CHAPTER ONE

CONSERVATIVE VERSUS OPERATIVE METHODS

IT is over thirty years since Arbuthnot Lane published his *Operative Treatment of Fractures*; but we still cannot compare conservative and operative principles from the viewpoint of basic science because the fundamental nature of fracture repair still eludes us. The best we can do is to compare the results of clinical practice; but there are so many variables (comminution, sepsis, mechanical details of the operation, blood supply, level of fracture, different observers, etc.) that a series of one or two hundred cases, which is a large series for any one operator, is soon reduced to statistical insignificance. Attempts to control the conditions of the fracture by using experimental animals have yielded nothing of importance compared with what we have learned 'the hard way' by developing operative techniques on the human subject.

The followers of Lane and Sherman believed that the failures of internal fixation would ultimately be eliminated by improved technique. We now know that internal splints are exposed to truly enormous forces and are subject to the phenomenon of failure by fatigue. Improvements in the design of plates and screws have reduced, but not eliminated, the mechanical failures which were common when techniques derived from the woodworker were used. The change to using electrolytically inert metals has only slightly diminished our problems, though there is no excuse for returning to the brass screws and reactive steel plates with which Lane himself achieved sufficient success to establish the method.

But despite improved technology, delayed union after internal fixation is still encountered. Immediately after any form of internal fixation there starts a race against time, between the bridging of the fracture gap by osseous union and the tendency for the mechanical fixation to loosen its attachment to the bone as a consequence of the millions of reversals of stress and strain which occur during the two or three months of convalescence. If osseous union has bridged the fracture line before the fixation becomes loose, then all will be well, but if union is delayed either the metal will fatigue and break (Fig. 1) or bending of the fixation will ensue (Fig. 2). It is unprofitable to argue that these failures are merely the results of inadequate fixation or that they could have been prevented by better engineering. In the two cases illustrated the surgeons were satisfied with the rigidity of the fixation at the time of operation. Blame should not therefore be transferred to defective fixation; the fault lies in the failure of osteogenesis to bridge the gap in the time during which mechanical fixation can reasonably be expected to hold firm. It will be one of the themes of this monograph that by open operation, the denuding of bone ends of periosteum in the case of cortical bone, or the prevention of collapse of fragments towards each other in the case of cancellous bone, carries

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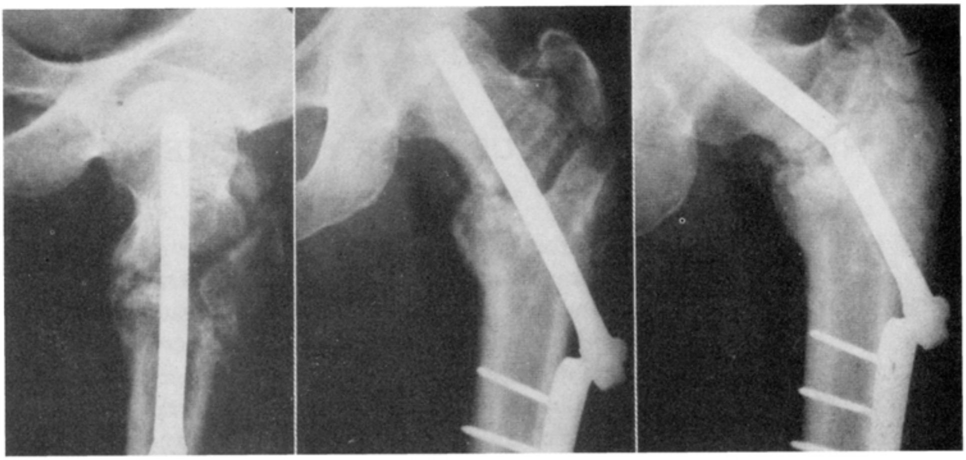

FIG. 1

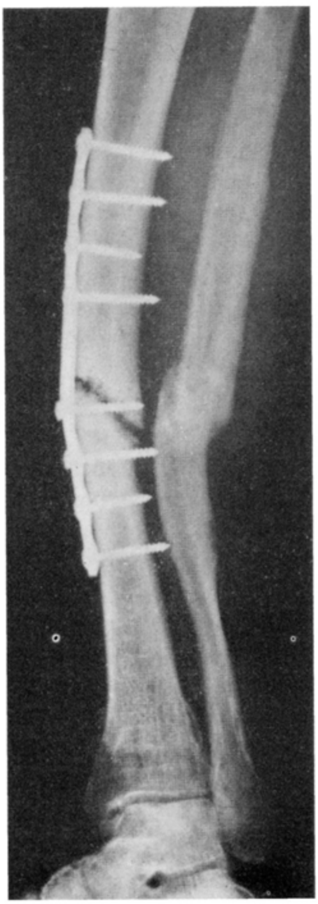

FIG. 2

Fig. 1.—Fatigue fracture of nail ten months after operation. Despite transmission of body weight the fracture remained distracted. This fracture in cancellous bone demands compression, not distraction. Spontaneous filling of a gap in cancellous bone is a slow process.

Fig. 2.—Failure to bridge the fracture line. Rigid fixation was obtained at the original operation. There was initially no significant gap between the bone ends.

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with it the serious risk of artificially depressing osteogenic activity, and that this therefore invites the loosening or breakage of fixation before union can take over. An attempt will be made to emphasise the biological background to fracture repair and the dominating role of blood supply in the healing of bones.

THE NATURE OF FRACTURE REPAIR

The development of conservative or operative methods must be based on our knowledge of fracture repair. I believe that there are fundamental differences between the process of union in cancellous bone and cortical bone, and I will therefore describe these separately. Because of certain difficulties in terminology, before one can describe processes of fracture repair it is necessary to define precisely the use of certain histological terms.

Definitions

It is important to understand what is meant by the terms *woven bone* and *lamellar bone* (which is the terminology recommended by S. L. Baker) because though the two tissues themselves are absolutely distinct and easily recognisable, the variations in terminology in current literature are very confusing.

Woven bone is the bone of ' provisional ' or ' temporary ' callus. It is rapidly produced—often being in evidence histologically three or four days after fracture. Histologically the osteocytes are distributed through it in a rather irregular fashion like currants in a bun. It is called woven bone because the collagen fibres which run through the osseous matrix are arranged in an irregular network though, strictly speaking, the appearance is more that of a ' felt ' than a woven textile (Fig. 3). Woven bone is essentially a temporary tissue, being later removed and replaced. It is the medium of ' clinical union.' Woven bone develops in spindle-celled fibrous tissue as a precursor. The bony matrix is first seen appearing as an amorphous intercellular substance, between the fibres connecting the spindle cells (Fig. 4), staining with eosin more densely than the adjacent intercellular material. As the matrix increases in amount the spindle cells swell up and become incorporated to form the ' osteocytes.' This process is thus eminently suitable for the bridging of gaps between bone ends, because the spindle-celled tissue, by reason of its flexibility, has no difficulty in maintaining continuity in the presence of a certain amount of movement. It is not difficult to see how the matrix

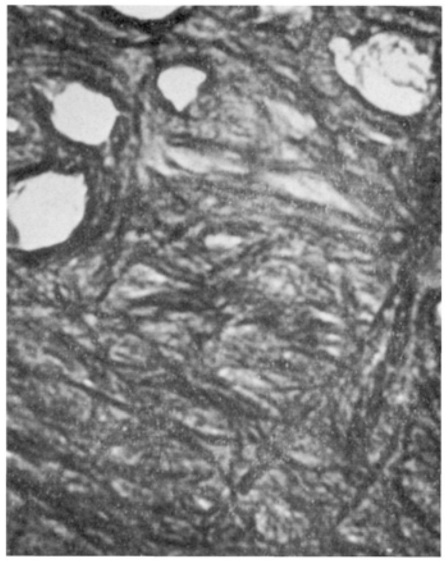

FIG. 3

Showing irregular arrangement of fibres in woven bone which constitutes callus. (×550.) (*Professor S. L. Baker's specimen.*)

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can harden by taking up calcium and so immobilise the tissues to which it is connected.

Lamellar bone, on the other hand, is the permanent bone of the mature trabeculæ and the shafts of long bones. Lamellar bone is laid down in orderly layers (Fig. 5) and the osteocytes tend to be distributed regularly between the layers (more like a sandwich than a bun !). The fibre structure of each layer is

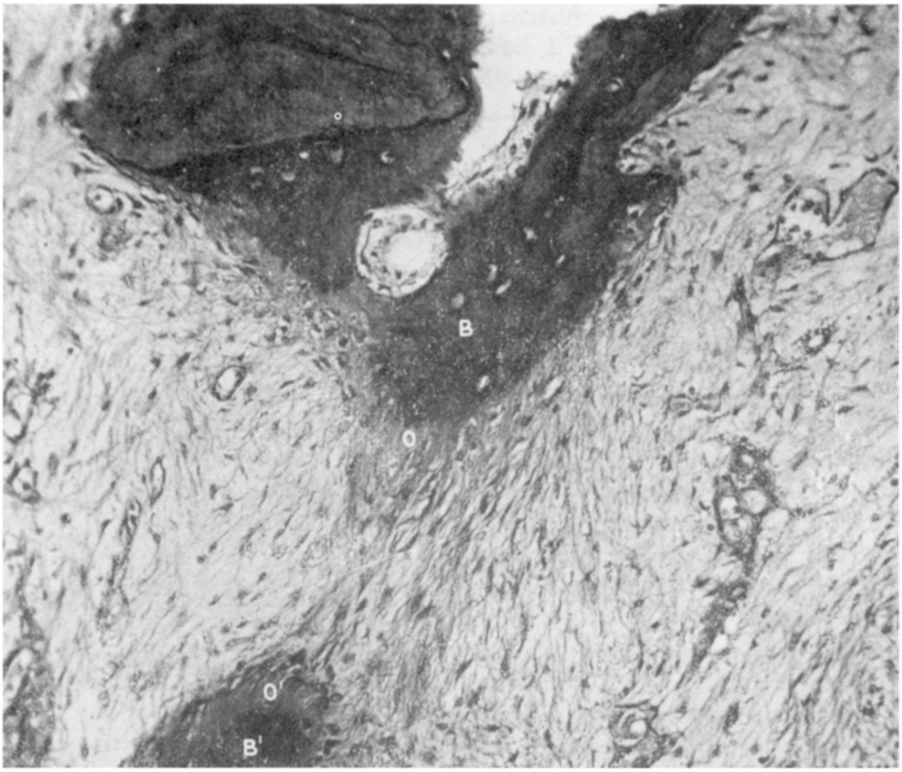

FIG. 4

The start of a fibrous trabecula composed of strands of collagenous substance with amorphous intercellular substance appearing between them. The fibres are streaming from one fragment of adult cancellous bone to another, and in so doing are crossing the line of arthrodesis. The intercellular substance is seen as a dark zone passing vertically down the centre of this illustration.

not an irregular felt-work as it is in woven bone but has a parallel arrangement, and in each layer the direction of the fibres crosses the direction of adjacent layers at an angle to give a 'ply' structure of very great strength. It is obvious that this complicated structure needs time for its deposition—unlike the hurried production of woven bone. In this connection another fundamental difference distinguishes the process of deposition of lamellar bone from woven bone—*i.e.*, it is essential for there to be a solid framework on which the first layer of lamellar bone can be deposited before it can proceed to build up its multiple layers. Lamellar bone cannot be deposited in fibrous tissue and cannot therefore bridge a moving gap spanned only by fibrous tissue. The solid framework on which lamellar bone is normally deposited is the woven bone of callus which has formed a temporary scaffold, and which is removed when the lamellar bone has acquired an adequate thickness. Later still, and continuing slowly over a long period of time, the first layers of lamellar bone are removed by osteoclasts and more lamellar bone is deposited on adjacent lamellæ in order to adjust the architecture of the trabeculæ to the forces acting on them in accordance with Wolff's Law.

