical vertebral interspaces was performed from the left side. Postoperatively, this patient had severe tracheitis for five days which was believed due to sensitivity to the intertracheal tubing used for intubation anaesthesia. It should be noted that a similar complication followed a thyroidectomy on this patient several years previously. The second complication was the development of a keloid. Postoperatively the patient complained of pain in the lumbar spine as well as in the neck. She had had multiple operations previously in the area of the cervical spine and one exploration in the area of the lumbar spine. Physical findings were unchanged from the preoperative state and therefore after ten months the result was classified as *poor*.

Approximately eleven months after the procedure of January 11, 1955, the patient was re-operated upon in her home area and the fifth and sixth intervertebral level of the cervical spine was found to be movable and was re-fused *via* the anterior approach. Roentgenograms and operative exploration showed bone fusion at the third and fourth and sixth and seventh cervical intervertebral levels. The total result of these procedures was not reviewed by the authors but the patient was reported improved by her attending surgeon. The total result from disc removal and interbody fusion is listed as *fair* twenty-five months after the secondary vertebral-body fusion (Figs. 7-A and 7-B).

Case 13. C. S., a white female beautician, thirty-four years old, stated that she had had neck injury in an automobile accident about eight months before surgery. For the past seven months there had been persistent pain in the neck and left arm and weakness, particularly partial weakness in the grip of the left hand despite non-surgical therapy with a collar and traction. Preoperatively the patient complained of pain in the neck, the left shoulder, the left hand, and numbness in the left shoulder, arm, and hand with suboccipital headaches. There was tenderness posteriorly over the neck between the fifth and sixth vertebrae in the mid-line. The extension test of the neck was positive and rotation of the chin to the right gave severe pain into the left arm and down to the index finger and the thumb. There was tenderness of the radial nerve and diminution of the radial styloid reflex. A myelogram made prior to surgery was negative and roentgenograms were not remarkable except for perhaps a slight straightening of the neck in the lateral view. Injection of contrast medium at the fifth and sixth and sixth and seventh cervical vertebral interspaces caused reproduction of the pain in the arm and the discogram showed a pattern typical of disc degeneration.

Operation was performed on October 27, 1955, when intervertebral-disc removal and interbody fusion at the fifth and sixth and sixth and seventh cervical vertebral interspaces was performed from the left side. There were no postoperative complications. The preoperative findings disappeared except for some tenderness and mild discomfort over the superior medial tip of the left scapula and very occasional aching in the neck. Sixteen months after the disc removal and fusion the patient considered that she was at least 75 per cent improved. An independent examiner judged that the patient had perhaps 15 per cent of residual disability in the neck. The final result is considered *good* (Figs. 4-A and 4-B).

Case 14. B. W., a white housewife, forty-three years old, gave no definite history of trauma in relation to the neck. Removal of intervertebral-disc material at the fifth lumbar and first sacral interspace and spine fusion at that level had been performed in 1953. Results of that operation were excellent.

At the onset the pain was gradual and intermittent, involving the neck, both shoulders, arms, hands, the fingers, and the interscapular area for eight years. The intermittent attacks had become more frequent and more prolonged so that in the year prior to surgery the discomfort had been practically continuous and accompanied by numbness in the right thumb with pain in the right anterior portion of the chest. Extensive conservative therapy, such as collars and traction, had failed. On examination there was a decreased biceps brachii reflex on the right and an absent periosteal radial reflex and biceps reflex on the left. The extension and rotation test of the neck reproduced the neck pain and that radiating into the right arm. There was on such tests some discomfort into the left shoulder and arm. On testing there was some weakness of the grip in the right hand. Roentgenogram showed definite narrowing of the fifth and sixth cervical vertebral interspace and discogram at this level showed a positive pattern and injection of contrast medium reproduced the patient's pain distribution. On November 15, 1955, intervertebral-disc removal was performed followed by interbody fusion at the fifth and sixth cervical vertebral interspace. In this case bone-bank bone (frozen bone from the rib) was used. Postoperatively the patient had no complications. The preoperative findings disappeared. She resumed full activity without complaint and when evaluated fifteen months postoperatively the result was considered *excellent* (Fig. 2-C).

DISCUSSION

Four of the patients in this particular series had had previous thyroid surgery. This series, as well as other patients with discogenic disease who have had previous thyroid surgery, strongly suggested to us the possible importance of a metabolic factor in intervertebral-disc disease.

A degenerated intervertebral disc can apparently create abnormal mechanics in the cervical spine even before roentgenograms show significant intervertebral-space narrowing or remarkable spur formation. From such a level shoulder, neck, occipital, and even arm pain may arise. The localizing signs may not be clear in these patients on physical examination. However, a discogram at the involved level should give a roentgenographic pattern typical of disc degeneration (Figs. 2-A, 2-B, and 2-C) and the pain which forms the chief complaint may be reproduced during the discographic procedure. Pain arising during discography may occasionally be so diffuse that the patient will have difficulty associating it with the pain which he originally had. Critical analysis of this pain reduplication during discography depends in large measure on the patient's emotional stability and the surgeon's experience with the procedure. However, the contrast medium flows with little resistance into a degenerated disc whereas into a normal disc only a small amount can be inserted and that only under great pressure. The discogram shows an abnormal pattern: instead of a neat lense-shaped outline of a normal cervical nucleus pulposus, an irregular extension of the contrast medium beyond the central nucleus occurs across the disc space to the region of the joints of Luschka and into the area of the intervertebral foramina. In the lateral view the contrast medium usually proceeds out of the disc space up and down under the posterior longitudinal ligament (Figs. 2-A, 2-B, and 2-C) when the disc is degenerated.

When true disc protrusion or large posterior osteophytes cause compression of the cord and evoke long-tract signs, posterior decompression of the spinal cord and possibly section of the dentate ligaments appears indicated [18, 23]. In those patients with long-tract signs a myelogram is indicated prior to such surgery. It is possible that in such situations spine fusion by the anterior approach may, by stabilizing the osteo-arthritic portion of the spine, decrease soft-tissue swelling over large posteriorly protruding osteophytes, or stop any irritation of the cord or of the anterior spinal artery, or of both, which may occur secondarily to osteophyte motion. However, the authors have used anterior spine fusion only once for such a situation. In that patient (Case 12, J. R.) spinal-cord irritation existed only intermittently and in mild degree. However, the patient's symptoms were relieved clinically by the anterior cervical-spine fusion at two levels.

Spurs on the superior element of the posterior cervical articulations and on the joints of Luschka are reported to cause intermittent or continuous pressure on the vertebral artery with spasm of the artery in some instances [7, 10]. Possibly they may also irritate or compress the posterior sympathetic plexus which accompanies the vertebral artery [1, 17]. This condition may eventually have to be differentiated from Ménière's syndrome and may possibly give rise to syncopal attacks although such a clinical syndrome is not as yet clearly defined [17]. So far the operation described has not been used primarily for this condition but it would appear to be indicated in such a situation if the exact level of vertebral-artery irritation can be precisely localized.

Originally we hoped that after cleaning out the intervertebral-disc material through the anterior approach it would be possible to wedge the vertebral bodies apart and that this would also increase the diameter of the intervertebral foramina (Fig. 3). Actually, however, opening up the interbody space may tend to extend the cervical spine, a position which causes pain in many patients having constriction of the intervertebral foramina by osteophytes. Extension alone does not effectively enlarge the intervertebral foramen. Furthermore, the bone graft is largely resorbed and remodeled. Even though it originally acts as a conductor of osteoblasts between the two vertebral bodies it eventually ceases to exist as an effective mechanical strut for separating the two vertebral bodies. Therefore, in late postoperative roentgenograms the two vertebral bodies that were propped apart at the operating table by the bone plug have either returned to their preoperative position in relation to each other or the space between them has become narrower than it was preoperatively.

CONCLUSIONS

1. Disc degeneration in the cervical spine usually associated with osteo-arthritic changes is a cause of nerve-root irritation and compression giving rise to occipital and hemicranial headaches, pain in the neck, shoulder, between the scapulae, in the anterior portion of the chest, and in the arm and hand. Instability of a cervical vertebra can also cause similar pain.

2. The cervical-spine level from which such pains arise when exactly localized can be fused after excising the disc by placing a bone graft anteriorly between the vertebral bodies. Such a fusion appears to stop the pain.

3. This method of treatment without serious complication has completely relieved the discomfort of nine of fourteen patients and caused improvement in four others. Conservative therapy and other surgical attempts had failed to relieve the discomfort of these patients prior to the disc removal and interbody fusion.

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DISCUSSION

Dr. J. E. M. Thomson, Lincoln, Nebraska: This presentation is timely and commendable in that it brings us closer to understanding one of the most confusing and illusive pain syndromes. The authors thoroughly covered the numerous etiological potentialities which cause local symptoms in the neck as well as those referred to the chest, back, and upper extremities. They correctly emphasized the importance of definite adequate diagnosis of the particular pathological conditions involved and its relative importance in connection with the effective conservative or surgical treatment.

The exposure of the anterior portion of the bodies of the cervical vertebrae has been ably demonstrated by Dr. Southwick and Dr. Robinson[a]. The method is intriguing but it seems to demand a very skilled and experienced hand. The transitory complications of two Horner's syndromes, two instances of paralysis of the vocal cords, one instance of tracheitis, one vertebral artery perforated, and then a ruptured esophagus in a later case forms a formidable group.

It is gratifying that the authors tried their technique on eight dogs before turning to human beings. We have not got beyond canine investigation, either from an operative or a discographic standpoint.

In the patient, E. M. (Case 3), the result of the disc removal and interbody fusion was poor and extensive bilateral foraminotomies at two intervertebral levels were later performed with fair results. In this case. one can agree with the authors' opinion that the subsequent extensive foraminotomies could not have been done as safely as they were without the stability afforded by the preceding fusion. Hence, although the result of anterior fusion itself was poor, it nevertheless made possible a subsequent procedure which improved the result.

The authors' comments concerning the attempts to force the vertebrae apart in order to enlarge the intervertebral foramina were interesting. The osteoclastic activity, invariably present, apparently has a flattening effect on the graft to the extent that ultimately the intervertebral space could be less than that before surgery. Therefore the assuring feature of this method after all is the fusion.

Dr. Smith and Dr. Robinson should be commended for their courageous approach to this problem. Their results indicate the importance of this method of treatment in a selected group of patients with cervical-disc nerve-root syndromes. If our specialty is to progress, we cannot afford to look askance at original approaches to difficult surgical problems and not add to our armamentarium those surgical techniques which, although unusual, have proved by experience to give a measure of good results.

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Dr. James Gordon Petrie, Montreal, Quebec, Canada: At the Montreal Neurological Institute and the Royal Victoria Hospital, Montreal, Dr. W. V. Cone and I have been much interested in this subject for many years in the treatment of trauma as well as in the treatment of neck pain with or without radiating pain.

We all know that skull traction in a young person will give some separation of the cervical vertebrae, but we have found that considerable traction, up to seventy-five pounds, as used occasionally with fracture-dislocation of the cervical spine, gives only minimal or no separation of the vertebrae at the level of an old degenerated disc, and in the adult, widening of the intervertebral disc at normal levels and under heavy traction is not marked. This raises the question as to how traction benefits some of these patients. Is it due to change of posture and relief of muscle spasm?

One point that should be stressed in the treatment of intervertebral lesions is that the operation is usually for pain, and therefore is one of election, and the simplest, safest procedure should be used. If muscle weakness is present then it should be considered an emergency. If fusion alone will relieve the pain we believe an articular-facet fusion along with parallel grafts is the shortest procedure. It is simple to fuse up to four vertebrae together. As Abbott and others have shown, cancellous bone possesses a high osteogenetic power, whereas cortical bone possesses strength but little osteogenetic power. We expect the articular facets to be well fused in two months, and the parallel cortical grafts to take a longer period of time to fuse.

We have had very little experience with discograms. We would not want to do them on normal discs, as Dr. Reuben Rabinovitch has shown with young animals (rabbits, dogs, and monkeys), using an eighteen-gauge needle, that disc material may be extruded from a normal disc following puncture. We do believe myelography is important, not so much in the diagnosis of a ruptured intervertebral disc, but rather to give us a clue as to the level of the involved disc or discs.

We believe the best indication for the anterior fusion is when a wide laminectomy, as far as the articular facets, has been carried out previously and there is increasing pain and deformity of the neck.

MAKING THE MILWAUKEE BRACE

(Continued from page 528)

A traction frame (Fig. 4) is fastened to the pelvic girdle to correct pelvic obliquity. Pins through the tibiae are incorporated in casts. Traction is made on the high side which has the short cast. A spring balance is interposed to measure the force. The leg on the low side with the toe-to-groin cast is pulled upward with heavy rubber bands in the back and front.

APPLYING THE BRACE

The brace is reassembled and put on the patient by the orthotist. It should be checked carefully by the orthopaedic surgeon. It should fit loosely with only slight corrective force. If the spine was considerably elongated during the application of the model, it will be necessary to shorten the brace one-half inch (1.27 centimeters) or more before applying it. No additional correction of the curve should be attempted until the skin is accustomed to the pressure of the brace. The patient should be able to raise his chin and occiput simultaneously from the head support, or rest the head on its support and shift the chest away from the lateral pressure pad. This situation must prevail at all times during and following the correction. The appearance of pressure areas is evidence that too much force is being used.

The brace should not be uncomfortable even when first worn. With the patient in the prone position, the pelvic girdle should be loosened and the skin of the entire torso given nursing care at least once a day for the first six weeks that the brace is worn. When the belt (Fig. 2, *B*) is to be fastened again, it is wise to pull on the patient's legs so that the girdle will fit snugly above the waist and not cause pressure on the lateral surfaces of the ilia. The gap between the posterior edges of the pelvic girdle must remain constant. As the belt stretches, it must be tightened further to maintain this position.

The chin must be capable of protrusion at any time. Pain at the temporomandibular joint or pain in the teeth means that the brace must be shortened. Vigorous distraction will obviously make pressure on the teeth. Rarely, in young children, protrusion of both upper and lower incisors has occurred. This protrusion has always receded rapidly upon removal of the brace at the completion of treatment. Permanent deformity has not occurred.

A marked overbite is a frequent finding in idiopathic scoliosis as noted by Chandler. Care should be taken to examine the jaws prior to the onset of treatment. If an abnormality exists, an orthodontist should be called in consultation and he should prepare a plaster mold of the teeth as a record. Mandibular deformities should not erroneously be ascribed to the brace. No change of bite has been observed with the use of the brace.

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THE NORMAL VASCULAR ANATOMY OF THE FEMORAL HEAD IN ADULT MAN

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From the Nuffield Orthopaedic Centre, Oxford

This paper gives an account of an investigation into the normal vascular anatomy of the adult femoral head. The work was undertaken to supply control material for research into the vascular changes accompanying osteoarthritis of the hip joint, and for this reason no account is given here of the conditions existing in the two decades preceding maturity. These will be presented on another occasion. Similarly we have not detailed the extra-articular course and anatomical variations of the arteries supplying the femoral head; they have been fully described by others. We shall commence our description of the vessels from where they are about to enter the bone, precisely the point at which the available information grows increasingly scanty; here they begin their physiological role, their function as conducting channels now having been fulfilled.

HISTORICAL REVIEW

In the past this subject has been approached by two different types of investigators; one group, comprising mainly surgeons and anatomists, successfully identified the arteries bringing blood to the upper end of the femur but were less interested in determining the fate of these vessels within the bone. A second group, constituted by pathologists and haematologists, were concerned with the structure and arrangement of the finest vessels within the bone mainly in relationship to haemopoiesis.