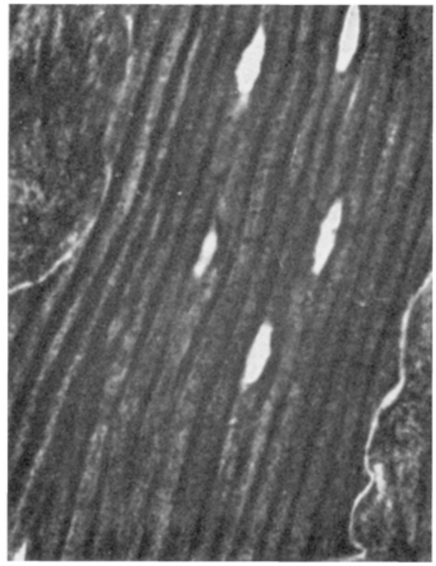

FIG. 5

Showing orderly arrangement in layers of lamellar bone. This constitutes mature bone no matter whether cortical or cancellous. (×980.) (*Professor S. L. Baker's specimen.*)

The Union of Cancellous Bone

Arthrodesis of the knee joint has presented a valuable source of human histological material for studying the healing of cancellous bone, described in detail elsewhere (Charnley and Baker, 1952; Charnley, 1953).

The observation which I think is the most significant in relation to the healing of fractures in cancellous bone was made on a biopsy four weeks after arthrodesis of a knee. In this particular case the surfaces of cancellous bone, produced by resection of the joint with a saw, were experimentally reduced to a small area of contact by making one of the bone ends wedge-shaped (Fig. 6). The knee had united solidly (under compression) four weeks after the operation, and the histology and microradiography of the biopsy are illustrated in Figs. 7, A and B, and 8, A, B and C. It is at once obvious that there has been very satisfactory union at the point of intimate contact; but the feature which is most significant in its bearing on fracture treatment is that *there is no evidence of 'callus' on the cut surfaces which are widely separated.* This is particularly well seen in the microradiograph. Histological examination of the cut ends of the trabeculæ on opposite sides of the gap shows only the faintest trace of the cellular activity which precedes the appearance of woven bone in these human biopsy specimens.

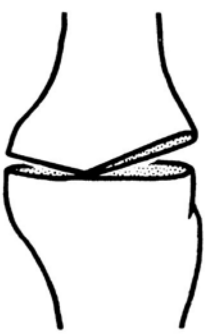

FIG. 6

Showing shape of surfaces in contact in knee arthrodesis described in text.

This observation, confirmed by the behaviour of other biopsy specimens, came to me as a very considerable surprise. I had been brought up to believe that cancellous bone was a highly osteogenic substance and that empty spaces between cancellous surfaces (as, for instance, in a foot stabilisation operation) would rapidly fill with new bone. I now believe that cancellous bone, even with an intact blood supply, has in fact a very restricted form of osteogenic activity. Cancellous bone

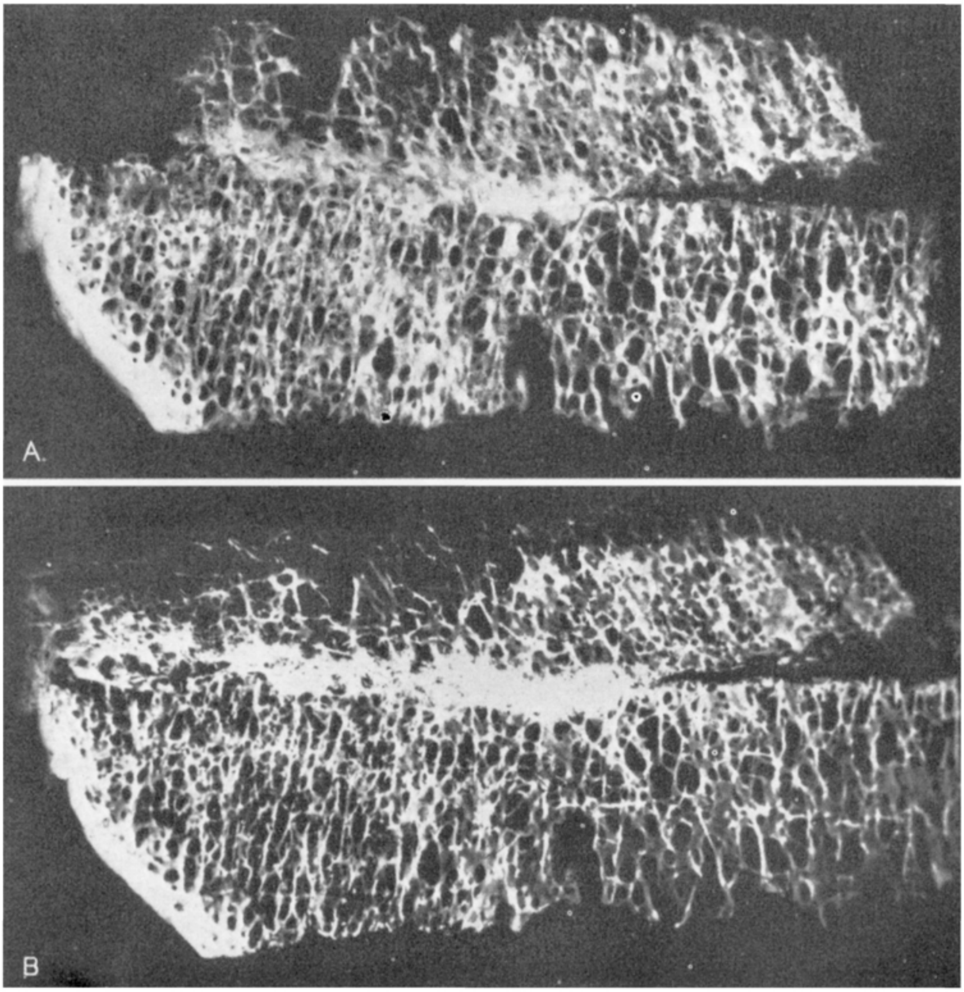

FIG. 7

Longitudinal section of coring from the 'crucial' experiment. A (*top*), Undecalcified, digested, specimen photographed by visible light (1 mm. thick slice). B (*bottom*), Microradiograph of same slice prior to digestion with trypsin. Note density of new bone maximal at site of maximal pressure and tailing off posteriorly where the pressure is less. Note absence of callus in gap where pressure is absent. Note absence of new bone on cut surfaces of the gap where there is no pressure and therefore no incentive to osteogenesis. Specimen at four weeks. Magnification approximately ×4.

certainly can unite very rapidly, but it unites rapidly only at the points of direct contact. Where cancellous bone is not in contact, the gap will be filled only by being encroached upon by the slow spread of union from the points of contact where it originally started. In other words, *a cut surface of cancellous bone, even with an intact blood supply, does not 'throw out' callus* as does, for instance, the

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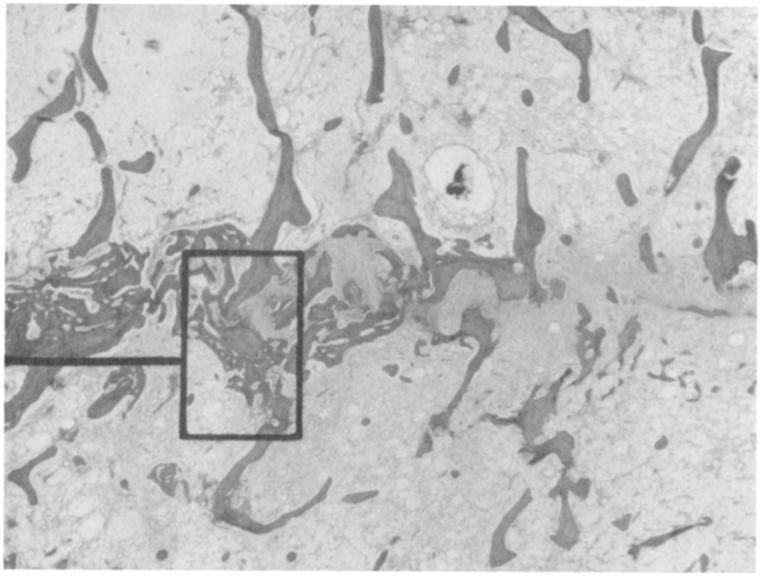
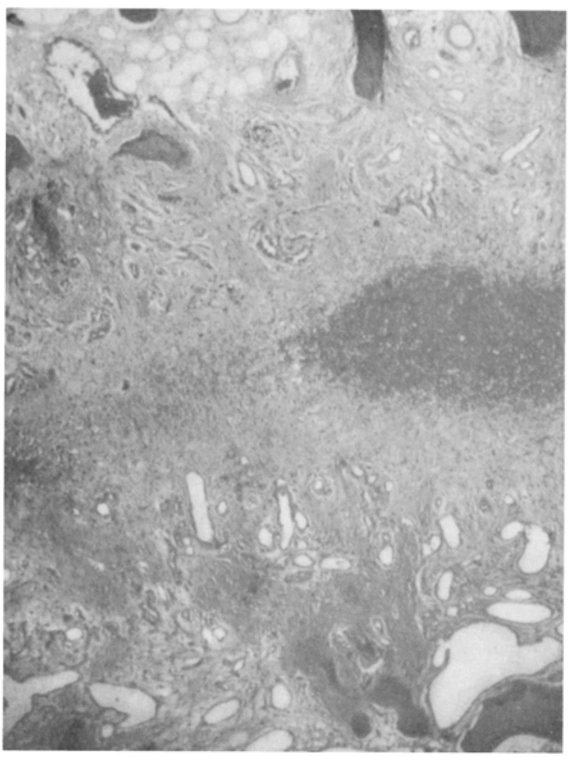


A



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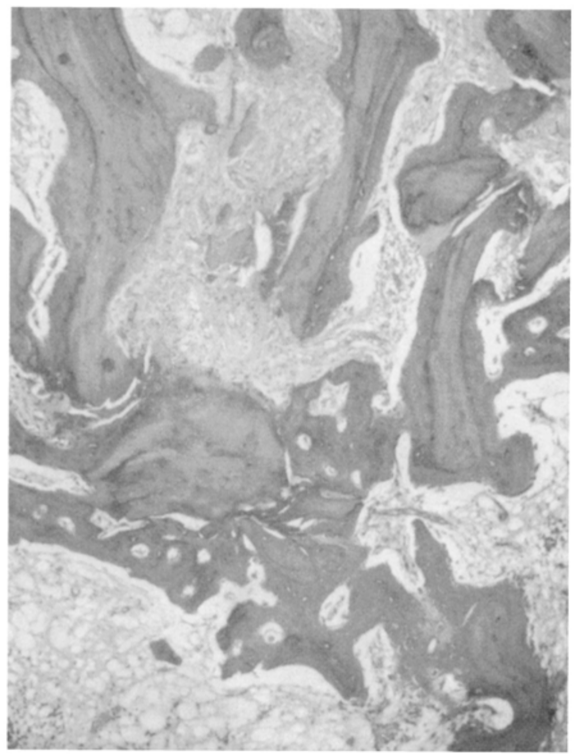

C

FIG. 8

Histology of biopsy taken from same knee fusion to which Fig. 6 and Fig. 7 relate. Four weeks after operation. Clinically solid.

A, Low power showing bridging of woven bone at point of contact (left side), with no bridging across the gap (right side).

B, High power of the gap, showing that the cut ends of the mature trabeculæ have not generated callus.

C, High power of site of union, showing lamellar bone, of original mature trabeculæ, overlaid by the woven bone of newly formed callus (this field has not quite the same vertical orientation as in rectangle of A).

FIG. 9A

Fig. 9A—Fracture in *cancellous* bone at end of a long bone. Note hardly any external periosteal callus though clinically united at three months.

Fig. 9B.—Fracture in *cortical* bone in the centre of a muscle-covered long bone (shaft of femur). Note voluminous ensheathing callus production by periosteum.

Note that periosteal callus springs from surface of bone a short distance from the end of the fragment; this indicates ischæmia of the bone ends.

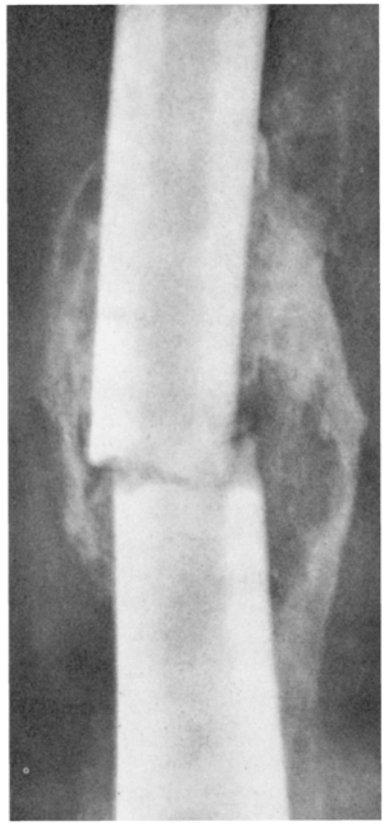

FIG. 9B

shaft of the femur. The trabeculæ of cancellous bone adjacent to a blood-filled space will produce the woven bone of callus for a thickness, at the most, only one or two cells deep. I shall emphasise this point repeatedly when describing the union of the shafts of long bones, because I think *the term ' callus ' should be reserved for the voluminous, space-filling, often space-bridging, tissue of woven bone which I believe is generated only in the periosteum (and endosteum) of long bones.*

This difference in the mode of union of fractures in cancellous bone and cortical bone is well illustrated in Figs. 9A and 9B. The total absence of external callus in the fracture through the lower end of the femur (Fig. 9A) was compatible with early union and this patient, aged seventy years, was walking on the leg at three months with 90 degrees range of knee movement, yet radiologically there is no evidence of external callus. By contrast, the external production of 'ensheathing' callus in the fracture through the shaft of the femur is evident (Fig. 9B).

This lack of callus production by cancellous bone explains the tendency to late collapse in the healing of fractures in cancellous bone which have been distracted. Thus after the reduction of a Colles' fracture a hollow cavity is left in the cancellous end of the radius and some degree of spontaneous collapse under conservative treatment is inevitable. The same thing is frequently observed in basal and pertrochanteric fractures of the neck of the femur; if these have been over-reduced into coxa valga and maintained like this on weight-traction they will often collapse, *even three months later*, when traction is removed—showing that consolidation has been delayed by holding the gap apart (Figs. 10 and 11). The practical application of this observation, if we are to achieve rapid and sound consolidation, therefore indicates the importance of inducing a *controlled degree of collapse* in all fractures involving cancellous bone. If cavities are left inside fractures by over-enthusiastic reduction, there is a danger of *defective consolidation, even in cancellous bone* which in the past has erroneously been regarded as highly osteogenic and incapable of ' delayed union.' A rather extreme example of this is seen in the basal fracture of the neck of the femur already shown in Fig. 1 (p. 2), which occurred in a vigorous sailor of fifty years of age and in whom the metallic internal fixation itself fractured *ten months after the injury*. The patient had evidently been walking on the metallic fixation which, until it fractured by fatigue, was holding apart an unconsolidated fracture in cancellous bone. Had the fracture been allowed initially to collapse into varus, as nature intended, prompt union would have resulted with rapid disappearance of the limp which persists if consolidation is unsound. Another example of this behaviour of cancellous bone is illustrated in Fig. 129, page 164.

In comparing the healing of cancellous bone with cortical bone it is to be noted that in cancellous bone *there appears to be no death of the osteocytes in the cut edges of divided trabeculæ*. This must be because the blood supply is good, and because the large surface area of the trabecular spaces, combined with the relatively thin trabeculæ, keeps the osteocytes nourished by diffusion. The osteocytes deep in the interior of *cortical* bone, on the other hand, cannot receive nourishment by diffusion from the periosteal and endosteal surfaces, and they need the circulation of the Haversian systems to survive. The death of certain areas of osteocytes

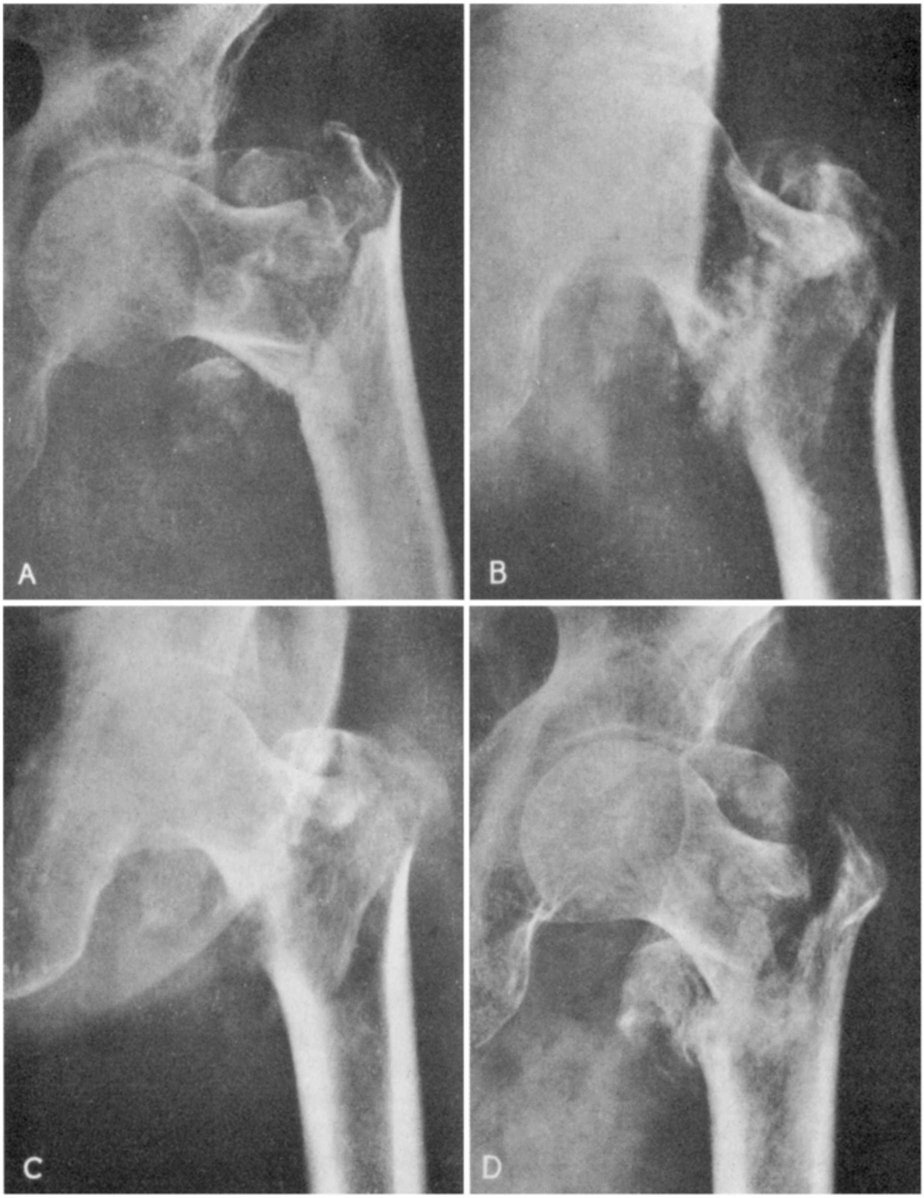

FIG. 10

Pertrochanteric fracture in patient seventy-one years of age treated on continuous traction for three months. A, initial deformity; B, distracted at end of first week; C, traction reduced and position at three months just before final removal of traction; D, position at four months when it appeared clinically united (patient died suddenly of embolism shortly after this film).

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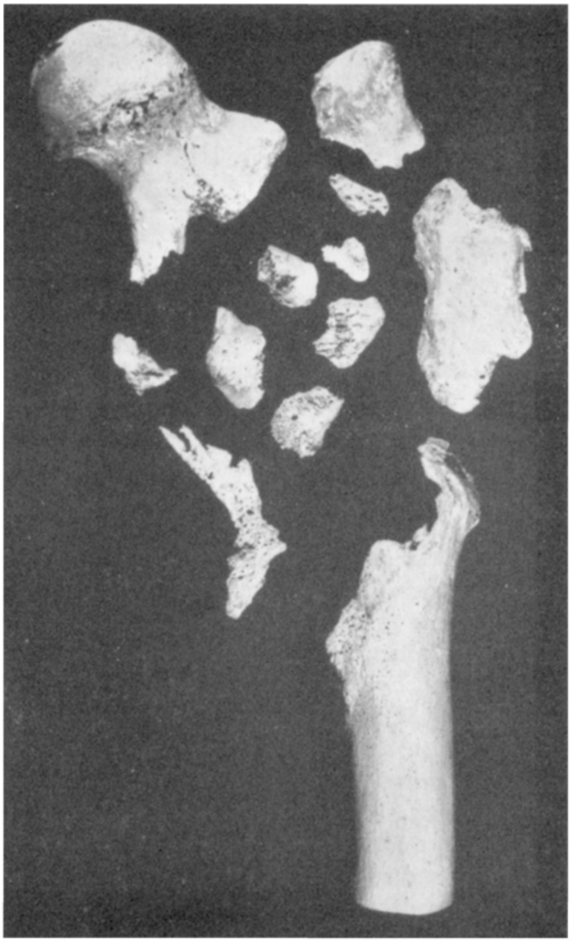

FIG. 11

Same patient as Fig. 10; specimen at four months; very strong fibrous union capable of taking weight; on digestion with trypsin the fracture was found completely un-united and callus formation minimal. This is probably a common state of affairs at four months if distraction permits the fragments to lie loose and in indefinite contact with each other. Callus did *not* fill up the vacant space left by distraction. Cancellous bone unites only by *contact*, not by throwing out callus to fill spaces.

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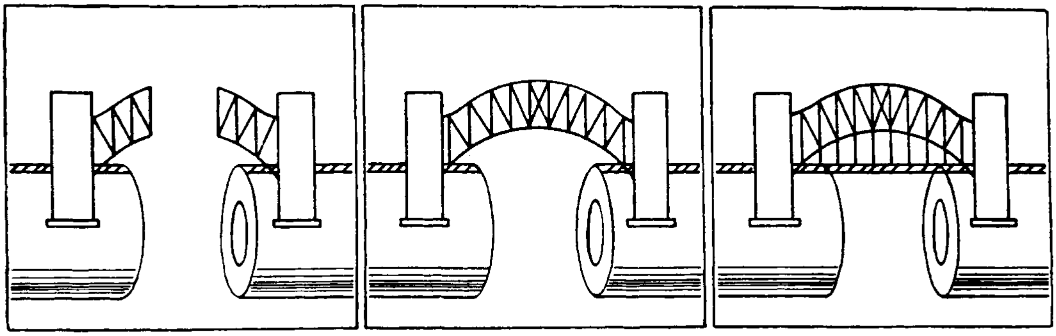

FIG. 12
Hell's Gate Bridge analogy of Urist and Johnson (see text).

in cortical bone would seem to be an inevitable sequel to the cutting of the Haversian systems and the interruption of the longitudinal circulation in the bone ends.