Palletta (1820), Cooper (1823), Sappey (1869) and Langer (1876) were among the nineteenth century workers who studied the vessels bringing blood into the upper end of the femur; they were followed in more recent years by Lexer *et al.* (1904), Nussbaum (1924), Kolodny (1925), Logròscino (1934), Vereby (1942), Wolcott (1943), Tucker (1949) and Howe *et al.* (1950). Some of the most outstanding of the early contributions to the anatomical knowledge of the finer vessels within the bone were by Neumann (1869), Langer (1876), Rindfleisch (1880) and Van der Stricht (1892); later workers included Doan (1922 and 1925) and Drinker (1922) and their associates. In studies devoted to the larger vessels, once the main arterial pathways had been identified further reports tended to centre on discussion whether, during growth, the epiphysial plate constitutes an absolute barrier to the circulations of epiphysis and metaphysis and also what arterial contribution to the blood supply of the femoral head, if any, is brought by the artery of the ligamentum teres. Parallel discussions have concerned the anatomy of the small vessels, as to whether the capillary circulation of the marrow is partly an open, or is a closed system.

No elucidation of either of these artificially separated problems has been achieved by this dual approach, and consequently our knowledge of the complete circulatory anatomy within human bone in general and this region of constant orthopaedic interest in particular is seriously deficient.

DEFINITIONS AND NOMENCLATURE

Throughout this article the term epiphysis is applied to that part of the head of the femur formed from the secondary centre of ossification. During the growth period the extent of the epiphysis is made obvious by the growth plate which limits it infero-laterally (Fig. 1), and in adult life a distinction continues in that the so-called epiphysial scar serves as a guide

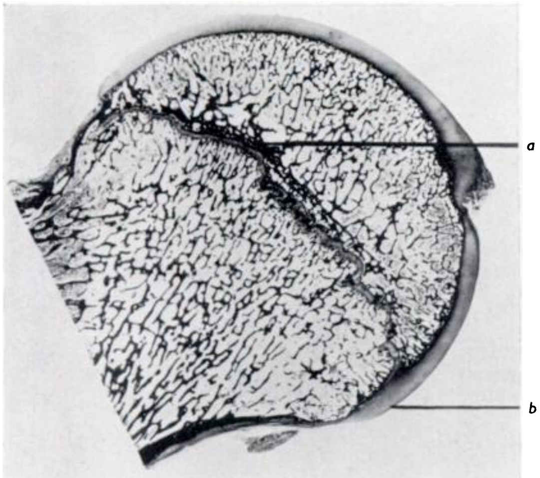


FIG. 1

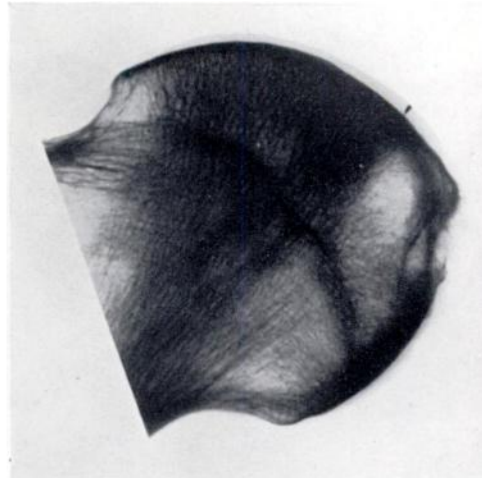


FIG. 2

Figure 1—Photomicrograph of a coronal section of a femoral head of a subject aged fourteen. *a*—Concentration of bone lamellae superficial to the epiphysial plate. *b*—Articular cartilage covering metaphysial bone (× 1·2). Figure 2—Slab radiograph, coronal plane, from the femoral head of a subject aged seventy-two. A radio-opaque zone, the "epiphysial scar," is seen to occupy a position close to that which the epiphysial plate did during the years of growth.

to the position which the growth plate previously occupied (Fig. 2). We have observed that the system of lamellar bone which constitutes the scar lies close to, but on the epiphysial side of the growth cartilage, and the scar does not represent a zone of intense ossification produced within the plate at the time of synostosis. It will be seen in Figures 1 and 2 that the upper femoral epiphysis does not form the whole of the femoral head either during or after the growth period; at both times the proximal part of the diaphysis, the metaphysis, forms a substantial part of the head and is covered by articular cartilage (*b*, Fig. 1).

MATERIALS AND METHODS

This study has been made exclusively on human specimens obtained after death. Due to certain factors as yet beyond control (agonal vasospasm, post-mortem intravascular clotting) there is a fortuitous element inherent in any attempt to fill the vascular tree, post-mortem, with

TABLE I

AGE DISTRIBUTION OF THE INJECTED MATERIAL SUITABLE FOR ANALYSIS

(Thirty-six specimens)

Age of subject at time of death (*years*)	Number of femoral heads
20– 30	2
31– 40	2
41– 50	1
51– 60	1
61– 70	12
71– 80	11
81– 90	5
91–100	2

contrast media and this has necessitated very many more injections than are reported here, the uninformative results being excluded from this paper. The material available for the analysis on which this report is based is shown in Table I.

The techniques used to visualise the blood vessels within the bone are based on those previously described in the investigation of another circulatory problem (Trueta *et al.* 1947). The arteries that supply the upper end of the femur have been injected with various materials: in most instances the injections have been given into the medial femoral circumflex artery, but the common iliac and common femoral arteries have also been used. When injecting a suitably excised specimen one can obstruct branches which might otherwise divert the injection mass away from the upper end of the femur. No attempt has been made to estimate the actual injection pressures used, because the pressure recorded in the syringe or nearby artery is no indication of the effective injection pressure in the vessels as they enter the bone.

The injection masses used in this study were barium sulphate suspensions (Ardran 1953), 10 per cent colloidal silver iodide, 2 per cent Berlin Blue, and Neoprene Latex solution. The barium suspensions and the colloidal silver, being radio-opaque, could be subjected to radiological analysis and, when necessary, microradiography; other injection media were studied by different techniques. Neoprene Latex casts of the vascular tree, obtained by digestion of the bone and marrow with acid after intra-arterial injection of Neoprene, can be dissected under water; Spalteholz's technique, by which the bone and marrow are rendered transparent, enables the vessels previously filled by one or more injections to be followed for long distances throughout their course by a binocular dissecting microscope. We have employed a number of different methods to reveal the vessels in order to minimise the errors of interpretation that can arise from the use of any one technique.

Radiographs were made in the antero-posterior and the medio-lateral positions of each specimen that had been injected with radio-opaque material. The specimen was then sawn up into slices approximately a quarter of an inch thick, the plane of section varying from specimen to specimen. These slices were radiographed at right angles to the plane of their section and were then decalcified; when this process was complete all the radiographic views described above were repeated, it being possible to reconstruct the specimen by fitting together the several slices. On many occasions stereoscopic radiographs were taken for any or all of the above projections. The microradiographic techniques used were those described by Barclay (1951).

The study of the smaller vessels has been mainly effected by microscopy of histological preparations obtained from injected material. Tissue embedded in 20 per cent low viscosity nitrocellulose was cut at thicknesses of either 15μ or approximately 400μ. Whereas the former were stained with Hansen's haematoxylin and eosin, the thicker sections were examined unstained by low power microscopy.*

RESULTS

We have found that the vascular patterns established during the phase of growth are not replaced at maturity but largely persist throughout life, and thus one can speak of epiphysial and metaphysial circulations even in advanced years; we shall show below that when the two territories become one by the disappearance of their cartilaginous frontier their circulations still retain some autonomy. The epiphysis and the metaphysis usually receive blood from separate sources and we shall call the vessels epiphysial and metaphysial in accordance with their destinations. By reference to their sites of entry into the bone (Fig. 3) the epiphysial arteries are named lateral and medial, and the main metaphysial arteries superior and inferior. The lateral epiphysial and both groups of metaphysial arteries usually arise from the medial femoral circumflex artery; the medial epiphysial artery is a continuation of the artery within the ligamentum teres which comes from the acetabular branch of the obturator artery.

A detailed assessment was made of the relative contribution that these sets of vessels made within each territory, and for this analysis fifteen injections were selected whose quality was such as to allow the finer branches of each artery to be followed to their limits. It was found that the lateral epiphysial arteries predominate in the epiphysis and the inferior metaphysial arteries in the metaphysis. The lateral epiphysial arteries supplied at least four-fifths of the epiphysis in seven cases, in a further seven they supplied two-thirds of the zone and in one case slightly more than half. The inferior metaphysial arteries were found

* If a block is sectioned serially, cutting alternately at 15μ and 400μ, it is possible not only to follow any vessel throughout the block by studying the thick unstained sections, but accurate superimposition of a stained thin section over its preceding or following thick section will allow identification of any particular vessel.

to supply about two-thirds of the metaphysial tissue that is within the femoral head. These proportions represent only the more usual arrangement and must be subject to considerable variation; for example, the contribution coming from the artery of the ligamentum teres may be negligible or absent in some cases.

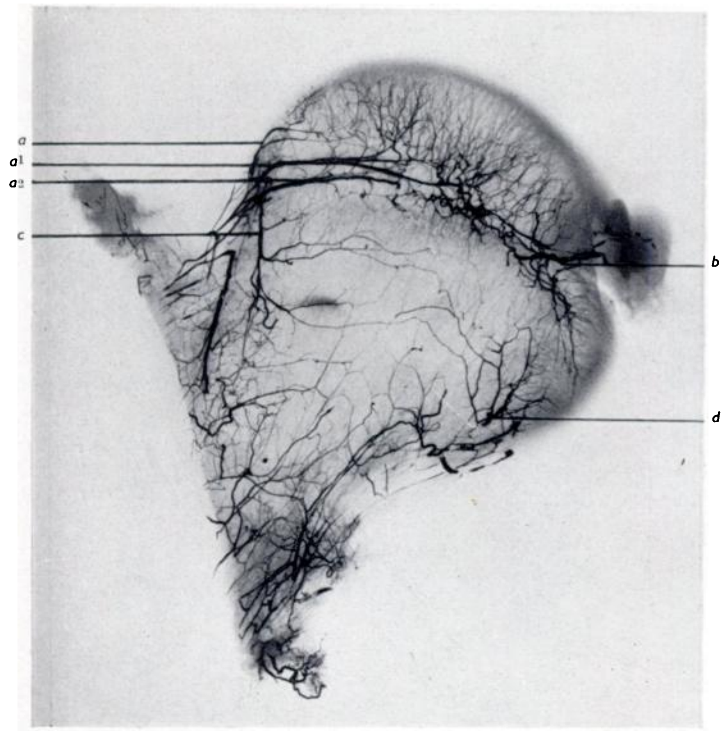


FIG. 3

Angiogram of a thick coronal slice of a femoral head of a subject aged twenty. Injection mass, barium.

a, a^1, a^2 —Lateral epiphysial arteries. *b*—Medial epiphysial artery. *c*—Superior metaphysial artery. *d*—Inferior metaphysial artery.

The epiphysial arterial pattern. *The lateral epiphysial arteries* (Figs 3, 6, 7, 12 and 23) enter the head superiorly and postero-superiorly, usually two to six in number and often spiral in form for a short distance after their entry (Fig. 4); in this position they always lie within a thick fibrous sheath (Fig. 5). In their course they follow closely the line of the old epiphysial plate, but lie some distance above it superficial to the epiphysial scar. They run downwards and medially, and, as can be seen in lateral radiographs, somewhat anteriorly as well, in a gentle curve directed towards a point on the articular surface between the fovea capitis and the inferior articular margin. The constituent arteries of the group vary in size: one is usually larger than the others and there is frequently one vessel whose branches are distributed exclusively to the supero-lateral segment of the epiphysis. *The medial epiphysial artery* (Figs. 3 and 23) and its main branches run laterally on the same level as the fovea capitis through which they have entered, until they meet and anastomose with the main lateral epiphysial vessels; the length of their course is proportional to their size. This anastomosis was frequently demonstrated by the outflow of the injection medium from the artery of the ligamentum teres on injection of the medial femoral circumflex artery.

The predominant direction of distribution of the branches from these main epiphysial arteries is into the epiphysis and towards the joint surface; in comparison the outflow to the metaphysis is small. The epiphysial vessels are arranged in a characteristic series of arterial

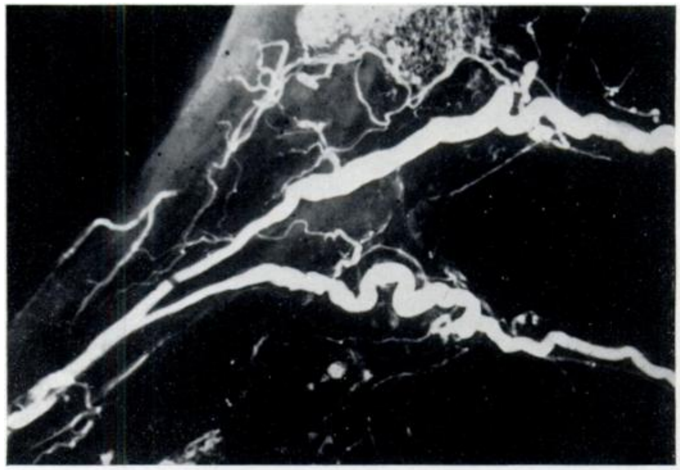


FIG. 4
Radiomicrograph showing a lateral epiphysial artery bifurcating immediately before entering the femoral head. Its branches describe a spiral in the first part of their intracapital course. Injection mass, barium (× 16).

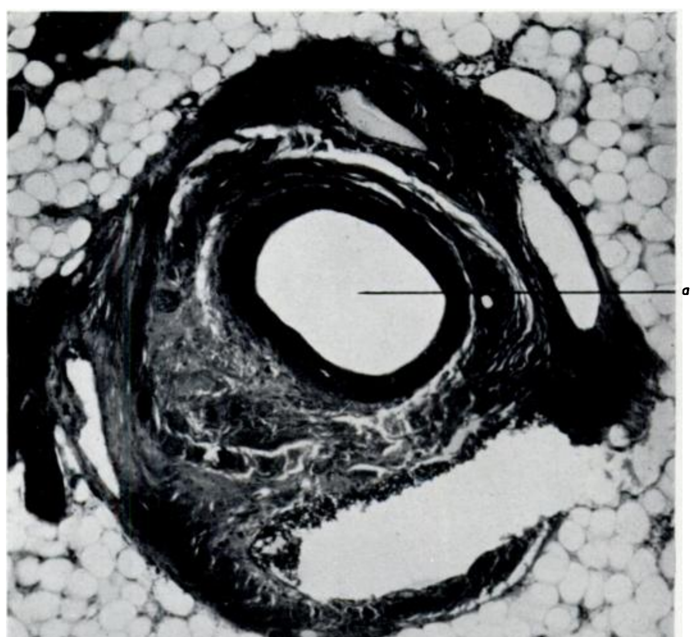
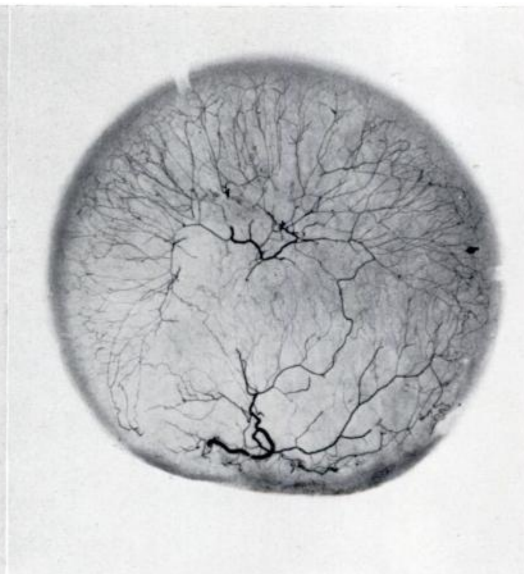


FIG. 5
Photomicrograph of a lateral epiphysial artery (*a*) cut in the sagittal plane. The vessel was approximately at the position shown in Figure 4 and lies in the centre of a fibrous sheath which also contains four veins (× 52).

arcades constituted in the following manner. The branches leaving the parent stem or its main divisions do so at an angle of approximately 90 degrees and follow a course directed perpendicularly to the joint surface; this radial arrangement obtains irrespective of whether the vessels are studied in coronal (Fig. 6), sagittal (Fig. 7) or horizontal sections. Neighbouring vessels running roughly parallel in this fashion form the sides of arches which are completed by a communicating branch usually of the same calibre as that of the two vessels it is uniting (Figs. 8 to 10). The summits of the arches, like their supporting pillars, are directed towards the surface and from these arches further branches are given off which themselves are subject to the same arrangement. Two or three tiers of such arches are found in the epiphysis lying



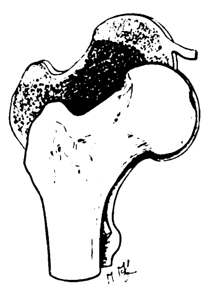
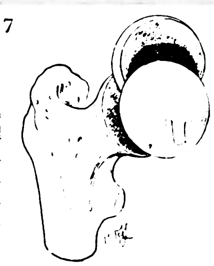


FIG. 6

FIG. 7



Preparations to show the arterial pattern within coronal (Fig. 6) and sagittal (Fig. 7) slices of the femoral head. Figure 6—Photograph of a Spalteholz preparation subject aged seventy-five. Injection mass, barium. A considerable part of the course of the lateral epiphysial artery is seen. This vessel separates the tiers of arterial arches in the epiphysis above from the vessels of the metaphysis below. Figure 7—Angiogram, subject aged seventy-six. Injection mass, barium. The epiphysial artery lies just above the centre of the specimen and its branches are distributed to the epiphysis, which in this section has the form of an inverted crescent. The large vessel lying inferiorly is the main inferior metaphysial artery and its branches anastomose with the epiphysial system.

between the main vessels and the articular cartilage. Stereoscopic studies reveal that any one of the radially running branches can contribute to several arches lying in different planes; it is as though a series of fountains were arranged in such a fashion that the spray from any one fell into the rising columns of its neighbours on all sides. This characteristic pattern of the smaller intra-osseous arteries is a feature of the epiphysis and not merely of the branches of the lateral epiphysial artery; the branches arising from the medial epiphysial artery behave in exactly the same manner.

The metaphysial arterial pattern (Figs. 3, 6, 7, 12 and 23)—There are usually two, three or four *superior metaphysial arteries* arising from the vessels which will soon give origin to

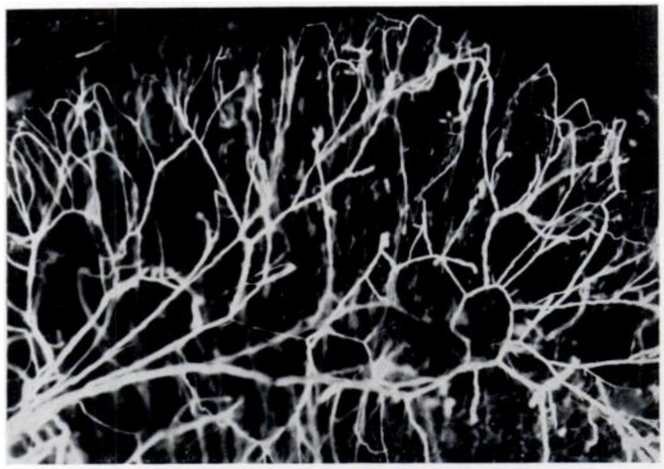


FIG. 8

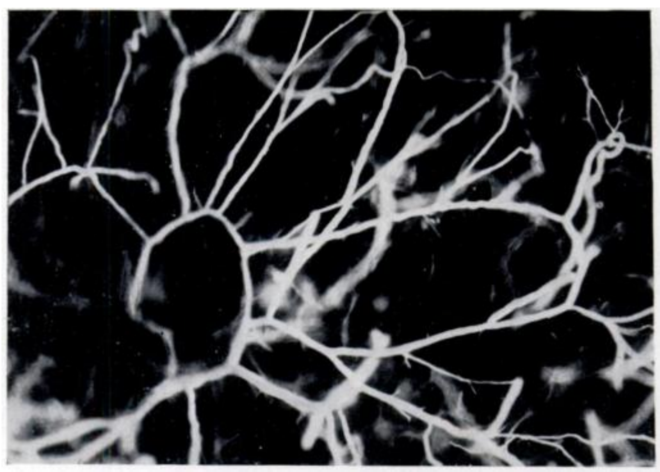


FIG. 9

FIG. 10

Photomicrographs of the epiphysial arteries within the femoral head of a subject aged seventy-five. In Figure 8 are shown the tiers of arches running from the main lateral epiphysial vessel below to the articular surface above (×2·6). Figures 9 and 10 show details of arch systems (×6). Injection mass, barium. Spalteholz preparation.

the lateral epiphysial group. These metaphysial vessels enter the superior aspect of the femoral neck some distance from the margin of the articular cartilage and have an absolutely straight course vertically downwards into the bone; when they have passed about a quarter of the way across the femoral neck they suddenly turn supero-medially in a smooth curve towards the site previously occupied by the epiphysial plate. The *inferior metaphysial arteries* enter the bone close to the inferior margin of the articular cartilage. There is frequently one vessel larger than any other of the group and it describes a short spiral before breaking up into branches which run up towards the epiphysis. The smaller arterial branches from these sets of metaphysial vessels are distributed throughout the metaphysis; the arching system of anastomoses seen in the epiphysis is absent here and the pattern is more one of branching vessels of decreasing calibre pursuing straight or angular courses towards the epiphysis.

The terms superior and inferior metaphysial arteries apply to groups of vessels which are in some respects less well defined than the lateral and medial epiphysial arteries. Before they enter the bone, the metaphysial arteries, by their frequent interconnecting anastomoses

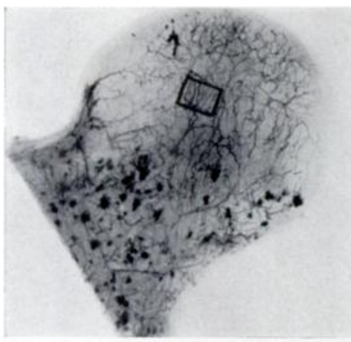


FIG. 11

The radiomicrograph on the right shows the spiral anastomotic vessels (×18) which, as can be seen in the smaller angiogram above, connect the epiphysial and the metaphysial circulations. Injection mass, barium.

in the sub-synovial tissues, conform to the pattern so clearly described by Hunter (1743) and named by him the circulus articuli vasculosus. On the neck of the femur the circle tends to be deficient anteriorly, and " the vascular border of the joint " is most evident superiorly and inferiorly; it is here that the main arteries running to the metaphysis are found. Quite frequently the circle has some representation posteriorly in virtue of small arteries on the back of the femoral neck running in part into the metaphysis but we have not described these as a separate metaphysial group, rather preferring to emphasise the major sources.

Anastomoses—There is a free anastomosis inside both the epiphysis and the metaphysis between the vessels which supply each territory; in addition there is anastomosis between the vessels of the two territories at the site previously occupied by the growth plate. A series of connecting branches leave the main epiphysial arteries at right angles and run downwards into the metaphysis; in calibre they are usually smaller than the vessels of the epiphysial arches and in form they are frequently spiral (Fig. 11). Just as the metaphysis is a somewhat arbitrary subdivision of the diaphysis so the free anastomosis there of the metaphysial arteries and those within the neck of the femur prevents any attempt to define the lateral limits of the metaphysial circulation. It may be noted here that we have not seen any evidence of the nutrient artery of the femur extending its area of supply up to the metaphysial region as has been so frequently stated.

Changes in the vascular tree with age—In this study we have examined specimens from persons who ranged in age from twenty to one hundred years and we have been impressed with the complete absence of any decrease in patency of the vascular tree with advancing years (Fig. 12). The failure to visualise a particular vessel or vessels by any of the techniques we have used gives no proof of their absence. In our experience a complete filling of even the arterial tree has never been achieved; tissue which had yielded our best angiograms, on subsequent histological section showed areas in which the vessels, though present, had not been filled. Whether this failure is due to the crudity of our present methods or whether it implies an intermittency of the circulation such as some authors describe in other organs (Richards and Schmidt 1924, Krogh 1929) cannot be decided; it has certainly been observed that the vessels of resting zones in other tissues have been extremely difficult to fill by injection.

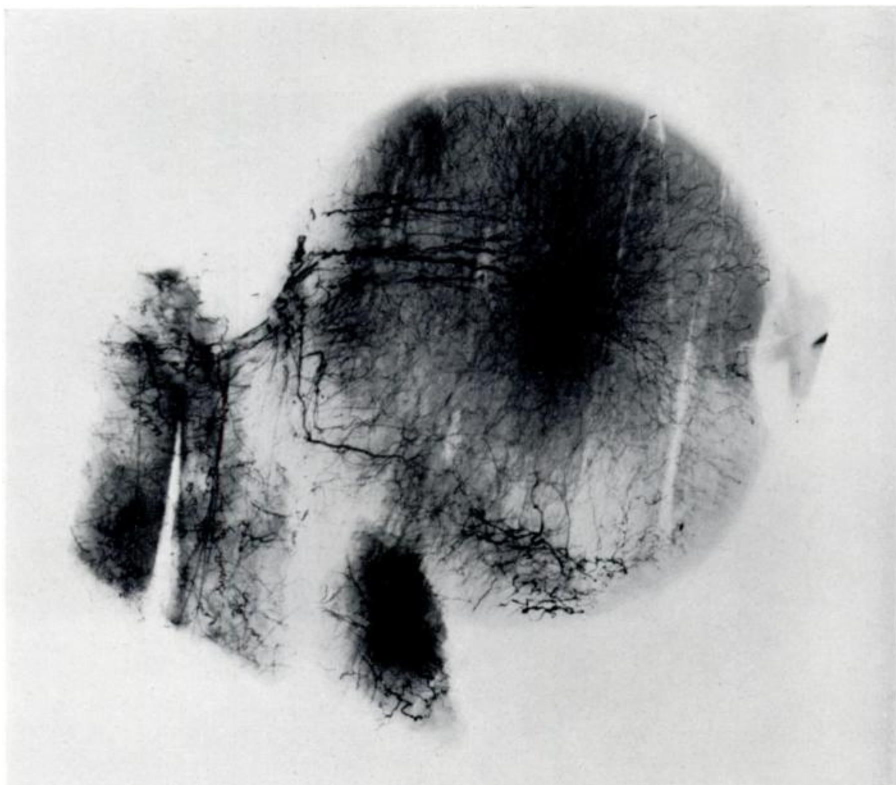


FIG. 12
Angiogram of a complete femoral head, subject aged seventy-six. Injection mass, barium.

The arterioles and smaller vessels of the marrow—Before we describe the smaller vessels that lead from the arterial systems already detailed, it is necessary to mention the distribution of the marrow within the upper end of the femur. This is because the arrangement of the small vessels, unlike that of the arteries, is independent of their situation in the epiphysis or metaphysis but is instead specific for the two types of marrow, yellow and red. During the years of growth the red, haemopoietic marrow is macroscopically visible both in the epiphysis and the metaphysis of the upper end of the femur; in normal adult life we have seen it mainly restricted to two areas, the metaphysis and a zone of epiphysis underlying the articular cartilage and the fovea capitis (Figs. 13 to 15). Most of the epiphysis is occupied by inactive yellow fat. Frequently we have seen a sharp line of demarcation between the two differently coloured marrows of epiphysis and metaphysis and the junction is a reminder of the situation the growth plate previously occupied.* In those specimens in which the metaphysis is only partly occupied by red marrow this striking partition is, of course, not seen. These findings are curiously at variance with many statements in the literature which localise the red marrow to the epiphysis or to the proximal portions of the adult femur.

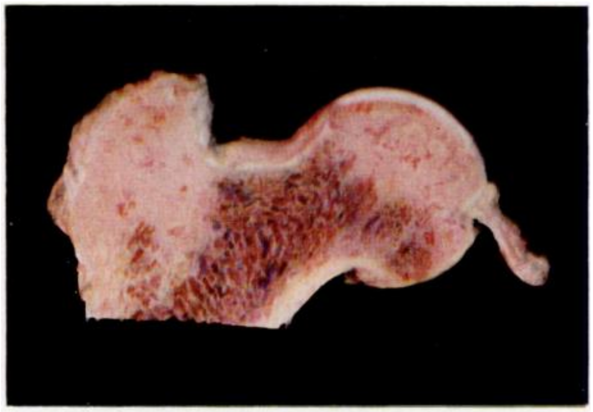


FIG. 13

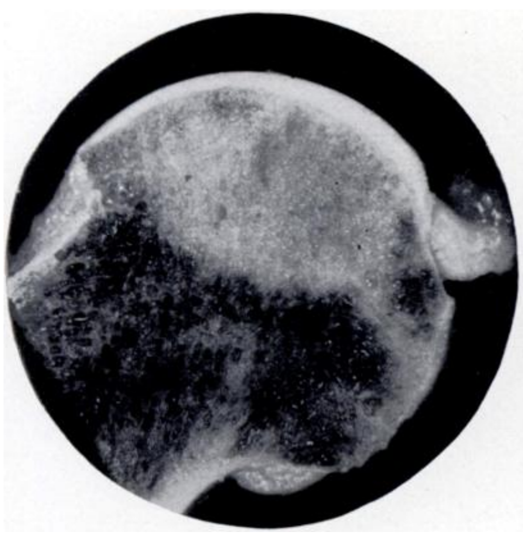


FIG. 14

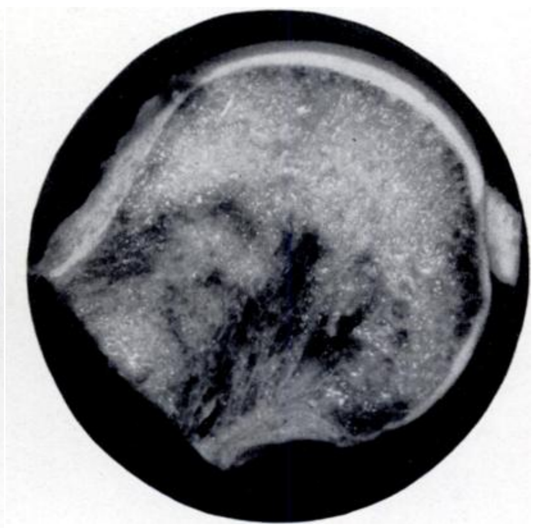


FIG. 15

Coronal sections of femoral heads. The epiphysis is largely occupied by yellow marrow and the metaphysis by red. Figure 13—Femoral head of a subject aged seventy-six. Figure 14—Femoral head of a subject aged fifty-six. Figure 15—Femoral head of a subject aged fifty-three.