The Union of Cortical Bone

The healing of a fracture through the shaft of human long bones, observed by biopsy studies, has already been described by Urist and Johnson (1943), and I am indebted to this source for the ' two-phase ' concept to be described. This two-phase concept is the practical application of the woven bone and lamellar bone sequence mentioned above. Urist and Johnson created the simple but instructive analogy between the healing of the fractured shaft of a long bone and the building of Hell's Gate Bridge (Fig. 12); in the first phase the suspension cables are thrown across the gap (periosteal callus) and in the second phase the permanent roadway is suspended from the cables (the cortical bone of the shaft).

Phase I.—Very soon after a fracture of a long bone, callus (woven bone) appears a short distance from the fractured end of the bone, distributed as a collar encircling the bone and lying in the periosteum between its outer fibrous layer and the surface of the bone. In longitudinal sections this collar of callus[1] is seen as a wedge with the pointed end trailing away from the fracture and the thick end presenting towards the fracture.

It is to be noted that this new bone appears in the periosteum, where a free blood supply is available, and that *the broken end of the bone*, where the longitudinal Haversian circulation is interrupted, *produces no callus whatsoever* (Fig. 13). Callus is also produced on the endosteal aspect of the fracture, where the circulation and endosteal cells are available for osteogenesis, but this does not appear to be such an active source of callus in the human as it is in small animals (probably because bone situated in the axis of the shaft is not mechanically efficient—hence the tubular structure of long bones).

[1] I shall frequently use the term *collar of callus* or *periosteal collar* in this sense in subsequent descriptions.

Under favourable conditions (which we do not yet by any means understand and which constitute the crux of the fracture-healing problem) the collars of periosteal callus bridge the fracture gap by extending through the periphery of the fracture hæmatoma. In some cases callus is apparently able to extend in this way through muscle. This spread of callus from each fragment is preceded by a spindle-celled tissue in which the intercellular spaces become œdematous and in which areas of amorphous intercellular substance appear to condense, to become in some parts islands of hyaline cartilage and in others the woven bone of callus.

This exuberant mass of callus generated by periosteal activity forms the well-known 'plumber's weld' between the fragments. It is often not realised how intense is the cellular activity of the tissue producing this temporary callus. Mitotic figures are seen and the whole mass, especially in bones such as the humerus and femur, often reaches a total diameter three times greater than the diameter of the shaft itself. The whole of this great volume of new tissue is produced in something like three weeks, a degree of activity rivalling that of any sarcoma, and in fact histologically it is not unlike a sarcoma and has occasionally been the cause of serious diagnostic errors. This type of exuberant cellular activity is never seen in the healing of fractures in cancellous bone.

FIG. 13

Callus and cortical fragment from fracture of shaft of femur at four weeks. Note voluminous external *periosteal* callus at left of figure (partly invaded by the woven bone of callus). Note total absence of callus from fractured surface of bone on the right of figure.

Inside the hollow sphere formed by the invasion of the outer regions of the fracture hæmatoma by callus, the broken bone ends, with their longitudinal circulation interrupted, project into the liquefied centre of the fracture hæmatoma and are seen as dead white fragments which to the naked eye appear inert and totally devoid of callus. These features are easily recognised in the specimen illustrated (Fig. 14) from a patient of sixty years of age who died from pulmonary embolus twenty-eight days after a fracture of the shaft of a femur.

The interesting mechanical feature of this phase of 'bridging the gap' is that periosteal callus can cross the gap *even though the fragments are moving in relation to each other*. This bridging seems to be achieved by the fact that the callus extends in the *outer layers* of the hæmatoma, because interstitial movement is less here

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than it would be in the layers close to the ends of the moving bones. To make an analogy, consider what happens if two sticks are put end to end, to represent a transverse fracture, and the junction is then gripped in the surgeon's closed

FIG. 14

Artist's drawing of periosteal ensheathing callus of a fractured femur clinically firm twenty-eight days after the injury. Note thickness of callus and the central cavity containing the white, ischæmic bone ends *which themselves are devoid of callus.*

hand (Fig. 15). The sticks can easily be angulated in relation to each other and movement is communicated to the skin on the inside of the closed hand; but the skin on the outside of the hand does not move. It is in this outer stationary zone of the ensheathing callus that the periosteal bone first spreads. Once continuity has been established the sheath of callus starts to thicken and contract down on to the fracture and so immobilises it (Fig. 16). Radiological examples of what is expressed diagrammatically in Fig. 14 will be seen by comparing Fig. 9B, a large hollow callus in the early stage, with Fig. 17 in the later stages. Nature has

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thus done its own internal fixation (or better still its own bone grafting) of the fracture. This is the stage of ' clinical union ' where function has started to return yet radiologically the fragments are still clearly visible inside the sheath of periosteal callus. Radiologically one would never suspect that inside the sheath of

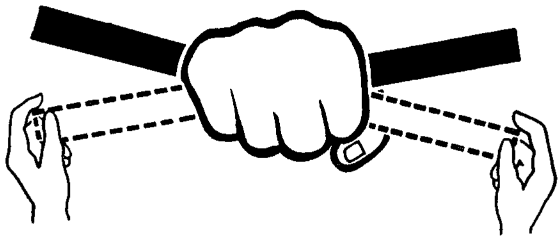

FIG. 15

Analogy of ensheathing callus gripping a fracture even though the fragments are moving slightly. The skin on the exterior of the hand is stationary, but the bones are moving inside the clenched fist.

callus the extreme ends of the fragments are ischæmic, but there is no doubt that this is often the case.

Phase II.—This is the start of the reconstruction of the tubular cortex by the

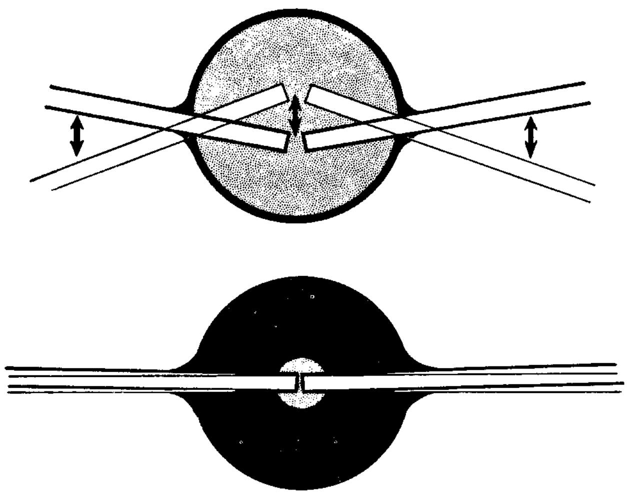

FIG. 16

Scheme to illustrate progressive fixation of moving fragments as ensheathing callus becomes thicker and shrinks on the enclosed fragments.

deposition of lamellar bone, and when it is complete, which takes many months, the ensheathing callus of Phase I will have been completely removed. Lamellar bone cannot be deposited unless there is a solid framework on which it can be deposited. This implies that it can never bridge a gap unless there is a solid scaffold of woven bone already passing across the gap. This is the only phase of fracture repair which necessitates rigid fixation.

The Function of the Periosteum

Fracture surgeons can be divided into two camps by the shibboleth of periosteal callus. One camp sees in profuse callus merely a sign of inefficient union. This idea derives from analogy with the exuberance of infected granulation tissue which we know is made even more exuberant by movement. Surgeons in this camp believe that 'ideal' fracture union should be devoid of ensheathing callus and that it should occur only between the bone ends. They see this absence of periosteal callus after open reduction and rigid internal fixation, and if callus develops after open reduction they suspect that the internal fixation is imperfect and that mobility is evoking periosteal callus.

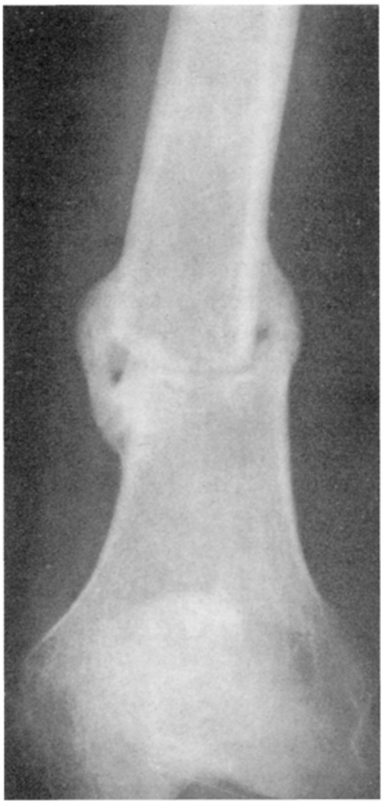

FIG. 17

Compare this illustration with Fig. 9B to see, in actual fact, shrinkage of callus illustrated diagrammatically in Fig. 16. Note persistence of central cavity. Ends of fragments probably still ischæmic though not demonstrable radiologically.

Surgeons of the other camp see in profuse ensheathing callus a highly specialised natural process, a unique process, by which internal fixation is spontaneously achieved between fragments which are moving in relation to each other. According to this concept, ensheathing callus is abolished by open operations, not by the immobilisation but because the bone ends have been stripped of the callus-producing periosteum. According to this opinion, internal fixation abolishes Phase I of normal fracture healing and throws on the surgeon the onus of providing internal fixation as durable as that produced at the end of Phase I until the start of Phase II is well under way. The defective replacement of Phase I, by imperfect internal fixation, will render it impossible for Phase II to start.

Most clinicians who are exponents of internal fixation subconsciously believe that union takes place between the bone ends. But repeated histological examination of the healing of human fractures, reported by many authors, has shown that the ends of cortical bone always show death of osteocytes and that there is never any osteogenic activity from the broken bone surfaces.

The absence of callus between the ends of the bones in a closed, and almost undisplaced, fracture is well illustrated in Fig. 18. The absence of callus between the ends of the bones obviously is not due to any defect of osteogenic potential in the patient, because profuse periosteal callus is bridging the gap in the immediate vicinity of the line of the fracture but separated from it by an appreciable distance. Examples of this pattern of periosteal callus distribution will be discovered very

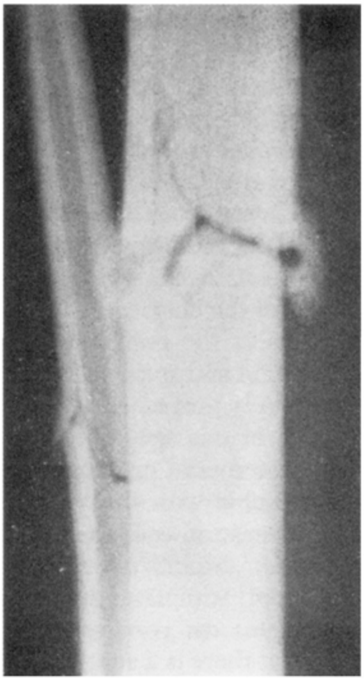

FIG. 18
Unusual amount of periosteal callus for a tibial fracture. There had been minimal displacement in this case. Rapid union.