Microscopically there is no clear-cut separation of the marrow into yellow and red; the two forms merge gradually into each other and there are an infinite number of marrow types ranging from the very cellular to the completely fatty. The red, cellular marrow consists of an argyrophil meshwork of reticular fibres attached to which are reticular cells. Within this mesh are found a great variety of blood corpuscles showing all degrees of development, occasional fat cells and the highly characteristic spacious thin-walled blood vessels, the

* We are aware that some of the specimens in which this observation was made may not come within the limits of strict normality in that the main or contributory cause of death may have provoked some increased haemopoiesis. Nevertheless the findings illustrate the individuality that the metaphysial marrow can show in its haemopoietic activity.

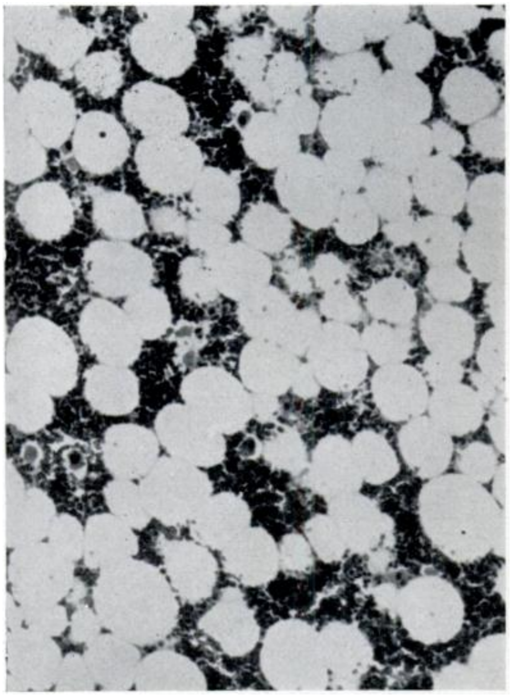


FIG. 16

FIG. 17

Photomicrographs of sections of the bone marrow 10μ thick. Figure 16—The red marrow (×105). Figure 17—The yellow marrow (×70). The difficulties of determining vascular arrangements in these types of preparation are obvious.

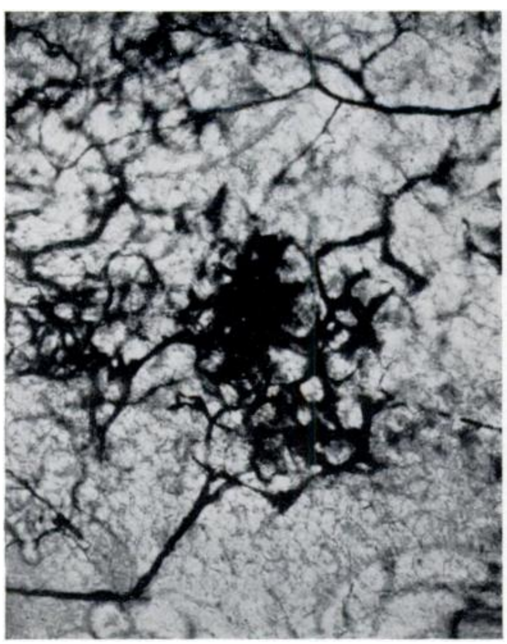


FIG. 18

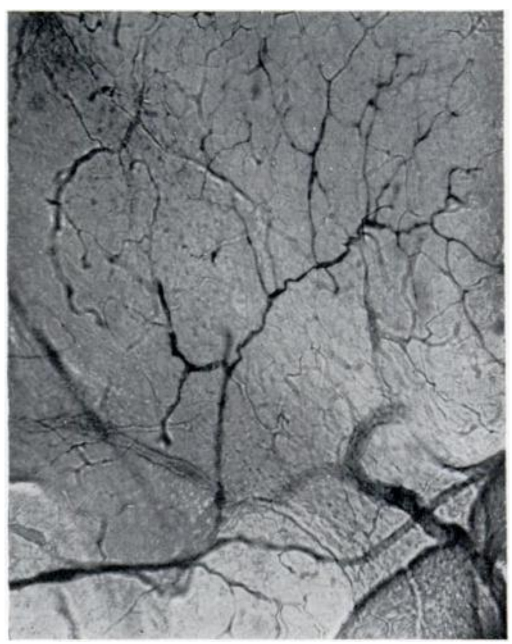


FIG. 19

Photomicrographs showing the vessels within the haemopoietic marrow (Fig. 18) and the fat marrow (Fig. 19). In both, an afferent vessel enters the field at the bottom left-hand corner. Injection mass, Berlin Blue; unstained sections 400μ thick. Figure 18—The afferent vessel ends in the anastomosing meshwork of the sinusoidal bed (×45). Figure 19—The afferent vessel distributes capillaries which run between the lobules of fat cells; sinusoids are absent. The large irregular vessel running to the bottom right-hand corner is a vein whose tributaries are coming from the capillary bed (×75).

venous sinusoids (Fig. 16). In the yellow marrow (Fig. 17) fat cells have replaced practically all these other types; scattered between the fat are small blood vessels of capillary size.

The arterioles of the marrow are singular in appearance in that throughout their course they undergo little or no decrease in calibre and their branches are approximately the same size as themselves; in their passage through the marrow they pursue a straight course, changing direction by sudden angulations. The blood conveyed by the arterioles eventually reaches one of the two available destinations, either the sinusoidal circulation of the red marrow (Fig. 18) or the capillaries of the fat marrow (Fig. 19). The fine-walled vessels of the haemopoietic areas, wherever they may be within the bone, take the form of the sinusoids (Figs. 20 to 22). These combine to form an irregular bulging and profusely anastomotic network which is found to correspond to the lobules of the red marrow; several precapillary vessels bring blood from various directions to each clump of sinusoids. Although the sinusoids are many times the size of ordinary capillaries their walls are as thin as the capillary wall. We have not found any evidence of an open circulation due to fenestrae in the sinusoidal wall, although it must be noted that the collections of injection material which we have accepted as extravasation due to rupture of the vessel wall have always occurred within the sinusoidal meshwork (Fig. 23).

The capillaries lying between the fat cells of the yellow marrow (Figs. 24 and 28) are similar to capillaries in other tissues. They arise from precapillary arterioles and drain into venules, and this type of circulation is also found scattered throughout the red marrow in those parts where fat cells are present in addition to the haemopoietic elements. In the capillary network the point of union of one capillary with another is frequently marked by a conical enlargement of the otherwise narrow lumen.

The many variations in the cytology of the marrow alluded to above are paralleled by the variations in the vascular picture; the capillaries and sinusoids are not only continuous but every grade of their admixture and partition is seen.

The relationship of the articular cartilage to the blood vessels of the bone—Normal articular cartilage is avascular, but in two situations it comes into contact with capillary vessels: on its deep attached surface and at its peripheral margin. The basal layers of the cartilage which are apposed to the underlying bone are calcified and the subchondral bone does not form an absolute barrier isolating this tissue from the circulation within the femoral head. Precapillary vessels arising in the marrow pass through canals in the subchondral bone (Figs. 25 to 27) and form single broad capillary loops at the deep surface of the calcified cartilage; post-capillary venules return from these loops through the canals to the marrow. This single capillary system regularly arranged against the deep surface of the cartilage is different from anything else seen within the marrow circulation and appears to be specific to the chondro-osseous junction. We have been unable to determine any specific arrangement of capillaries in the subsynovial tissues at the circumference of the normal articular cartilage.

The veins—Our knowledge of the venous anatomy is as yet incomplete. The venous radicles coming from the capillaries (Fig. 28) and the sinusoids are broader and run a more irregular course than the equivalent arteries. In certain zones, such as the inferior metaphysial region, venules draining the sinusoids empty quickly into capacious thin-walled veins (Fig. 29); elsewhere veins of a smaller calibre commonly follow the course of an artery either alone when they may spiral around the latter (Fig. 30) or in association with another vein, one on each side (Fig. 31). In cross-section the larger veins which are soon to leave the head present a characteristic elliptical appearance as they lie adjacent to the artery in the fibrous sheath previously referred to (Fig. 5).

In our material certain observations made after injecting consecutively two materials differing both in colour and particle size have led us to suspect the existence of arterio-venous anastomoses within the bone. We have not so far been able to demonstrate these to our complete satisfaction.

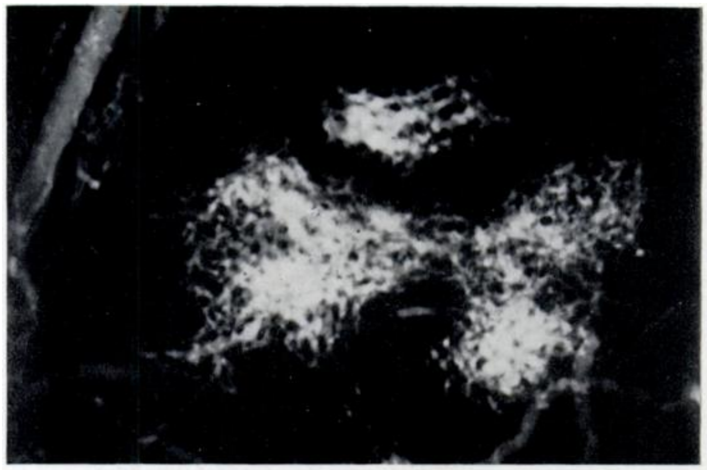


FIG. 20

FIG. 21

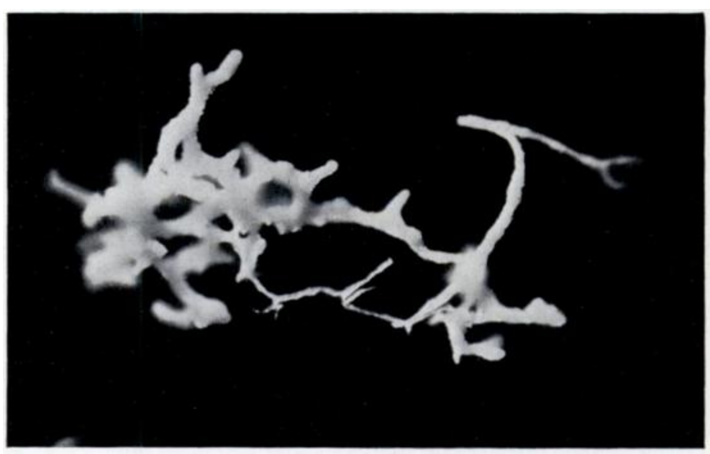


FIG. 22

The sinusoids of the haemopoietic marrow. Figure 20—Radiomicrograph showing four groups of sinusoids. The vessel on the left of the field is an artery. Injection mass, barium (×18). Figure 21—Photomicrograph showing an afferent vessel leading into a sinusoid. Injection mass, Berlin Blue. Unstained section 400μ thick (×174). Figure 22—Photomicrograph of a Neoprene cast of sinusoids (×50).

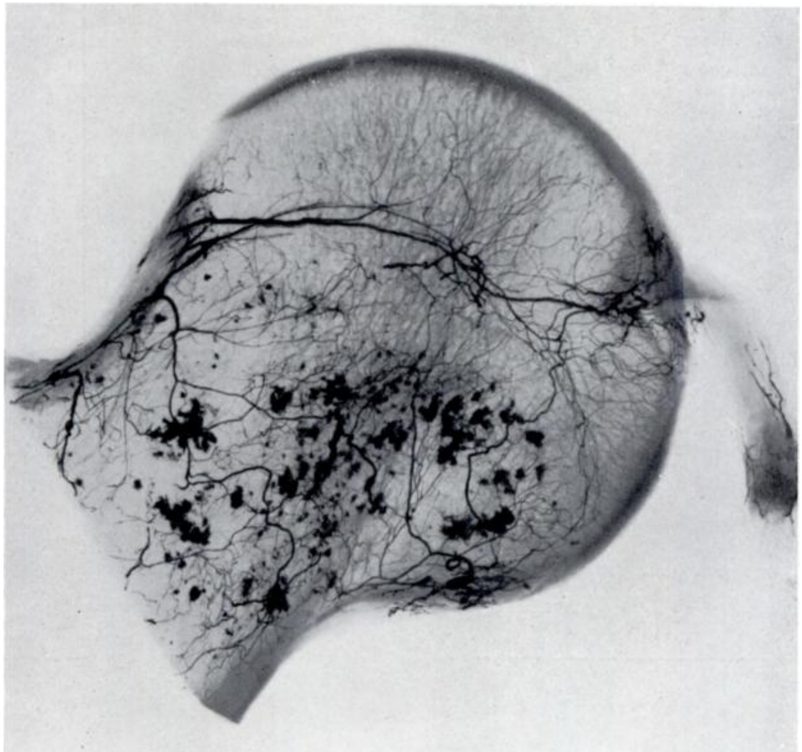


FIG. 23
Angiogram of a coronal slice of a femoral head, subject aged seventy. The irregular opacities within the metaphysis are mostly areas where sinusoids of the red marrow have in part been filled and extravasation has then occurred. Injection mass, barium.

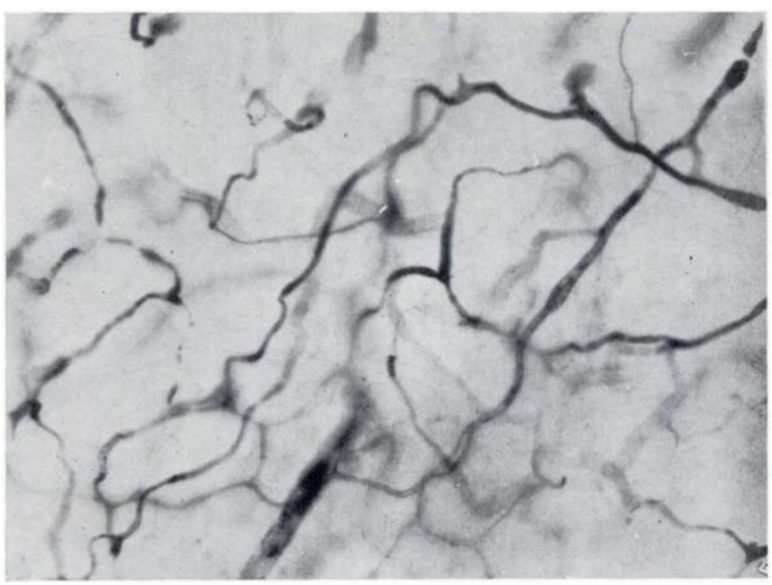


FIG. 24
Photomicrograph of capillaries within the fat marrow. Injection mass, Berlin Blue. Unstained section 400μ thick (×174).

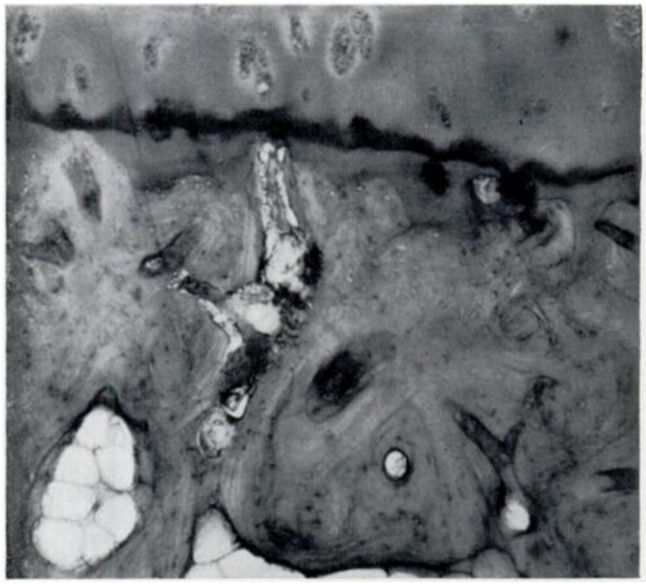


FIG. 25

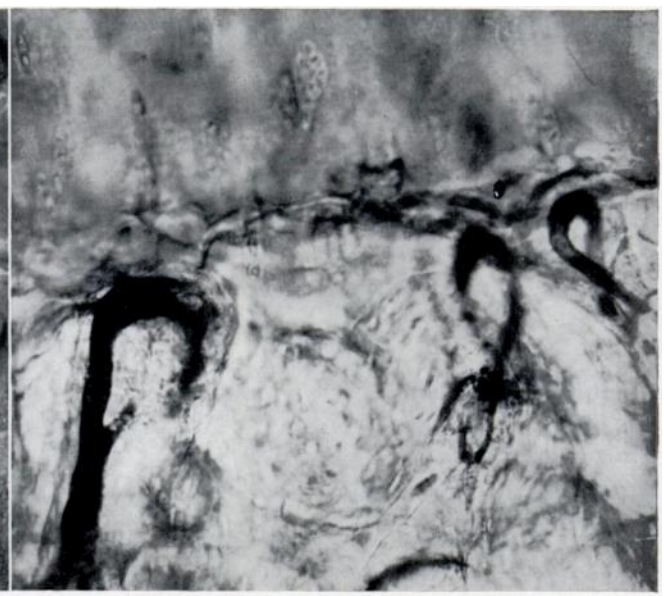


FIG. 26 FIG. 27

Juxta-chondral blood vessels. Figure 25—Photomicrograph of the junction of articular cartilage and bone. Canals in the subchondral bone lead up towards the calcified layer of the cartilage. The irregular horizontal wavy dark line marks the superficial border of the calcified cartilage (H.E. $\times 70$). Figures 26 and 27—Two fields from a different specimen showing the junction between the articular cartilage above and the bone below. Four vessels pass up through the subchondral bone to the calcified cartilage, whose irregular upper border can be distinguished despite the unstained nature of the section which is 400μ thick. Injection mass, Berlin Blue ($\times 210$).

DISCUSSION

We have emphasised that throughout maturity and even in old age we have been unable to detect any decrease in the richness of the arterial tree within the femoral head, and the only explanation we can offer for the many statements to the contrary that exist in the literature (Langer 1876, Walmsley 1915, Láng 1916, Kolodny 1925, Cheynel 1947 and Etienne and Granel 1949) is that these are based on technical errors and the wrong interpretation of negative findings. This integrity of the circulation in the older subjects is particularly noteworthy in relationship to the cartilage degeneration and other features of osteoarthritis which are encountered in joints increasingly commonly with advancing age (Heine 1926, Bennett *et al* 1942). In the course of another work we have confirmed the occurrence of these changes in the hip joint. The present report suggests that they are not preceded or accompanied by any general ischaemia within the femoral head. The marked changes in the vascular pattern which we have found to accompany the various stages and lesions of osteoarthritis will be detailed in a subsequent paper.

The lifelong persistence of the epiphysial arterial pattern, with the predominance therein

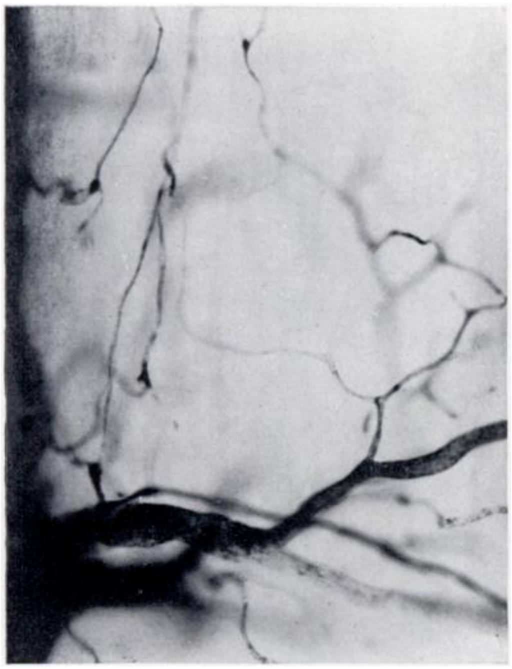


FIG. 28

FIG. 29

Venous drainage of the marrow. Figure 28—Photomicrograph of the fat marrow showing capillaries draining into a venule in the lower portion of the field. This vessel proceeds into a vein. Injection mass, Berlin Blue. Unstained section 400μ thick (× 123). Figure 29—Photomicrograph of the red marrow showing sinusoids in the top half of the field being drained by short venules into the large vein inferiorly. Injection mass, barium. Unstained section 400μ thick (× 34).

of the lateral epiphysial arteries, may increase our understanding of one of the main factors responsible for the greater incidence of necrosis of the femoral head after unimpacted adduction fractures of the femoral neck when compared with abduction fractures. In the former variety the lateral epiphysial arteries are lying at the site of the greatest tearing of the tissues, whereas in abduction fractures these important vessels are not subjected to the same risk of injury.

The nutrition of cartilage has been the subject of an immense amount of research and is still an unsolved problem. The present study brings a contribution to this, in that it has revealed the form of a capillary system which appears to be directed towards the cartilage; the anatomical pathway for the conveyance of nutriments from the subchondral circulation to the cartilage can be said to exist. The canals in the subchondral plate and their termination close to the calcified zone of the cartilage can be seen in ordinary histological preparations of uninjected material, as has been recently emphasised by Holmdahl and Ingelmark (1950).

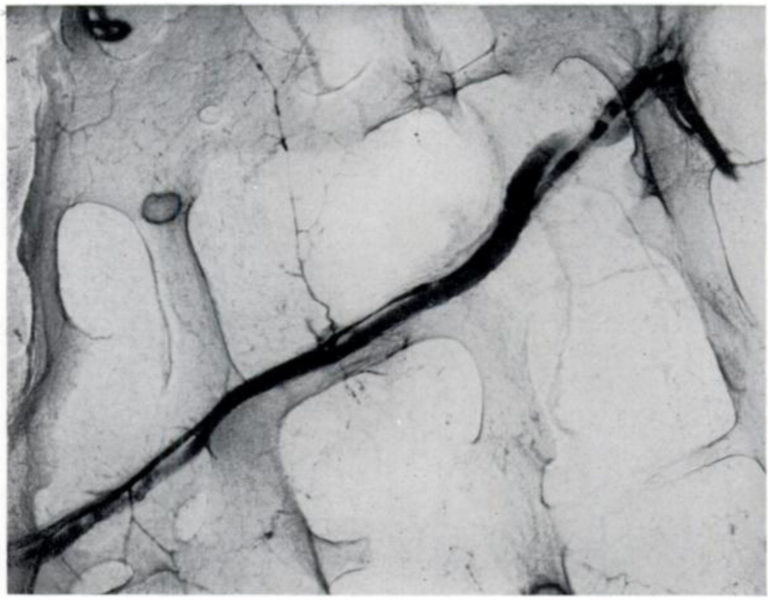


FIG. 30

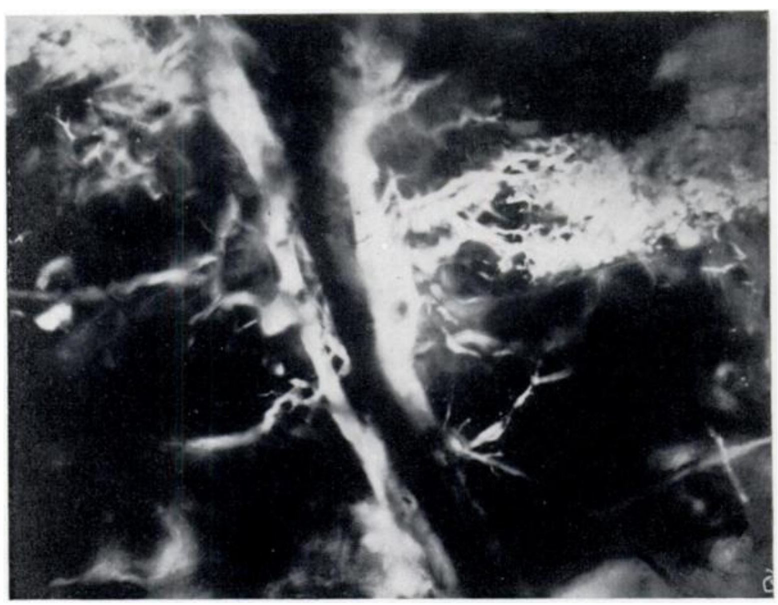


FIG. 31

The course of the veins. Figure 30—Photomicrograph. A single broad vein describes a gentle spiral around a slender artery. Injection mass, Berlin Blue. Unstained section 400μ thick (× 30). Figure 31—Photomicrograph showing two white venae comites, filled with barium, on either side of an artery filled with Berlin Blue. Sinusoids are seen draining into the vena comes on the right of the artery. Spalteholz preparation (× 18).

Arteries of spiral form are seen frequently in our material. They are invariably present in the synovial membrane; other sites where their presence has impressed us by their frequency are the early intra-osseous course of the lateral epiphysial and the inferior metaphysial vessels, the site of the old growth plate and to a lesser extent the centre of the metaphysis. It is uncommon to find them in any profusion in the epiphysis. Their occurrence in the synovial membrane and at the point of entry of the main trunks into the head might suggest that the spiral shape serves to adapt these vessels to the demands of joint movement; but this explanation cannot be applied to those spiral vessels located deep in the head. The proximity of these latter to the sites of red marrow formation invites the suggestion that some correlation could exist between vessel form—assuming this is not an injection artefact—and haemopoiesis. Reynolds (1948) working with the ovary, and Harrison and Weiner (1949) working with the testis, have considered the possible ways in which the spiral arteries associated with these organs could be related to the conditions necessary for the cellular proliferation that occurs there.

The description of the capillaries and sinusoids of the marrow which we have given is at variance with much that is to be found in the literature and we would suggest two reasons that might account for this. Firstly, previous investigators have worked mainly with animal tissues; and secondly, in the past, interpretations have been made from the study of thin microscopic preparations (less than 20μ); we have found these latter to be not only uninformative of vascular orientation but positively misleading. The finest anastomosing vessels within the fat marrow are true capillaries; the term sinusoid, coined by Minot (1899–1901) and first applied by Doan (1922) to the vessels of the haemopoietic marrow, seems to us an apt name in that it distinguishes these vessels from the capillaries within the fat. The sinusoids do not resemble capillaries morphologically nor does their form suggest the function inherent in the latter type of vessel.

Doan (1922, 1925), working with animal material, considered that the " venous sinusoids form normally the principal functioning vascular bed for the actively circulating blood in the marrow; *i.e.*, they correspond largely to the capillaries of other organs." By the use of a special starvation technique he rendered the marrow of the pigeon hypoplastic, and then was able to demonstrate therein " a most extensive system of capillaries, hitherto unsuspected." He believed that these latter vessels were not connections between arteries and veins but ran from sinusoid to sinusoid, which structures they entered with a conical enlargement of their lumen; that this capillary bed was normally non-patent and functionally dormant as far as the active blood circulation was concerned; and that in the epiphysis the capillaries surrounded each fat cell. We have enumerated here the differences between the occult circulation described by Doan and the one that we have constantly found to be present and patent within the normal fat marrow; we have not seen in our material a collapsed intersinusoidal capillary bed such as Doan described. He believed that these capillaries were the site of erythropoiesis and that they might be thrown open to the circulation under conditions of increased activity of the marrow, as in anaemia (see below). Whatever their haemopoietic potentialities may be, we judge from their distribution and morphology that the capillary bed described above by us is responsible for the metabolic needs of the cells of the fat marrow.

We have described how the distinction between the vascular epiphysis and metaphysis can be made in the adult and that one of the hallmarks of the epiphysis is the arching arterial pattern. We have also seen that the common association between this pattern and the fat marrow of the epiphysis is not unchangeable. The constant association between vessel form and marrow type is found only in the finest ramifications of the arterial tree. Here the capillary net is the vascular counterpart of yellow marrow, the sinusoids of the red. This is well demonstrated in states of anaemia, in which the increased demand for red blood cells results in the transformation of the epiphysial marrow from yellow to red. The arterial arch pattern of the epiphysis is unchanged in such circumstances but the capillaries of the previously fatty marrow are replaced by sinusoids. Since there are, at this level of the circulation, only two types of vessel, the capillary and the sinusoid, we are unable to escape the conclusion that such extension of the haemopoietic tissues is accompanied by the conversion of capillaries into sinusoids.

While it is dangerous to base speculations concerning function on morphological appearances, it seems likely to us that as the slender afferent vessels debouch into the capacious sinusoids the rate of blood flow therein must be severely slowed. The sluggish circulation which would thus obtain might in part be responsible for the arrest and localisation of metastatic tumour deposits and certain infections within the bones.

SUMMARY

1. The form and distribution of the blood vessels within the adult human femoral head are described.

2. It has been found possible to delimit the proximal femoral epiphysis in mature years by reference to arterial form alone.

3. Two morphologically different sets of vessels are described interposed between the arterioles and venules of the bone marrow. One, a true capillary bed, lies mainly within the fat marrow; the other, constituted by sinusoids, lies within the red marrow. The departure of these findings from current views is noted.

4. A capillary system is described in relationship to the calcified zone of the articular cartilage.

5. No evidence has been found in support of the common belief that the circulation within the femoral head decreases quantitatively with advancing age.

It is a pleasure to acknowledge the help we have received from many people in the course of this investigation. In particular, Dr G. M. Ardran, of the Nuffield Institute for Medical Research, Oxford, has not only provided all the radiographic facilities but has frequently given us his advice on the interpretation of results. Dr F. Schajowicz, of Buenos Aires, working in this centre for four months made available to us the full extent of his knowledge of the minute anatomy of the locomotor system. He introduced many valuable histological and microphotographic techniques and it was he who first pointed out to us the partition of the marrow described above. We are, however, most indebted to him for his never failing enthusiasm. We are grateful to Dr Robb Smith, Director of Pathology, Radcliffe Infirmary, Oxford, and Dr Cosin, Director of Cowley Road Hospital, Oxford, for the post-mortem facilities which they have extended to us. Lastly we would like to thank the staffs of the Photographic Department and the Pathological Laboratory of this centre, and in particular Mr Hill, our laboratory technician, for his invaluable help with every technical process involved in this investigation.