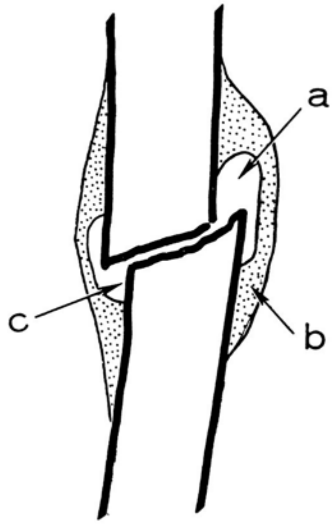

FIG. 19
Illustrating the three essential features of ensheathing callus which can usually be detected in a fracture healing under natural conditions: (a), central cavity inside callus; (b), callus springing from the periosteum some distance from the end of the bone; (c), short length of external bone surface, immediately adjacent to the fracture, from which no callus is produced.

frequently once the surgeon starts to examine radiographs with this in mind and the diagram in Fig. 19 emphasises the essential features.

Exuberant Callus and Defective Fixation

The generally accepted opinion that the loosening of internal fixation stimulates the production of periosteal callus, and vice versa, needs careful scrutiny and I doubt the validity of this traditional statement for the following reasons:

1. The production of periosteal new bone after defective internal fixation is *not* callus in what I believe should be the true sense of that word. New periosteal bone generated in the presence of inefficient internal fixation is merely the same thickening of the bone ends which is seen in any pseudarthrosis. It is a *late* phenomenon, not becoming evident until the fracture is at least three or four

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months old. Though histologically it is woven bone, and is arising in periosteum (see Fig. 29, p. 28), this is not what I mean by the term *callus*. The ensheathing callus of a normal fracture is visible in the radiograph *very early* (*i.e.*, from three to six *weeks*) and is seen as a cloud or haze standing away some considerable distance from the surface of the bone. This is especially seen in bones such as the femur or humerus which give origin to muscle fibres (Fig. 20A). The total volume of this ensheathing callus after three weeks is many times greater than the greatest enlargement of the bone ends in a pseudarthrosis. This type of early *true* callus I most emphatically maintain is never seen after an open reduction if the bone ends have been stripped of their periosteum.

2. If rigid internal fixation is performed *without stripping the periosteum*, a cloud of *true* callus will develop at the usual time of three to four weeks if the bone is one which normally produces callus. This can frequently be demonstrated in the human subject by inserting an intramedullary nail into a transverse fracture of the shaft of the femur *without disturbing the periosteum*, which can be done if blunt dissection alone is used during the exposure of the bone ends. It is instructive to note the difference in *true* callus production in the two cases illustrated in Figs. 20A and 20B. In Fig. 20A the fixation was rigid and *special care had been taken to avoid periosteal stripping*; the callus production is profuse and what one would expect in the conservative treatment of a patient of this age (eighteen years). In the second case (Fig. 20B) an assistant did not use special precautions to preserve the periosteum and at the same time he had trouble with the 'jamming' of an intramedullary nail which had to be cut off because it could not be extracted; the case was thereafter treated on a Thomas splint. Mobility was present because internal fixation was defective, but this did not stimulate the production of exuberant callus, *even though the patient was only sixteen years of age, when callus production is usually vigorous*. It is to be noted that there is a suspicion of ischæmia of the end of the proximal fragment. There was no clinically recognisable infection.

Those who deny any great importance to the adult periosteum are in part influenced by the insignificant appearance of this tissue if looked for at operation in elderly patients, and in part by the fact that the regeneration of bone after subperiosteal resection is not a particularly noticeable feature in the adult. Similarly, the last echoes still sound of the famous dispute on the function of the periosteum which was settled for the last generation by the weighty opinion of Sir William Macewen in the statement that the periosteum was merely a limiting membrane with negligible osteogenic activity.

That the production of early, voluminous periosteal callus is a purposive mechanism in fracture union (as opposed to an accidental side-effect of movement, not beneficial, and not primarily concerned in fracture repair) must surely be suggested by the enormous histological activity concerned in the growth of periosteal callus. This activity has no counterpart in the repair of any other normal tissue in the body and it can only be compared to a controlled neoplastic growth similar to a sarcoma. In three weeks the volume of ensheathing callus can attain a size three or four times the diameter of the parent bone. This is surely a unique phenomenon with a very definite purpose.

A similar teleological argument is seen in the structure of periosteal callus which obeys mechanical laws. Mechanically the most efficient place in which to use a scanty amount of a relatively weak substance (woven bone) to make a structure rigid, is to place it as far from the axis of movement as possible. This is the principle of 'stressed skin' construction in aircraft and it is the principle extensively used in nature when designing bones as tubular structures.

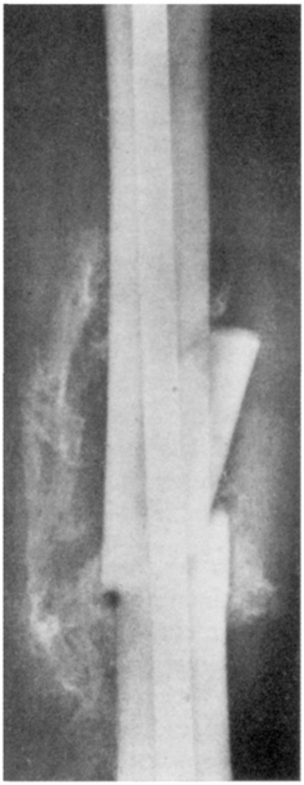

FIG. 20A

True periosteal callus (early and profuse) in youth of eighteen years, six weeks after fracture of shaft of femur. Special care taken not to scrape away periosteum at operation. Fixation rigid.

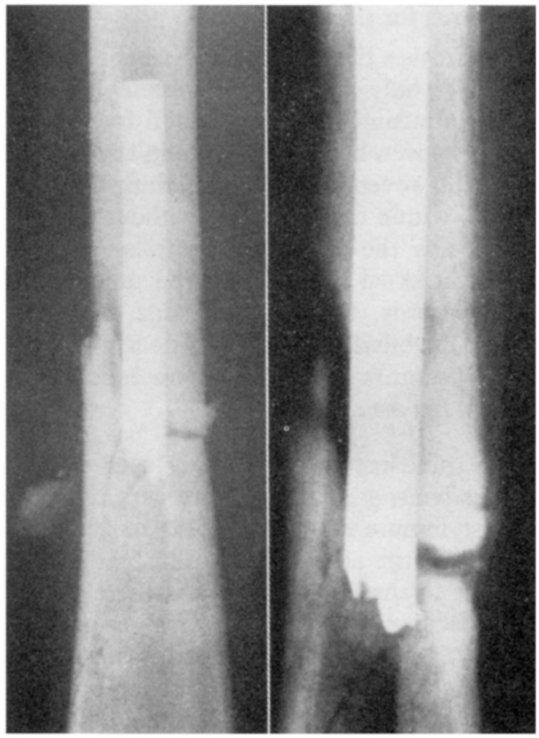

FIG. 20B

Absence of periosteal callus in youth of sixteen years of age. Fixation was defective. Periosteal surface of the bone had been exposed and cleaned during operation.

The Role of Fixation in Fracture Union

When fractures occur in bones which naturally produce a large volume of ensheathing callus, union will proceed in the presence of movement because the ensheathing callus, when it hardens, produces a natural internal fixation. There are, however, other bones, such as the lower third of the tibia, in which fractures do not produce enough ensheathing callus to ensure internal fixation, and in these it might seem reasonable to imagine that defective ensheathing callus might be compensated by the artificial enhancement of fixation. This is the orthodox

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argument which is usually accepted without question as a self-evident truth. I believe that a logical examination of this orthodox argument will show that it is by no means as sound as might at first sight appear.

The orthodox argument in favour of the fixation of fractures is that whenever minute bridges of ensheathing callus succeed in jumping the fracture gap they are immediately ruptured by movements of the bone ends. It is assumed that these minute bridges will be ruptured by smaller ranges of movement than would be needed to rupture the bridging of a profuse ensheathing callus. This argument is fallacious for three reasons:

1. It makes the assumption that the gap *has indeed been successfully bridged* even if only by a single minute bridge. It therefore assumes what is the fundamental problem of fracture union—*i.e.*, *how* the first strand of woven bone gets across in the presence of movement.
2. The woven bone of ensheathing callus is almost certainly capable of bending, within certain limits, without being ruptured.
3. When the fragments are *completely immobilised*, as is easily obtained by internal fixation, delayed union is still a frequent occurrence. In other words, the minute bridge of callus, which we assume that faulty immobilisation ruptures, does not hypertrophy even if it is protected from rupture by extreme immobilisation, *for the simple reason that the bridge has never existed.*

The fundamental error in delayed union would seem to be the inability to *start the bridging* of the fracture gap, not the inability to maintain or to augment the first minute strand of callus to get across. The fundamental defect would seem to be the absence of ‘ callus pathways ’ to conduct osseous union from one fragment to the other. There is therefore no logical reason why fixation, *per se*, should facilitate the bridging of a gap if the callus shows no readiness to ‘ jump the gap ’ because no callus pathways are present. There is something in this idea rather analogous to the function of a ‘ flux ’ in soldering metal; the solder, which can be present in adequate amount, is of no avail if the flux is absent or unsuitable.

An argument advanced in favour of internal fixation is that if rigid fixation can be maintained without mechanical failure for an adequately long period of time all fractures so treated will unite. If the mechanical device fails, by defects of mechanical design in the apparatus at present available, they argue that this does not upset the fundamental premise, and this spurs them on to stronger designs of internal splints. Those who argue in this way are not perturbed by the possibility that the method of fixation may depress osteogenic activity; they maintain that even if osteogenic activity is depressed the nutrition of the whole limb is improved and joint movement is encouraged, so that when union eventually does occur the result will be better than from conservative treatment.

An element of truth in this last practical argument cannot be denied, but as regards the fundamental nature of osseous union the theory of absolute fixation is specious. A fracture which is ‘ plate solid ’ after good internal fixation can only be revealed as un-united when the apparatus of internal fixation breaks or becomes loose. To illustrate this, consider the case illustrated in Fig. 21.

The patient was a man of thirty-five years with a closed fracture in the midshaft of the femur with slight comminution. An intramedullary nail was inserted one day after the injury but no graft was used (Fig. 21C). The magnitude of the original displacement (Fig. 21A) indicated that delayed union was probable. The radiograph eleven months later is seen in Fig. 21B; there is very little periosteal callus and callus is 'piling up' at the fracture line and not flowing across the fracture line as would happen in normal union eleven months after such a fracture, but no definite pseudarthrosis can be diagnosed.

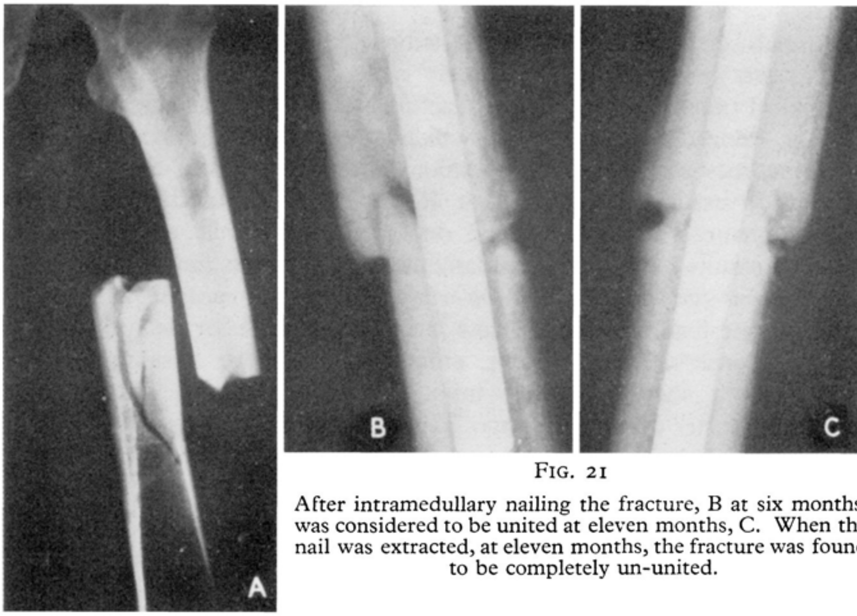

FIG. 21

After intramedullary nailing the fracture, B at six months, was considered to be united at eleven months, C. When the nail was extracted, at eleven months, the fracture was found to be completely un-united.

The radiograph is compatible with union but not proof of union. On clinical tests the fracture was thought to be united and was regarded as an excellent result. Unfortunately the Kuntscher nail was too long and the distal end was threatening to involve the knee joint though causing no symptoms. For this reason it was thought desirable to remove the nail as soon as possible and the decision to do so was made on the clinical evidence of union, hoping that osseous union might be more advanced than the radiograph suggested. At operation the fracture was clearly un-united when the nail was extracted. A second nail, thicker and shorter was easily driven down the track of the first nail and a graft of autogenous iliac bone was laid on the surface of the fibrous union.

The protagonists of internal fixation will say that this nail did not produce absolute fixation. In cases where the intramedullary nail has fractured by fatigue, so demonstrating that the bone is not united,[1] this argument is difficult to deny because the fracture is mobile when it is examined. In the above example, however, it was possible to examine the state of union before extracting the nail;

[1] Fatigue fracture of a femoral Kuntscher nail has occurred most often in my experience between ten and twelve months after insertion.

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the patient possessed a thin thigh which made manual testing quite easy, and with the patient under anæsthesia no detectable motion could be elicited.

This example shows that immobilisation of the fragments of a fracture for eleven months to a degree which is considerably more perfect than is ever possible by conservative means did not enhance the power of union in the fragments.

Fixation and the Speed of Union

In considering whether the role of fixation is fundamental to the union of fractures, it is interesting to examine logically the significance of *speed* in osseous union.

In animals, and even in the human subject, the development of clinical union after a fracture is often an astonishingly rapid process. It is not uncommon to detect clinical union six weeks after fractures of long bones which have been left overriding. Indeed the human tibia, which is notorious for its tendency to delayed union, sometimes can show clinical union in six weeks, even in the adult. Is it not logical to assume therefore that if any factor is fundamental to osseous repair, to enhance this factor should do more than merely eliminate non-union in the end results? If truly fundamental, to enhance fixation should *shorten the average time for clinical union towards the commonly encountered minimum.* If lack of adequate fixation were the sole factor responsible for delayed union of the tibia under conservative treatment, enhancement of the missing factor, as by internal fixation, should produce union so rapidly that it would have been recognised a quarter of a century ago. In practice, internal fixation usually delays the appearance of the radiological signs of osseous union.

Coaptation

I have argued that the essential cause of non-union lies in the failure to bridge a gap and that there is nothing to support the idea that fixation can facilitate the bridging of a gap.

The deduction that coaptation is more important than fixation will be rejected by those who have had the experience of delayed union after internal fixation *when there has been perfect coaptation.* The crux of the matter must surely lie in the *vitality of the bone ends* which have been accurately coapted. If these bone ends have had their blood supply completely interrupted, and their capacity to produce ensheathing callus destroyed by the periosteal covering having been stripped from the edges of the fracture, the perfection of coaptation, judged radiologically, is of no significance. In this case two utterly inert fragments have been coapted. This is proved by the experience reported in relation to Fig. 21.

Ischæmia of Bone Ends Increased by Surgery

Examples of the devitalisation of bone fragments by operative intervention on fractures are illustrated in the following case histories:

1. Fig. 22 is a gross example of the inhibition of callus formation at the actual site of the fracture produced by operative exposure. The failure of callus to 'jump

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the gap' between the bone ends is astonishing in view of the fact that the power to produce callus must have been considerable since it could successfully take such a devious pathway. This must surely indicate that the ends of the fragments were dead and ischæmic even though there is no radiological evidence of this.

FIG. 22

Example 1 (see text).

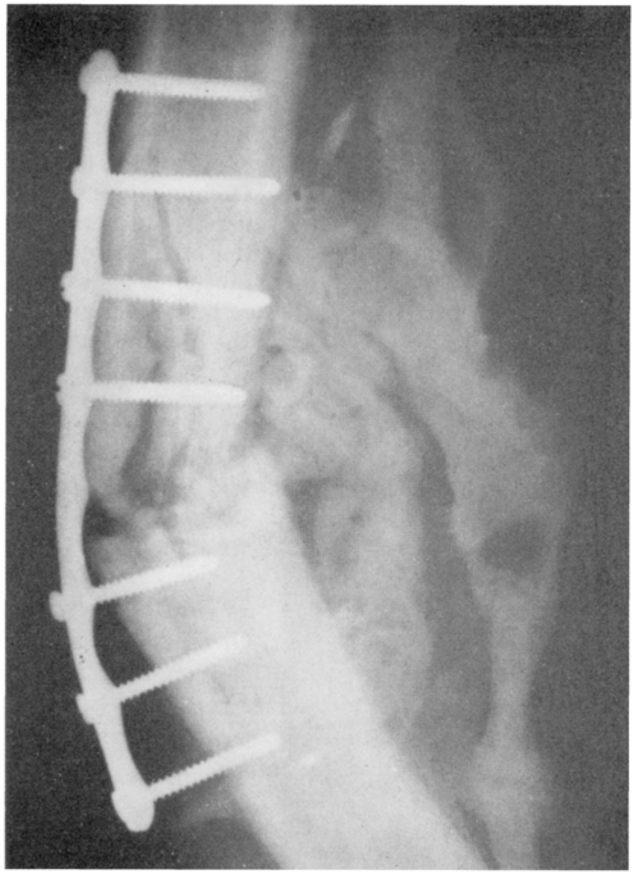

FIG. 23

Showing absence of callus between ends of the bone, after internal fixation, even in a case possessing a strong potential for callus production.

2. A similar circuitous method by which callus has by-passed a fracture is illustrated in Fig. 23. There is obviously no lack of osteogenic potential in this patient, but none of it has been revealed between the bone ends. This example indicates in an exaggerated way the usual process of union after the operative treatment of fractures.

3. Fig. 24 illustrates an oblique fracture of the tibia in a man of sixty-two years of age treated by the insertion of two transverse screws and the application of a plaster cast. Four months later the fracture was mobile and it was apparent that the screws had cut out. The fracture was re-operated on to apply bone grafts of autogenous iliac bone, and it was immediately obvious that the proximal fragment of the tibia was dead and white. A biopsy was taken and the site of its removal is visible in the radiograph. Histologically there was no evidence of infection. There would seem to be no doubt that

the initial operative intervention destroyed any osteogenic potential in this fracture and union would probably have been uneventful if the case had been treated conservatively.

4. (Fig. 25.) This was a spiral fracture in a youth of twenty, which was treated by two transverse screws. The technical details of the operation were beyond criticism and the reduction was such that the fracture line was invisible in the post-operative film. Eleven weeks after the operation the youth fell over a raised curb, re-fracturing his leg while still in a long leg plaster. X-ray of the displaced fracture shows that the osteosynthesis has come apart exactly as it was before the operation and that this is due to breaking of one screw and avulsion of the other. It is therefore reasonable to deduce that little or no osseous union was present at eleven weeks, and that the fracture was dependent only on the screws. By contrast, I am quite certain that under conservative treatment it would have been impossible to move a spiral fracture of this kind eleven weeks after injury if, for example, a remanipulation for mal-position had been needed. Operative interference has thus depressed the osteogenic activity of a very simple fracture.

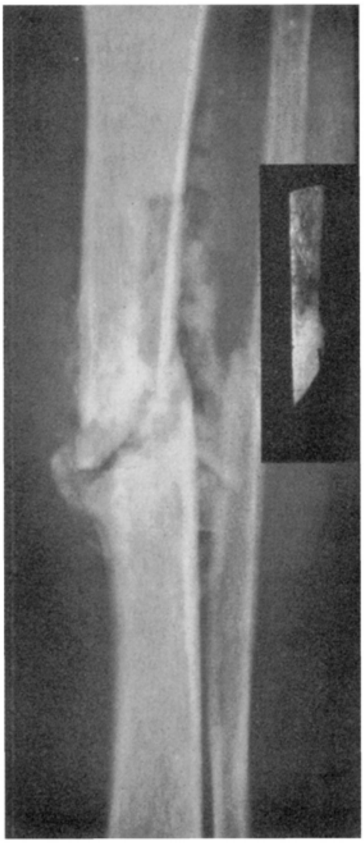

FIG. 24

Inset is biopsy specimen reproduced to same scale as radiograph and site in proximal fragment from which it was removed is visible. Note the dead white end adjacent to fracture. Two transverse screws through an oblique fracture destroy more bone than one screw. Meddlesome surgery.

Further examples extending the thesis of the ill-effects of open operation on callus formation are given in Chapter XV on fractures of the tibia.

Circumferential Wiring

The evil effects of a circumferential suture of bone have been recognised ever since the 1914-18 war as the result of experience with Parham's band. There is still a tendency to revive the use of the circumferential suture of wire stimulated by the invention of attractive wire-tightening gadgets. Results, typical of the evil effects of this method, are illustrated in Figs 26 and 27. This result can be explained by the fact that:

1. Periosteal stripping has suppressed ensheathing callus.
2. The metal encirclement presents a permanent barrier to bridging by collars of periosteal callus.

Biologically and mechanically this method is the worst of any method of internal fixation. It is an even more pernicious way of killing part of a long bone than by sandwiching it between two large metal plates; in the latter there is at least

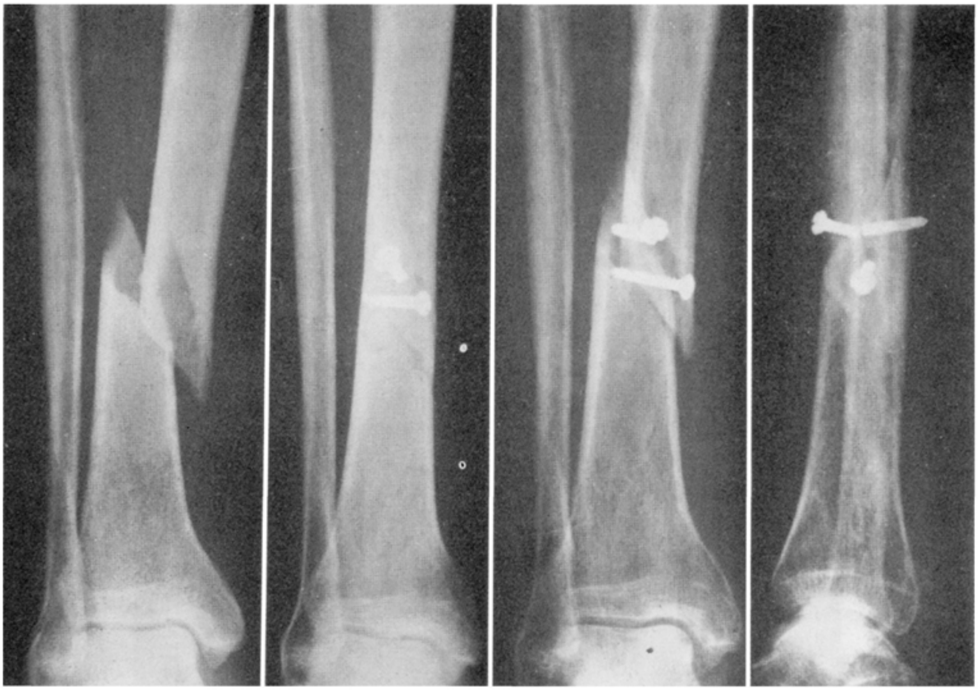

FIG. 25

Anatomical reduction, but the anatomically reduced ends have been devitalised by operation. Complete re-fracture eleven weeks later. This spiral fracture could have been treated better conservatively.