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Closed intramedullary nailing of femoral fractures. A report of five hundred and twenty cases

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Closed Intramedullary Nailing of Femoral Fractures

A Report of Five Hundred and Twenty Cases*

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ABSTRACT: **Intramedullary nailing was performed on 520 femoral fractures in 500 patients. The series included eighty-six open fractures and 261 comminuted fractures. Closed intramedullary nailing was used in 497 femora and open intramedullary nailing with cerclage wiring, in twenty-three. The union rate was 99.1 per cent. The range of motion of the knee at follow-up averaged 130 degrees. Complications included four infections (0.9 per cent). Shortening of more than two centimeters occurred in ten patients (2.0 per cent) and malrotation of more than 20 degrees was observed in twelve patients (2.3 per cent). After prompt emergency measures had been taken, routine treatment included strong preoperative traction followed by accurate positioning of the patient on the operating table; selection of the correct insertion point for a properly sized, prebent, flexible, bullet-tipped nail; and accurate reduction of the fracture. Careful rehabilitation of the patient also contributed to the excellence of the results.**

In 1940, Küntscher[18] stated that closed intramedullary nailing of the femur offers an ideal anatomical, functional, and physiological treatment for fresh femoral fractures. Subsequent reports of the results in many series have substantiated this statement[1,2,5,6,8,10,17,27,29,34]. At University Hospital and Harborview Medical Center, we began to apply Küntscher's principles in 1968, and we reported our initial results with closed intramedullary nailing in 1971[6]. We have continued to use the procedure extensively, and are presenting our results in a large series of fractures of the femoral shaft treated by intramedullary nailing. We also summarize the preoperative treatment, operative technique, and postoperative management, emphasizing the changes that we have instituted.

Clinical Material

We reviewed a series of 520 fractures of the femoral shaft in 500 patients who were treated by intramedullary nailing at University Hospital and Harborview Medical Center, Seattle, between 1968 and 1979. This consecutive series included the first femoral fracture treated with closed intramedullary nailing at our institution and all subsequent femoral fractures that were managed by this method, including forty-five that were reported on previously[6]. The patients ranged in age from ten years and ten months to ninety-two years old (mean, 29.5 years). There were 347 men and 153 women. One hundred and eighty-seven patients were transferred to our institutions for the operation. Although many staff and resident physicians performed the surgical procedures, we supervised almost all of them.

Eighty-six fractures were open, and the remaining fractures were closed. The soft-tissue injuries were classified as grade I, II, or III, depending on the size of the skin wound and, more importantly, the extent of soft-tissue stripping from bone, reflecting disruption of the external blood supply. There were seventy-six grade-I fractures (small skin wound with minimum or no stripping of soft tissue from bone), eight grade-II fractures (moderate skin and muscle injury with wound contamination), and two grade-III fractures (severe injury with devitalized skin, muscle, and neuromuscular structures threatening the survival of the limb)[9]. In general, patients with a grade-III open femoral fracture were treated by other methods.

The fracture was located in the proximal one-third of the femur in eighty-five limbs, in the middle one-third in 325, and in the distal one-third in 110. There were 124 transverse fractures; 101 short oblique fractures; thirty spiral or long oblique fractures; 261 comminuted fractures, including twenty-six segmental fractures; and four longitudinal fractures.

The comminution of the fractures was categorized as type I, II, III, or IV, depending on the degree (Fig. 1)[35]. In the ninety-two fractures with type-I comminution, only a small piece of bone had broken away. The fifty-four fractures with type-II comminution had a larger butterfly fragment, but the cortex was at least 50 per cent intact, allowing control of rotation and length. In fifty-four fractures with type-III comminution a large butterfly fragment was present, precluding control of rotation or length, or both. There were thirty-five fractures with type-IV comminution; that is, severe comminution with no abutment of cortices at the level of the fracture to prevent shortening.

Injury was caused by a variety of mechanisms: automobile accidents (216 fractures), motorcycle accidents (108 fractures), automobile-pedestrian accidents (seventy-nine fractures), and miscellaneous causes (twenty-three fractures). Thirty-five fractures were sustained in a fall from a height and twenty-two, from a fall at home. Twenty-one

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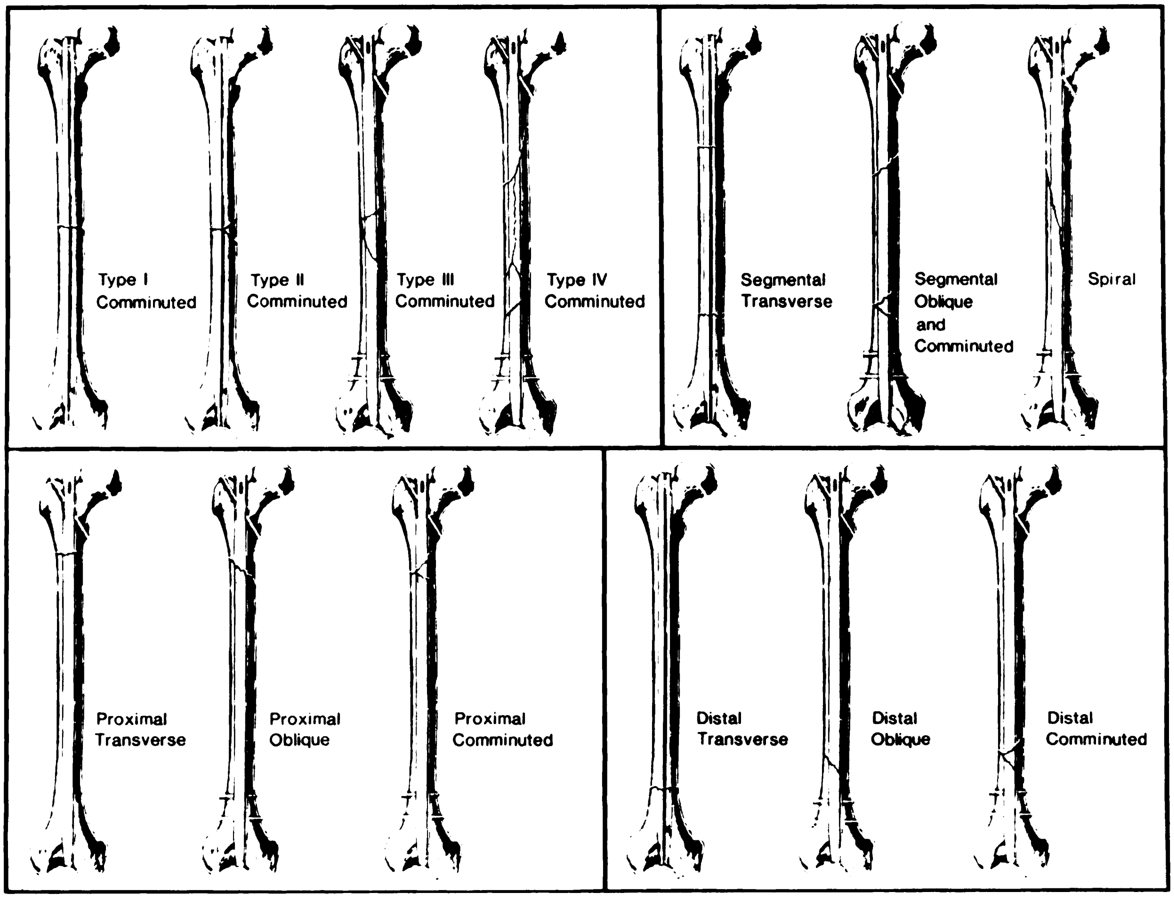

FIG. 1

The types of comminuted fractures are illustrated. Our recommended treatment method (standard intramedullary nail or interlocking nail) for femoral fractures of various patterns is also indicated.

fractures were sustained in sports activities; twelve, in a bicycle accident; and four were a gunshot wound.

Associated injuries were extremely common and played an important part in the determination of initial treatment of the fracture and in the rehabilitation of the patient. One hundred and forty-three patients had injuries to the head, chest, or abdomen. Twenty-seven had a bilateral femoral fracture; fifty-four had ipsilateral femoral and tibial fractures; and twenty-seven had an ipsilateral fracture of the hip, including femoral neck and intertrochanteric fractures. Eighteen had an ipsilateral patellar fracture and twenty-three sustained significant ipsilateral ligament injuries of the knee. Only twelve patients had an associated arterial injury and only ten had an associated nerve injury.

Methods

Preoperative Treatment

Emergency care was given, with special attention to cardiopulmonary status, abdominal status, and the status of the central nervous system. Roentgenograms of the injured femur were then made, as well as routine roentgenograms of the pelvis and ipsilateral knee. Examination of the knee for points of tenderness allowed detection of related ligament injuries. The arterial status of the lower limb was analyzed carefully, particularly when the fracture was in the distal one-third of the femur. The patient was then placed in skeletal traction in the emergency room. Usually balanced suspension traction was used because it provided greater comfort for the patient, but fixed traction was applied if the patient had to be transported. We used rather strong traction, ranging from twenty-five to thirty-five pounds (eleven to sixteen kilograms) in women and from thirty-five to forty-five pounds (sixteen to twenty kilograms) in men. Sufficient traction was applied to restore normal femoral length or to slightly distract the fracture. Lateral roentgenograms were made to ascertain the adequacy of the traction because anteroposterior roentgenograms can lead to a false measurement of distraction[10].

Early in the series, the need for preoperative distraction of the fracture was not sufficiently appreciated. Experience showed, however, that when the fracture was allowed to shorten, reduction became extremely difficult. Thus, we began to emphasize traction as a vital part of the delayed procedure. We prefer to gain slight distraction preoperatively on the hospital ward and to use minimum traction during operation.

Although we used prophylactic antibiotics routinely, we changed the drug regimen during the period of the study. Initially, we gave methicillin and kanamycin twelve hours preoperatively and seventy-two hours postoperatively[6], but later we changed to a cephalosporin, with one dose administered one hour before operation and four doses given during the twenty-four hours after operation.

As emphasized in our previous report[10], roentgenograms of the normal femur were made at a tube-to-plate distance of one meter, using an ossimeter to allow accurate measurement of the length of the femur and the width of the medullary canal. These measurements allowed the physician to anticipate the appropriate size of the nail. The normal femur was measured from the tip of the trochanter to the lateral joint-line of the knee because this measurement gave the most accurate determination of length. The initial roentgenograms were also used to determine the correct insertion point for the nail in the region of the trochanter.

The timing of the operation was considered carefully for each patient. Initially we delayed the operation for five to seven days, as had been emphasized in previous reports[4,6,19,20,31]. One advantage of this delay was an increased rate of union[4,20,31]. A second advantage, emphasized by Küntscher[19] and by Clawson et al.[6], was that the danger of development of a fat-embolism syndrome was past. A third advantage was that the surgeon and operating-room team had additional time to consider and prepare for the individual patient. After we had gained extensive experience with multiply injured patients, however, it became evident that there was an advantage to immediate stabilization of the femoral fracture so as to provide better initial treatment and decrease the mortality rate[3,11,28]. Because the condition of the multiply injured patient tends to worsen two to three days after injury rather than to improve, prompt stabilization of the fracture or fractures decreases further blood loss and injury to the soft tissues and allows earlier mobilization of the patient with chest and abdominal injuries. When a patient had an associated head injury we performed closed intramedullary nailing as early as possible.

The potential for development of a fat-embolism syndrome was an important consideration in the timing of the operation. Patients with multiple injuries, including those with more than one long-bone fracture, were observed routinely for twenty-four hours in an intensive-care unit, with frequent monitoring of blood gases and if necessary administration of proper pulmonary support. In our early experience with delayed nailing of 250 acute fractures, we did not have a single patient with clinically significant fat embolism postoperatively, and therefore we concluded that the nailing contributes very little to the chance of fat embolism[28]. Because the onset of a fat-embolism syndrome generally occurs twelve to thirty-six hours after injury, we now prefer either to perform the nailing immediately or to delay the operation for five to seven days. The effects of hemorrhage and muscle spasm, which are maximum in the intervening three to four days, make closed reduction technically difficult during that interval.

Our treatment for patients with an open fracture changed somewhat with experience. At the beginning of the series, we treated all open fractures with primary débridement, wound closure approximately seven days after injury, and intramedullary nailing at an average of fourteen days after injury. Later in the series, we performed primary cerclage wiring of butterfly fractures at the time of the initial débridement, but continued to delay intramedullary nailing for approximately fourteen days. Our approach by the end of the series was to perform primary débridement and immediate internal fixation with an intramedullary nail in all grade-I and grade-II open femoral fractures, leaving the wound open with an antibiotic coverage[32], and closing the wound after five to seven days. A further change in the care of patients with an open fracture was the recognition that nutrition plays a vital role in rehabilitation; nutritional needs are now analyzed, met routinely, and followed carefully.

At the beginning of the series we considered the minimum age for treatment with intramedullary nailing to be sixteen years, but in 1973 we began to lower the age-limit. Between 1973 and 1979, closed intramedullary nailing was performed in thirty femoral fractures in twenty-eight patients ranging in age from ten years and ten months to fifteen years and seven months old. In fourteen patients, fusion of the epiphysis was evident roentgenographically; in the other fourteen, the length of the nail was selected to ensure that the nail did not penetrate the distal femoral epiphysis.

Operative Treatment

The operative technique has been modified slightly since the time of our first report[6]. The modifications include: (1) a change in the position of the patient on the fracture-table, (2) a change in the insertion point for the nail in the region of the trochanter, (3) a decrease in the amount of reaming, and (4) a change from the original straight Küntscher nails to pre-bent nails.

Early in the series, when we positioned the patient on the fracture-table we allowed the uninvolved lower limb to drop into wide abduction, but this position was awkward for the patient and impeded the surgeon's view of the limb to be operated on. In 1974 we began to place the uninvolved lower limb in a straight line with the body, and the hip of the injured extremity was placed in slight flexion and slight adduction with straight traction. If strong traction was required or if the fracture was distal, a small Kirschner pin was placed in the distal part of the femur at operation, the knee was flexed, and traction was applied through the femoral pin to prevent stretching of the sciatic nerve.

We strongly prefer to place the patient in the lateral position[10]. Even now we use the supine position occasionally, but only to avoid multiple positionings for the multiply injured patient or to facilitate retrograde intramedullary nailing in ipsilateral fractures of the femoral neck and shaft. We have found, however, that the supine position poses more technical difficulties than does the lateral position with regard to insertion of the nail, particularly with more complex fractures.

During the study period a variety of fracture-tables and image intensifiers were used, and it became apparent that the two must function well together and that the orthopaedist must be familiar with both. The table that has been used during the last few years has a perineal post that can be offset distally. This table also allows traction during operation and easy access with an image intensifier. We switched to an image intensifier that is smaller and more mobile than the older units, allows better visualization of the fracture site, and has image retention, which markedly decreases radiation exposure.

When the patient was placed on the table, the perineal post was swung distally to allow visualization of the trochanter in the anteroposterior and lateral planes. The axilla was supported to prevent neural injury. The uninvolved lower limb was then placed in traction in a straight line with the body. The testes were allowed to hang free. The thigh on the side that was not to be operated on was carefully supported, either by raising the pelvic pad or by lowering the perineal post. This support prevented venous congestion of the involved extremity and abduction of the proximal fracture fragment by the perineal post.

After the patient was positioned on the table, correct positioning of the fragments with reference to rotation was essential. We originally arranged the limb so that the patella was parallel to the floor, but unfortunately this practice led to external rotation at the fracture site in several patients[22]. In subsequent patients we rotated the limb gently inward and outward to achieve the proper rotational position through relaxation of the soft tissues. Careful attention to the skin folds then allowed us to detect excessive tension from internal or external rotation. This method proved to be both accurate and easy.