FIG. 26

Destruction of bone by 'encirclage' (see text).

good fixation, even if the vitality of the bones is imperilled, but in the former there is neither fixation nor vitality. Some of the evil of circumferential wiring can be diminished by drilling a hole through both fragments and encircling only half of the circumference of the fracture, but the fixation is not as good even as that

FIG. 27

Evil effects of multiple encirclage. There was no clinical evidence of infection in this case. The illustration on the left was six weeks after the operation ; on the right are the appearances nine months later.

obtained by a transverse screw in oblique fractures, which I have criticised elsewhere.

When one considers the diagram in Fig. 28 the disastrous effect of ' encirclage ' on an oblique fracture is fairly obvious. The fact that many cases are still able to unite after this operation is no tribute to the method—it merely indicates that the bones in such cases had remarkable powers for uniting *in spite of* the method.

Fracture Union as a Local Phenomenon

No account of the phenomenon of fracture union is complete without a reference to the possible existence of systemic factors. Every patient with delayed union wants reassurance that his diet is adequate and whether or not he should take calcium and vitamins. There are a number of clinical facts indicating that in delayed union systemic factors are of negligible importance and that local factors are all-important:

1. Old people, and patients with debilitating disease, often have less trouble with the union of fractures than do strong healthy men. This is particularly the case in the tibia, and it is possible that this can be explained by the fact that when cortical bone becomes porotic it is because of the enlargement of its Haversian canals, and therefore it has an exceptionally good blood supply; the dense bone

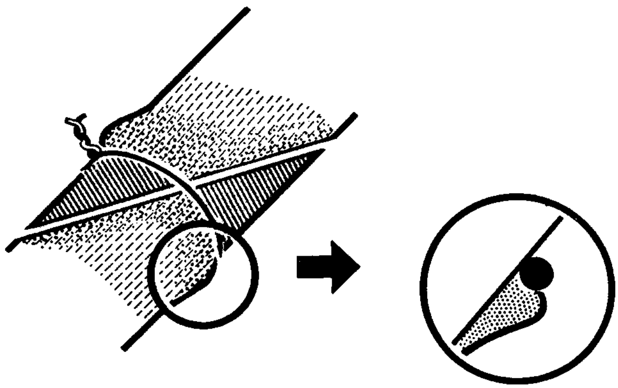

FIG. 28

Diagram showing the idea that encirclage can devitalise bone fragments and also prevent the extension of periosteal callus.

of the athletic young adult, on the other hand, has small Haversian canals because they are encroached on by the much greater amount of inert bone mineral needed for the function of weight-bearing.

2. When multiple fractures occur in the same patient, one of these, such as the shaft of a femur, may unite rapidly whereas another, such as the shaft of the tibia, may show delay in union, and even progress to true non-union.

3. In double fracture of the same bone, one fracture almost invariably unites quickly while the other is delayed, or even develops into non-union.

4. A close inspection of any established non-union reveals that there is considerable new bone formation, as shown by the piling up of subperiosteal bone on each side of the fracture gap, which produces considerable thickening of the bone ends. It is evident that the essential failure of union is the failure to bridge the gap, *not the failure to generate bone*. This is well demonstrated in Fig. 29 where the increased width of the shaft of a metacarpal in the presence of non-union can be compared with the width of the bone at the time of the fracture.

Sepsis and the Periosteum

In any discussion on the operative treatment of fractures the serious effects of sepsis cannot be ignored. Why should bones be more susceptible to infection than most other connective tissues? Again, it is possible that the answer is to be found in the function of the periosteum. The vitality of the surface of a bone resides in its periosteal blood supply, and with its clothing of periosteum preserved intact a bone possesses very high resistance to infection, even if surrounded by pus on all sides. Inflamed periosteum reacts by producing new bone which is seen to an extreme degree in the 'involucrum' of hæmatogenous osteomyelitis. When, however, the periosteum is stripped from the underlying bone, as in performing the internal fixation of a fracture, the vitality of the surface of the bare bone is abolished and the physical conditions are thus highly favourable for

FIG. 29

Delayed union. Compare the diameter of fragments immediately after fracture and four months later. Plentiful production of callus but essential error is *failure of callus to bridge the gap.*

the continuation of sepsis—and even more so if metallic foreign bodies are present. One cannot help thinking that many cases of delayed union after internal fixation may be the result of deep infection which has been masked, and which has eventually subsided, under the influence of antibiotics (*i.e.*, Fig. 27 is compatible with this possibility though no clinical evidence of infection was present).

An instructive lesson can be learned from inspecting the 'coronet' or 'ring' sequestrum which used to be a common occurrence in infected amputation stumps with the old surgeons. It is probable that the coronet sequestrum reveals the volume of bone rendered avascular by the division of the longitudinal circulation at the time of section and by the periosteal stripping at the site chosen for sawing the bone. Without sepsis this volume of bone would be ischæmic but would become reincorporated without ever becoming recognisable radiographically; but the addition of infection will kill the ischæmic zone completely and the adjacent bone will form a line of demarcation and a radiological sequestrum will then be revealed. It is but a short cry from this example to that of an infected fracture, because an amputation is nothing more than the proximal half of a compound fracture. The two illustrations (Figs. 30 and 31) illustrate the 'ring'

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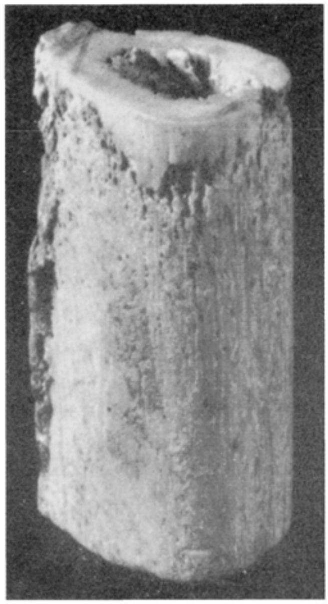

FIG. 30
'Ring' sequestrum of femur from septic amputation stump, discovered in John Hunter's Collection, Royal College of Surgeons of England. Sepsis has demarcated zone of ischæmia produced by interruption of the longitudinal circulation. (*By courtesy of the Curator, Dr Proger.*)

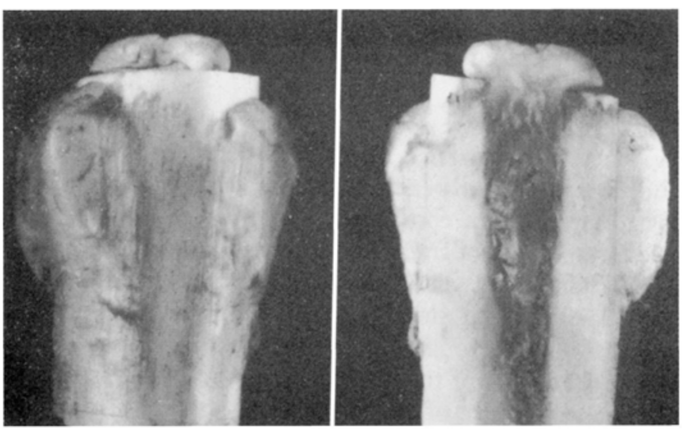

FIG. 31
Septic amputation stump dissected and prepared by John Hunter (collection of Royal College of Surgeons of England) to show fibro-cartilaginous callus. Note ischæmic end of bone and how external callus does not reach end of bone. *No callus produced by the end of the bone itself.* (*By courtesy of the Curator, Dr Proger.*)

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sequestra encountered in amputation stumps when infection has rendered irreversible the area of ischæmia produced in the bone end by section of the longitudinal Haversian systems by the saw. Had these amputation stumps been aseptic these ring sequestra would have been reincorporated. These illustrations show vividly the futility of expecting the ends of cortical bone to join when they are coapted or compressed together. Union in this case could only be by the development of an ensheathing callus. It is interesting to observe that the specimen in Fig. 31 shows how the ensheathing callus heaps up round the bone end but fails to project beyond the end of the bone and even falls short by the distance the cortex is ischæmic. It is fascinating to record that these two specimens are from John Hunter's own collection and that they are nearly two hundred years old. They were found and photographed for me by Dr Proger, Curator of the Hunterian Collection, and I am deeply indebted to him and the Royal College of Surgeons for permission to make use of these historic exhibits.

Anatomical Explanation of Ischæmia of Bone Ends

The anatomical explanation of local ischæmia affecting the ends of a broken long bone is illustrated diagrammatically in Fig. 32, A and B. The longitudinal arrangement of the blood vessels inside the Haversian systems is shown and the manner in which they connect with each other by transverse anastomoses. The blood vessels of the periosteum reinforce this longitudinal circulation through similar transverse channels, as do also the medullary vessels on the endosteal aspect. When the bone is severed a continuous circulation of blood inevitably must stop in those parts of the divided Haversian canals which lie between the broken surface and the nearest subjacent transverse anastomosis. When the periosteum is stripped in the vicinity of the bone ends, the deprivation of blood supply to the bone ends is significantly increased and corresponds to the ' ring ' sequestra illustrated in Figs. 30 and 31. (John Hunter's specimens.)

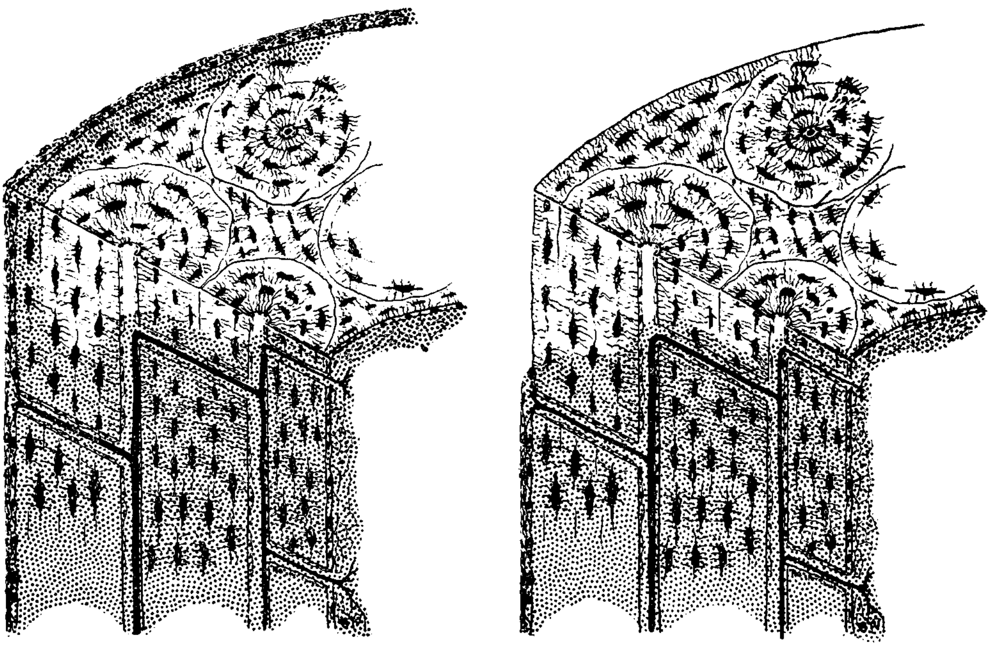
Compression in the Union of Fractures

There is evidence that powerful mechanical compression, acting continuously for three to four weeks, has a beneficial action on the union of *cancellous* bone (Charnley, 1953), but I am not convinced that there is good evidence that compression stimulates the union of fractures in *cortical* bone. The interruption of the longitudinal circulation in the ends of long bones, caused by the fracture interrupting Haversian systems, is in itself enough to explain the futility of compressing together bone ends which are composed of little more than an inert mineral substance. The broken ends of the cortex are the only inert surfaces in a fracture where everywhere else is a hive of cellular activity.