The closed reduction required an experienced unscrubbed surgeon who participated actively throughout the operation. First, he or she examined the preoperative anteroposterior and lateral roentgenograms carefully to determine the direction of reduction of each fragment. Traction was then applied to allow the appropriate length to be gained. The surgeon had to take care to avoid excessive traction, which would have pulled the soft tissues too tightly, making the reduction even more difficult, and also would potentially have jeopardized the peroneal nerve by stretching it. After studying the roentgenograms, the unscrubbed surgeon performed the reduction by applying localized pressure just proximal and distal to the fracture with either leaded gloves or rings. He or she checked the reduction with anteroposterior fluoroscopy and held it carefully, converting to lateral fluoroscopy to ascertain that the reduction had been achieved. At this point the surgeon had to think in three dimensions rather than continuing to work in a single plane. The feasibility of reducing the fracture was ensured and the mechanism of reduction was ascertained before the patient was prepared and draped.

A rotatory manipulation was frequently required, and occasionally an increased angulation was needed[10], before reduction of oblique fractures could be achieved. In proximal fractures, an intramedullary nail was inserted in the proximal canal during operation to aid the reduction. We considered proximal fractures to be suitable for intramedullary nailing if they were at least 2.5 centimeters distal to the trochanter[19,27]. In more distal fractures a femoral traction pin was inserted anteriorly just proximal to the adductor tubercle to allow reduction of the distal fragment, which was being pulled posteriorly by the gastrocnemius muscles and posterior part of the capsule. The pin was drilled from inferomedial to superolateral to allow us to pull the fracture out of valgus angulation. The knee was then flexed to allow the gastrocnemius muscle and posterior part of the capsule to relax, and traction was applied through the femoral pin. The foot was placed on a Mayo stand, which was raised or lowered to control rotation. For intramedullary nailing of distal fractures we prefer that there be at least ten centimeters of intact bone above the intercondylar notch.

Obtaining the correct point of insertion on the trochanter is the most important feature of the operative portion of treatment. Küntscher[19] and Müller et al.[24] advised the selection of a point on the lateral aspect of the trochanter to reduce the risk of intracapsular infection and avascular necrosis of the femoral head. We followed this advice early in our series. Unfortunately, because that point is so far lateral to the axis of the medullary cavity, eccentric reaming and comminution of the fracture site frequently occurred in the medial part of the femoral cortex during insertion of the nail, particularly in the more proximal fractures. Thus, we have chosen an insertion point in the piriformis fossa just medial to the body of the trochanter and posterior to the gluteus medius muscle. We now check this point carefully with anteroposterior and lateral fluoroscopy before proceeding further with the operation. Inspection of this point under both anteroposterior and lateral image intensification — probably the most important technical aspect of the operation — ensures that the insertion point is accurate.

After insertion of a sharp awl, a T-handled hand-drill was used to penetrate the proximal metaphyseal bone. A bulb-tipped guide with a slight bend was inserted. The bend, which is essential for closed reduction, is only two centimeters from the end of the bulb to allow passage around corners. The bulb-tipped guide was moved gently down to the fracture site. The unscrubbed surgeon reduced the fracture, and the scrubbed surgeon lined up the bulb-tipped guide approximately. Both surgeons remained still while the image intensifier was switched to a lateral plane. Minimum adjustments were made, and the bulb-tipped guide was inserted with light tapping of a mallet. If the reduction was in question, both views were checked repeatedly until the bulb-tipped guide was successfully placed in the distal fracture fragment. The guide was then moved down to the subchondral bone of the distal part of the femur, and its length was measured to provide a final determination of the length of the nail.

The reaming was started with an eight or nine-millimeter end-cutting reamer. During each passage of a reamer across the reduced fracture site, careful monitoring of the reduction was required to prevent eccentric reaming. The size of the reamers was progressively increased by one millimeter in diameter until the surgeon felt that the reamer was in contact with the cortex. The reaming then progressed by one-half-millimeter increments. It was essential that the bulb-tipped guide remained centrally placed and that the reduction remained accurate. Observation of the fracture with both anteroposterior and lateral fluoroscopy prevented excessive thinning of the cortex. The bulb-tipped guide was held during reaming to prevent it from backing out, and the surgeon was careful to keep sponges and gloves from being wrapped up in the reamer.

Early in the series we reamed the cortex to the thickness necessary for obtaining a 2.5-centimeter (one-inch) length of contact between the nail and the cortical wall both proximal and distal to the fracture. Often the cortex was reamed to as much as one-half of its original thickness. We found that this reaming was excessive, however, because it necessitated the use of a nail with a larger diameter, which increased the tendency toward comminution of the fracture, with a resultant loss of stability. Later we tended to ream the cortex at the isthmus of the medullary canal for only one to three millimeters at the most and to use smaller nails. From our original average nail diameter of sixteen millimeters in men and 14.5 millimeters in women, we switched to an average diameter of 14.5 millimeters in men and 13.5 millimeters in women. This change seemed to prevent further comminution of the fracture fragments during driving of the nail.

We frequently over-reamed the proximal fragment by 0.5 millimeter, except in fractures of the proximal one-third of the femur. Breakage of the reamer was not uncommon in our experience; removal of the bulb-tipped guide allowed retrieval of the broken reamer. Occasionally a reamer jammed as it was backed out, particularly if a small comminuted fragment had been pulled up from the fracture site into the isthmus, where it blocked extraction of the reamer. In that event, a small guide was passed alongside the reamer to push the fragment down to the fracture site and allow the broken reamer to be extracted.

Although we always tended to use flexible cloverleaf Küntscher nails, the technically improved versions were employed as they became available. The cloverleaf nail that was used initially was straight, with a blunt tip. Because the shape of this nail did not match the contour of the femur, its use led to splitting and further comminution of the bone. We then changed to a pre-bent nail with a bullet tip. The pre-bent aspect of this nail decreased the incidence both of splitting and of further comminution of the femur, and the bullet tip allowed easier passage across the fracture site. At the end of the study period we switched to a pre-bent cloverleaf nail with a conical tip, which further facilitated passage of the nail across the fracture site. This nail extends the full length of the femoral canal down to subchondral bone and is twelve millimeters in diameter or more.

After reaming, we inserted a larger nail-driving guide to help keep the nail central in the canal. Again, as the nail passed the fracture site, accurate reduction was necessary to prevent comminution of bone. Supporting the fracture during final driving of the nail was important, particularly in distal fractures. Once the nail was in position, the wound was closed and the patient was transferred to a regular bed, where the traction pin was removed and the knee ligaments were examined carefully[26]. Rotation of the extremity was also checked, and if it was not accurate the patient was turned to a prone position and attempts were made to correct it. The lower limb was then set gently in an antirotational splint.

For fractures requiring cerclage wiring, such as type-III or IV comminuted fractures, the patient was also placed in the lateral position on the fracture-table and the lateral aspects of the hip and thigh were prepared with iodine alcohol down to the knee to allow lateral exposure of the femur if open reduction became necessary. The fracture was approached through a lateral incision, and the cerclage wire was applied to the fragment before reaming was begun. The nailing was then performed in a manner similar to that already described.

Postoperative Management

After the operation the patient was taken to the recovery room and received blood transfusions only if necessary. Quadriceps muscle-setting exercises and straight leg-lifting were begun on the morning after operation. As soon as the patient had control of the extremity, he or she was allowed to begin walking with crutches and protected weight-bearing. The patient was encouraged to use the crutches for at least six weeks, until good control of the quadriceps muscle had been obtained.

An important change that was made in postoperative management was an increased emphasis on quadriceps rehabilitation after the patient's discharge from the hospital. Early in our series, the patient was discharged from the hospital while still using crutches, and little attention was given to continuing rehabilitation. Later we came to realize that it was important for the patient to work with a physical therapist for about three months to strengthen the quadriceps and to regain motion of the knee more rapidly. After the hospitalization period, quadriceps muscle rehabilitation consisted only of straight leg-lifting with weights and was carefully supervised for at least three months[25]. Range-of-motion exercises of the knee were given minimum attention for the first four to six weeks. Once the patient had gained 90 degrees of knee motion, he or she attempted to gain complete knee flexion with an exercise that involved sitting back gently on the heels from a kneeling position. Patients with severe quadriceps-muscle injury or with inflammatory callus that looked similar to myositis were not encouraged to pursue the exercises for range of motion of the knee too vigorously because early manipulations caused increased inflammation and provided only a transient gain in motion. These patients required a longer period to obtain knee motion, but with gentle work and patience they continued to gain motion over four or five months. Toward the end of the series, the patients were tested on an isokinetic muscle-training machine (Cybex II) whenever possible to obtain an objective measure of the level of rehabilitation.

Postoperative traction or a spica cast was sometimes required for patients with a somewhat unstable fracture or who were considered to be unreliable[35]. Occasionally, a patient with a distal fracture was kept non-weight-bearing with a cast-brace postoperatively. This treatment was generally continued for four to six weeks, after which partial weight-bearing was allowed. In patients with a slightly comminuted fracture, such as a type-II injury, toe-touch weight-bearing was prescribed for the first six weeks.

The protocol for preventing pulmonary embolism in our patients was to prescribe aspirin and to have the patient begin walking as soon as possible.

Our routine for removal of the nail was limited to young people, and the procedure was done one year or more after injury, as convenient. Removal of the nail required planning and appropriate equipment but tended to be relatively simple. In our series we removed 169 nails and did not encounter any that could not be removed. The patients were allowed unlimited weight-bearing without crutches after removal of the nail. No stress fractures of the femoral neck or shaft occurred.

Results

The patients' progress was followed by means of clinical examinations and roentgenograms by us and by the referring physicians. Forty-seven patients were lost to follow-up, and eleven died within one year of injury. The other 442 patients were followed for at least one year.

Of the eleven patients who died within a year of injury, one did so two months after injury from complications of severe brain trauma; five died from associated multiple injuries; three patients, averaging seventy-five years old, died in a nursing home two, six, and nine months after injury; and the remaining two patients died of causes unrelated to the injury. No death was directly related to the femoral fracture.

The average time from injury to nailing was seven days. Forty-one nailing procedures were performed acutely in patients with an open fracture or in multiply injured patients. We tended to perform more acute nailing procedures as the series progressed. For patients with an isolated femoral fracture, the average hospital time was 13.3 days, the time before walking with crutches was begun averaged 3.2 days after operation, and the time on crutches averaged 5.8 weeks. For multiply injured patients, the total hospital time averaged 26.9 days.

The time to bone union, as determined from roentgenograms, was difficult to ascertain. According to our judgment, 87 per cent of the fractures appeared to be solidly united at three months. The operating time for individual patients decreased during the study period and was approximately an hour by the end of the series. Because of associated blood loss from the injury, the blood loss attrib-

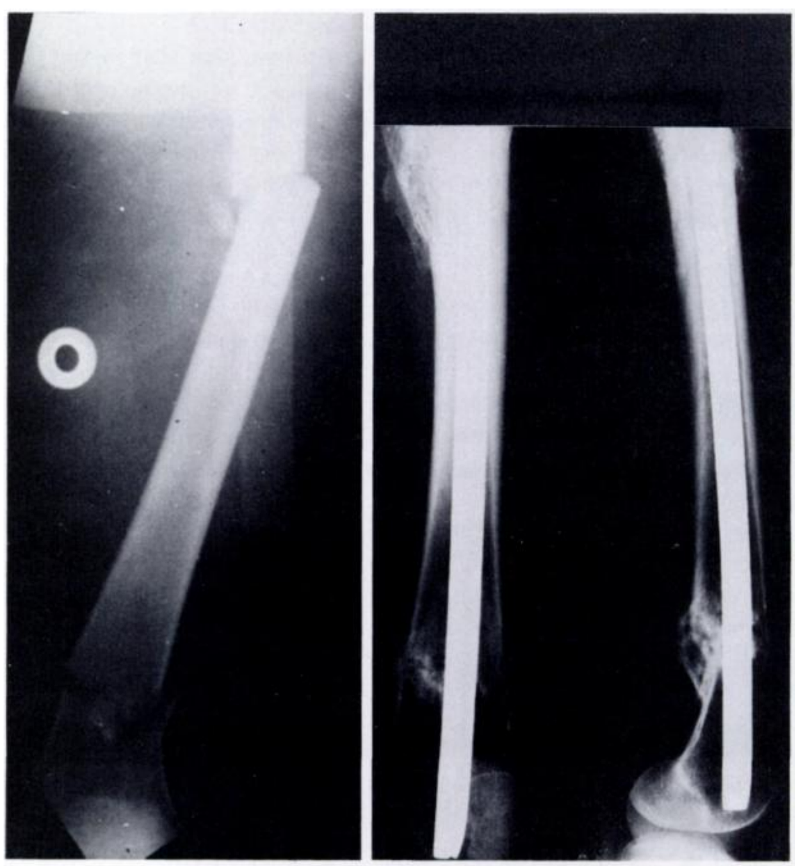

FIG. 2-A FIG. 2-B

Fig. 2-A: A twenty-six-year-old man sustained a segmental fracture of the femur in a fall from a power pole.
Fig. 2-B: Eleven months after injury the bone has united.

utable to the operative procedure itself was difficult to determine, but it was about one and one-half to two units, including losses from reaming and subsequent bleeding at the fracture site.

In patients who were younger than fifty years, the average diameter of the nail was 13.3 millimeters in women and 14.6 millimeters in men. In both men and women who were older than fifty years, the average diameter of the nail was 16.0 millimeters. The incidence of significant injuries to the knee ligaments was 9.0 per cent[26].

The postoperative range of motion of the knees was excellent, averaging 132 degrees (Figs. 2-A and 2-B). Only thirteen patients had knee flexion of less than 125 degrees; the least amount of flexion was 90 degrees, in a patient with an ipsilateral tibial fracture. Two patients attained 100 degrees of flexion; three patients, 105 degrees; four, 110 degrees; and three, 115 degrees.

Complications

Despite the closed nailing technique and careful management of the open fractures, there were four infections in the series, giving an infection rate of 0.9 per cent.

One infection developed around a closed fracture in a forty-three-year-old chronic alcoholic who had had previous infections in multiple areas. Unfortunately, prophylactic antibiotics were not administered, and this oversight may have had a role in the development of the infection. The nailing itself was technically faultless, but two months after operation a serious wound infection and pain developed about the hip. The patient's sedimentation rate was 105 millimeters per hour. Both the fracture site and the site at the proximal end of the nail were decompressed, and *Staphylococcus aureus* was grown on culture. The wounds were packed, a larger nail was inserted (because the original nail was backing out)[14,21], and antibiotic treatment was begun. Healing was uneventful, and the nail was removed one year later. At nine years of follow-up the patient had not had a recurrence.

The second infection was in a patient with an open fracture that was debrided routinely. A delayed closure was performed after one week, at which time the wound appeared clean. The fracture was nailed fourteen days after injury, and again the wound appeared benign. Two weeks after nailing a fever developed and there was erythema about the wound. The wound was drained again at the fracture site and at the proximal end of the nail, and *Clostridium perfringens* was grown on culture. The patient was treated with antibiotics and wound dressings. The fracture proceeded to union, and the nail was removed one year later. Although spores were seen in the specimens taken at the time of nail removal, the infection did not recur in four years of follow-up.

The third infection developed in a nineteen-year-old woman with multiple injuries, including a grade-I open, split segmental fracture of the right femur. Intramedullary nailing and cerclage wiring of the fragments was performed several days after débridement of the wound. The fracture fragments had no soft-tissue attachments. Six weeks after nailing, a fever developed and there was marked swelling of the thigh. Cultures grew *Enterococcus cloacae*. The fracture was again debrided and drained, and the proximal end of the nail was decompressed. Serial dressing changes were performed. After further healing of the bone, the nail was removed and a large sequestrum was debrided. A Wagner external-fixation device was applied, and open cancellous bone-grafting was performed. At four-year follow-up examination the patient had solid bone union, no signs of infection, and 135 degrees of knee flexion.

A fourth infection was seen in a fifty-seven-year-old man with chest and abdominal injuries and multiple fractures of long bones. He underwent closed intramedullary nailing of a closed femoral fracture and an infection developed after he had a gram-negative septicemia related to the abdominal injuries. After débridement of the fracture site and decompression of the nail, the wound healed without any sign of subsequent infection.

There were four patients with non-union, an incidence of 0.9 per cent for the series[11]. One non-union occurred in a seventy-three-year-old woman with a grade-II open fracture in the distal one-third of the femur. The wound was debrided and intramedullary nailing was performed immediately. The wound healed uneventfully, but nine months after the injury the patient still had slight aching at the fracture site; roentgenograms showed a non-union. The nail was replaced with a larger one, and four months later the bone appeared to have united.

The second non-union occurred in an eighteen-year-old woman whose injuries included a massively swollen thigh and a split segmental fracture of the femur. The fracture was nailed two weeks after injury, and despite attempts to maintain the length of the femur by traction, shortening occurred. The nail was reinserted but again shortening became evident despite the application of thirty-five pounds (sixteen kilograms) of traction, and the nail was again reinserted. At three months the fracture was still tending to shorten even with twenty-five pounds (eleven kilograms) of traction, and it was thought that the fracture was not healing in a satisfactory position. Therefore the fracture was exposed surgically, cerclage wiring was applied, and re-nailing and bone-grafting was performed. The patient was considered to have had a non-union despite the fracture's progress to union after this treatment.

The third non-union occurred in a sixty-seven-year-old man who had had a plate inserted in the femur for a fracture at the age of seven years and had sustained a stress fracture distal to the plate sixty years later. That fracture was treated with closed intramedullary nailing, but it failed to unite and required subsequent treatment.

A fourth non-union occurred in a sixty-three-year-old man with multiple injuries, including a contralateral above-the-knee amputation. Nailing of the open femoral fracture posed no technical problems. The patient was not permitted to bear weight for four months, but at eleven months the femur still had not healed. We removed the nail and inserted a larger one using closed technique, and the bone subsequently united.

Shortening of more than two centimeters occurred in ten (2 per cent) of the patients. The maximum amount of shortening was 5.0 centimeters, in a patient with a split segmental type-IV comminuted fracture. The patient refused postoperative traction and signed out of the hospital against medical advice. Shortening of 2.8 to 4.0 centimeters occurred in three other patients with a type-IV comminuted fracture and in three with a fracture that was comminuted during intramedullary nailing. Shortening of 3.0 to 4.5 centimeters occurred in two fractures that became comminuted when the patients fell at home after discharge from the hospital. Also, one patient with a type-I comminuted fracture of the proximal one-third of the femur had 2.5 centimeters of shortening. Three patients had shortening of 2.1 to 2.4 centimeters.

Shortening of 1.0 to 2.0 centimeters occurred in thirty-seven limbs (7.1 per cent), primarily in patients with a type-II (five of fifty-four), type-III (eight of fifty-four), or type-IV (eight of thirty-five) comminuted fracture and in elderly patients with a spiral fracture (nine of thirty). Shortening rarely occurred in patients with a type-I comminuted fracture (two of ninety-two), a segmental fracture (three of twenty-six), or a fracture with stable pattern[34] — that is, a short oblique (three of 101) or a transverse fracture (none of 128).

Patients with 2.0 centimeters of shortening or less rarely had any limb or back pain[30,36]. Our present guidelines are to accept 1.5 centimeters of shortening in young patients and as much as 2.5 centimeters of shortening in most patients who are more than sixty-five years old, particularly if the fracture is spiral.

We used open reduction and cerclage wiring in twenty-three patients to obtain rotational stability and regain length, and we used postoperative traction in thirteen to maintain length.

External rotational malunion (10 degrees or more) occurred in forty-three patients, and in twelve of them the deformity was more than 20 degrees. One patient had 60 degrees of deformity, two had 45 degrees, and six had 30 to 40 degrees. Internal and external rotation was measured by a goniometer with the patient prone and the knee flexed 90 degrees. It is interesting that five of the twelve patients with the greatest rotatory deformity had a fracture of the proximal one-third of the femur, whereas the maximum rotatory deformity in any distal fracture was 20 degrees. There were no internal rotational deformities. Seven patients had pain in the knee and an awkward gait because of the deformity. Two of these patients, in whom the deformity was detected before union of the fracture, had manipulation under anesthesia to align the bones before they united. The deformities (60 and 45 degrees) were corrected. Three patients required closed intramedullary derotation osteotomy; their deformities measured 20, 30, and 45 degrees. Two other patients, with 30 and 40 degrees of deformity, were symptomatic but decided not to undergo surgical correction.

There were five causes of rotatory malunion in the patients in our series, and often there was more than one cause in a particular patient.

1. Early in the series, external rotational deformities were produced by the position of the patient on the operating table, with the patella parallel to the floor. This problem was eliminated when we permitted the lower limb to rotate freely and determined the correct rotation from the relaxed position of the soft tissues.

2. Malrotation also occurred on occasion immediately after operation, before the patient had gained good muscle control. The unrestrained lower limb tended to fall into external rotation, and a deformity was produced. Later we began to use an antirotational splint during the early postoperative period.

3. A third cause of malrotation, instability of the fracture, was commonly seen in type-III and IV comminuted fractures[35]. To control rotation in these fractures, we began to use a cerclage wire, a postoperative spica cast, postoperative traction, or a combination of these methods.

4. Malrotation was sometimes observed, presumably because of muscle imbalance, in slightly comminuted or transverse fractures of the proximal one-third of the femur. By the end of the study period, we sometimes used a single-hip spica cast postoperatively if the fracture site approached the proximal limits for the use of an intramedullary nail. Occasionally we opted to use a different implant, such as the Zickel nail.

5. A fifth cause of malrotation was a fall by a patient while walking with crutches. Five patients with a rotational malunion fell at home during the first two to three weeks after nailing. No malunion had been observed in these patients prior to the fall.

Valgus angulation occurred in eight patients in our series; all had a fracture in the distal one-third of the femur. Seven of these deformities were due to technical complications related to the nailing. Inadequate support of the thigh and consequent inadequate reduction of the fracture during the procedure caused the fracture to be nailed in a valgus position[10]. In the eighth patient, a segmental fracture with a distal oblique fracture line slipped after nailing, and the fracture fragments drifted into valgus angulation. The angulation, which ranged from 5 to 11 degrees in the eight patients, was never symptomatic and did not require correction. Toward the end of the series, we began to use cylinder casts or cast-braces for four to six weeks for patients with an unstable distal fracture. Varus angulation occurred in four patients, all with a mid-shaft fracture. The bow of the nail was turned too far laterally, and the nail pushed the fracture into slight varus angulation. The angulation, which did not exceed 5 degrees, was asymptomatic in all patients and did not require correction.

Ten patients had a peroneal-nerve palsy. In six the palsy was caused by the initial injury. In the other four it was related to the surgical procedure; that is, inadequate distraction of the fracture before operation necessitated very strong traction during operation. These four cases of palsy occurred early in the series; recovery was complete in three patients and about 80 per cent in the fourth. No palsies occurred after we changed the position of the patient on the fracture-table. The uninvolved lower limb is now pulled in a straight line with the body; the extremity to be operated on is slightly flexed at the hip and the knee is kept straight. This position simulates a straight-leg-raising test, and if strong traction is applied the sciatic nerve can be stretched. Therefore, if strong traction is to be used in the operating room, we now insert a femoral pin in the distal part of the femur and keep the knee bent to relax the nerve.

A fat-embolism syndrome, or adult respiratory-distress syndrome, was seen in fifty-five patients and was related to the severity of the initial injury and accompanying shock. These patients were given routine treatment, including pulmonary support. There were no deaths, and all of the patients recovered completely.

There were nine patients with a pulmonary embolism. Eight had multiple injuries and the ninth patient, who died from the embolism, had an isolated femoral fracture.

Discussion

In the present series of 520 femoral-shaft fractures treated by the same method, intramedullary nailing, it is important to note that although we chose that single form of treatment we modified and refined it in important ways over the eleven-year study period. We continue to revise our procedures with experience. We have made major changes in our approach to the patient, in the equipment and technique used for intramedullary nailing, and in the indications for this fixation method with regard to fracture pattern.

In the years encompassed by this study there were major advances in trauma care at our institution, and our over-all approach to patients with fractures of the femur changed accordingly. In 1968, when this series began, the prevalent attitude was that if the patient survived after hours in the emergency room and days or weeks on the hospital ward or in the intensive-care unit, he or she was then considered a candidate for intramedullary nailing. With continued improvements in the care of the trauma victim at every stage of treatment, we gradually changed to a more aggressive approach, and now attempt immediate fracture fixation. The objective is to aid the patient's survival as well as to enhance the function of the limb. Continual upgrading of our city's paramedic system over the past ten years has been important in advancing trauma care, as has the dramatic improvement in the response of the emergency-room staff at our trauma center. In the last seven years, placement of the trauma patient under the care of the general surgeon, with the orthopaedist as the consultant, has also enhanced patient care.

Early in the series our great concern over the possibility of fat embolism from intramedullary reaming and nailing led us to delay the nailing for five to seven days after injury. During the last decade, however, we have performed intramedullary nailing earlier relative to the time of injury, and we have noticed no increase in the incidence of fat embolism. Rapid restoration of fluids in these patients may have aided in preventing this complication. Also, because blood gases were carefully monitored in the intensive-care unit, no deaths occurred from a fat-embolism syndrome alone. With attention to blood-gas measurements, this syndrome was anticipated early and treated promptly in the fifty-five patients who sustained the complication. Studies by Meeks et al.[22] and Riska et al.[28] support our finding that immediate fixation of the femoral fracture does not increase the risk of fat embolism. Furthermore, a primary advantage of early fixation of all long-bone fractures is that it allows earlier mobilization of the patient, thus facilitating pulmonary care and preventing secondary complications related to prolonged bed rest and traction.

As we reached the end of the study period, immediate internal fixation was performed in all patients with multiple long-bone fractures, including those with bilateral femoral fracture or ipsilateral fractures of the femur and tibia and those with a femoral shaft fracture and concomitant injuries to the head, chest, or abdomen. It is important to note that the more seriously injured the patient was, the greater was the need for earlier internal fixation.

Our change, late in the evolution of the regimen, to immediate internal fixation of all grade-I and II open femoral-shaft fractures produced no increase in the number of infections and eased the care of the patients considerably. The increased attention to the nutritional needs of the patients also seems to have contributed to the excellence of our results.

Major modifications have been made in the equipment and surgical technique for intramedullary nailing. Only the basic concept of closed nailing remained the same throughout the series; all of the procedural facets of the regimen itself were refined as our experience grew. We used strong preoperative traction when delayed open reduction was planned, we changed to a better fracture-table and image intensifier, and we modified the patient's position on the table. These three refinements led to a simpler technique for closed reduction of the fracture. A change in the point of insertion for the intramedullary nail, from the tip of the trochanter to the piriformis fossa, prevented eccentric reaming and comminution of the medial part of the femoral cortex; a change in the shape and size[33] of the nail, as technically improved nails became available, led to a decrease in the complications of splitting and further comminution of the bone and also permitted easier passage of the nail across the fracture site; and our emphasis on rehabilitation of the quadriceps also contributed greatly to the improvement in postoperative range of motion of the knee in our patients (average, 132 degrees, with no patient having less than 90 degrees). These results far surpass those obtained with any other method of treating femoral fractures[23].

Although for the younger patient there are alternative methods of fracture treatment with a low risk, we thought that after gaining a few years' experience with intramedullary nailing our technical expertise was sufficiently great, and the complication rate was sufficiently low, to shift the risk-benefit ratio in favor of intramedullary nailing in this population. Internal fixation of the femoral fracture offered a significant benefit over other methods in younger patients with a head injury, multiple injuries, an open fracture, or an ipsilateral tibial fracture[15].

A review of our results has led us to modify our procedure somewhat with regard to certain fracture patterns. Because our initial approach of performing closed intramedullary nailing for almost all femoral-shaft fractures led to unsatisfactory amounts of rotation[7] and shortening in several types of fractures, we now use interlocking nails in those situations[12,13,16] (Fig. 1), two screws usually being used in the distal fragment and one, in the proximal fragment.

In our experience, transverse fractures in the middle one-third of the femur are ideal for intramedullary nailing, and we have not encountered rotatory malunion in them or in transverse fractures in the distal one-third of the bone. Because significant rotatory malunion has occurred in transverse fractures in the proximal one-third of the bone, we have recently used an interlocking nail with a proximal screw in these fractures.

Oblique fractures present a similar problem. We have found that oblique fractures in the mid-part of the shaft of the femur are well suited for intramedullary nailing, but with oblique fractures in the proximal part of the femur both shortening and rotation may occur because of the wide metaphysis. Shortening and angulation also tend to occur in oblique fractures in the distal part of the femur. Therefore, we now tend to use interlocking nails in oblique fractures near either end of the femur.

Although the patients with a spiral fracture in this series had only about two centimeters of shortening, we found that interlocking nails offered a better treatment option for them as well. Throughout the series, we usually treated spiral fractures with cerclage wiring and intramedullary nailing, but we now believe that the use of interlocking nails is a superior means of maintaining length that still allows us to adhere to the principle of closed reduction. This principle is particularly important in older patients, in whom long spiral fractures predominate.

We have found that segmental fractures can generally be treated with simple closed intramedullary nailing if the perimeter of the cortex in the intercalated segment is intact. If the fracture is near the proximal or distal end of the femur, or if it is comminuted at either fracture site, at present we often use interlocking nails. We carefully assess each level of the fracture to determine where an interlocking nail might be needed (Fig. 1).

Our study showed that type-I comminuted fractures can be treated successfully with intramedullary nailing alone. Type-II fractures of the mid-part of the shaft can be treated with simple intramedullary nailing, but rotational problems in proximal or distal fractures with this degree of comminution have led us to consider the use of interlocking nails. Poor rotatory control and shortening in type-III comminuted fractures have led us to change our treatment for them as well. We found that a spica cast was often necessary for maintaining rotatory control in some of these fractures, or that cerclage wiring was required for reattaching a butterfly fragment to control rotation and maintain length. Blood loss was considerable when cerclage wiring was performed, and although fortunately there were no infections in this group of fractures, the appeal for treating this type of fracture in a closed manner persisted. Although we switched to the use of intramedullary nailing combined with traction, shortening still occurred. Thus, our current preference is to treat type-III comminuted fractures with interlocking nails. Because of the need for control of rotation and length in type-IV comminuted fractures, we treated these with nailing and traction or nailing and cerclage wiring. Since the completion of the study we have switched to the use of interlocking nails in these fractures to maintain closed reduction and allow rapid mobilization of the patient.

The excellent results in our large series suggest that intramedullary nailing is an ideal treatment for patients with a femoral shaft fracture. The fracture patterns that are appropriate for treatment with this method are readily recognizable. When properly selected, femoral shaft fractures can be treated successfully by intramedullary nailing with minimum complications. The immediate use of this method demands that the patient be evaluated carefully for associated injuries and be resuscitated adequately. The technique of intramedullary nailing is demanding, and the constant upgrading of the equipment necessitates up-to-date knowledge. Thus, we recommend that primary nailing not be attempted in the multiply injured patient unless an experienced multidisciplinary team is available to manage potential problems.

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