On two occasions I have applied mechanical compression to transverse fractures of the tibia by transfixing the bones above and below the fracture with Steinmann nails and applying compression clamps as in compression arthrodesis of the knee. After six weeks of compression there was no evidence of clinical union. After six weeks of compression in cancellous bone clinical union would be present in three cases out of four.

Various writers have reported successful union following the application of compression to *delayed union* and even to *non-union* in fractured long bones. That osseous union might be precipitated by this means is consistent with general experience that weight-bearing is beneficial *in the later stages* of fracture treatment, but experience has not shown weight-bearing to be beneficial in the early stages of treatment.

Eggers (1949) found evidence of increased osteogenic activity in pressure experiments on the rat's skull, but it was difficult to dissociate these results from



A B

FIG. 32

Diagram of Haversian systems in the cortex of the divided end of a long bone. The nutrition of the divided end of the bone is indicated, A, when the periosteum is intact and B, when the periosteum has been stripped for some distance near the end of the bone. (*Adapted from Fig.* 138, *Ham*, '*Histology*,' 1950, *J. B. Lippincott.*)

the mere effects of 'contact' without compression. Eggers found destructive changes when the 'contact-compression factor' was excessive. Friedenberg and French (1952), using an ingenious spring compression device on the ulna of the dog, found evidence of good union when forces not more than 30 lb. were used, but above this union was impeded; their technique, though ingenious, would seem to me to prejudice the circulation of the experimental fracture.

Magnitude of Initial Displacement in Relation to Union

Of all the factors which influence the speed of union of a fracture through the shaft of a long bone probably the most important relates to the magnitude of the initial displacement. If we consider the particular case of a fracture in the shaft of the tibia, no one will dispute the general statement that a fracture with only slight displacement will unite rapidly after the most perfunctory treatment, even though the tibia is a bone notoriously prone to delayed union. On the other hand, a fracture of the tibia with gross initial displacement will often fail to unite even though it may be reduced perfectly; indeed, so perfectly that the radiological appearance may be superior to the previous example in which the initial slight displacement is accepted without reduction.

The bone of an undisplaced fracture is broken just as completely as regards loss of continuity of the osseous substance as a grossly displaced fracture. There are no degrees in the state of being fractured between the two extremes of being *broken* or *not broken* except in the greenstick fracture of childhood. Any difference in the rate of union of displaced and undisplaced fractures must therefore be traced to differences in the state of the associated soft parts.

An argument which might challenge this statement is the occasional undisplaced fracture which fails to unite. This is most commonly seen in oblique fractures of the tibia with an intact fibula. I can only suggest that in this type of case the initial radiograph does not reveal the true magnitude of the displacement sustained at the moment of violence. It is possible that the elasticity of the fibula, combined with the flexibility of the tibio-fibular articulations, could protect the fibula from fracture while the tibial fragments were momentarily separated by a distance great enough to tear all local soft tissue connections. It is often forgotten that the initial radiograph of any fracture is made after first-aid workers have 'straightened up' gross external deformities existing at the site of the accident.

This certainly can happen in Pott's fractures of the ankle; I have seen this fracture diagnosed as 'undisplaced' on the initial radiograph, and for this reason entrusted to an inexperienced assistant to apply a plaster, with the result that 'spontaneous' displacement has been discovered later. This is explained by gross tearing of soft parts being present, due to gross initial displacement at the moment of injury which has not been suspected from the innocent appearance of the first radiograph.

The deduction which I think we can reasonably make from this is that the 'bridge' or 'callus pathway' which conducts periosteal callus from one fragment to another must lie in the soft tissues investing the fragments. In the case of the tibia an intact connection of both fragments to the interosseous membrane is probably the deciding factor because it is at the site of attachment of the interosseous ligament that callus most often is first seen to bridge the tibial fracture.

This conception of the role of the soft tissues in conducting periosteal callus across a fracture is particularly important in those bones which do not possess the ability to throw out profuse periosteal callus and less important in those muscle-covered bones such as the femur, humerus, and shaft of fibula, which tend to produce a voluminous investing callus. This *fatalistic concept of delayed union as a function of soft-part damage* is expressed diagrammatically in Fig. 33.

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Traction and Distraction in the Treatment of Fractures

If we accept the idea that the capacity for rapid union, or for delayed union, is established by the amount of damage to soft parts at the time of injury, arguments condemning the use of continuous traction in the treatment of fractures need to be re-examined. It has been customary to condemn weight-traction because of the danger of causing 'distraction.' A fracture which initially was grossly displaced, associated therefore with extensive tearing of the soft parts, would still suffer from delayed union even if accurate coaptation were obtained without traction.

The two previous editions of this book were dominated by the fear of distraction, and for this reason fixed traction was advocated in preference to all forms of weight-traction. I am now convinced that much of the harm which originally was attributed to weight-traction ought to be transferred to the rupture of the pathways which conduct osseous union between the fragments.

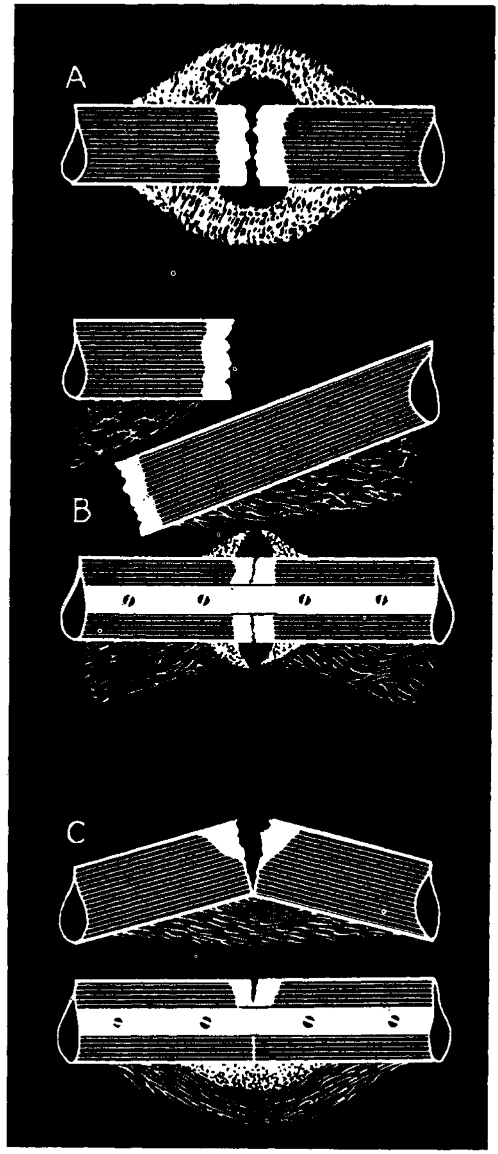

Fig. 33

Fig. 33—The fatalistic concept of initial displacement in relation to soft-tissue damage and to osseous union: the preservation, or destruction, of the 'callus pathway' between the fragments.

A, Successful union in that type of bone which is capable of generating profuse periosteal callus. The ischæmic bone ends, even if reduced end to end, do not impede the bridging of callus in this type of case.

B, Fracture with gross initial displacement *in a bone incapable of generating profuse periosteal callus.* End-to-end contact puts the collars of periosteal callus out of reach of each other. No intact soft-part bridge exists as a callus pathway. It is possible that union might have occurred if the fracture had been left undisturbed in this position with overriding and full displacement.

C, Successful union *in a bone incapable of generating profuse periosteal callus,* because minimal displacement preserved a soft-part bridge and hence a callus pathway on the concave side of the fracture.

NOTE.—Open reduction and internal fixation was unnecessary in C; open reduction and internal fixation in B still might not eliminate the necessity for a bone graft.

We have heard a great deal in the last few years about the harmful effects of distraction in delaying osseous union without considering instances where union has occurred in the presence of distraction. The following case illustrates this point in an exaggerated degree:

The patient (Fig. 34) was eighteen years of age, and a leg-lengthening operation had been performed two years previously, using a long Z-section of the shaft of the femur. The operation succeeded in achieving an elongation of 2½ inches but was followed by slow consolidation. This slow consolidation, without the appearance of periosteal callus, I attributed to extensive periosteal stripping of the femur at the line of operation. While in a walking caliper splint the femur re-fractured three times because the attenuated part of the bone did not show any tendency to hypertrophy. Each of the re-fractures was accompanied by the production of good periosteal callus, which I interpreted as indicating that by this time a new periosteum had formed. All three re-fractures took place while the patient was wearing the caliper splint, so that extensive tearing of soft parts was not to be expected. When the third fracture occurred it was treated by weight-traction which was deliberately excessive and distraction of 1 inch occurred. Callus bridged this gap and the limb was clinically united in three months.

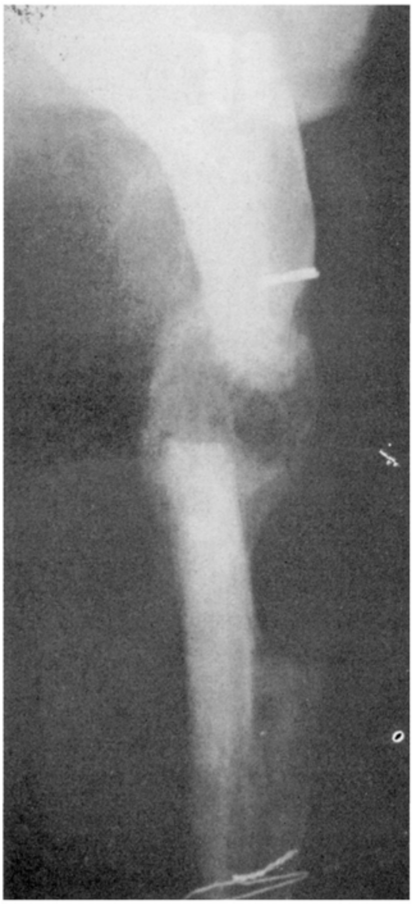

FIG. 34
Showing that the distraction of bone fragments is not in itself the cause of failure to produce callus.

This example is unusual as regards the common behaviour of callus in the healing of a fracture of the femur, but it is customary in the process of leg-lengthening in young patients. It illustrates that distraction by itself is not the sole cause of the failure of callus to bridge a gap. In this example I suggest that the soft parts were still in continuity across the gap and that they were stretched by the traction without being ruptured.

If distraction occurs, using ordinary amounts of traction force, it indicates that severe soft-tissue damage was sustained at the time of the injury and it is a warning that the fracture is likely to suffer delayed union no matter what form of initial treatment is adopted. There is no excuse for tolerating the distraction of fractures, but there is no need to condemn weight-traction as a principle if distraction is avoided. Weight-traction renders a patient much more comfortable than is possible

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on fixed traction, and for this reason I am now adding balanced traction to methods which originally were designed strictly to avoid continuous traction.

Fibrous Septa as the Callus Pathway

My belief that callus spreads from one fragment to another via the interosseous membrane is illustrated by the example in Fig. 35, where the initial displacement is seen on the left and the appearance six months later is on the right. In this

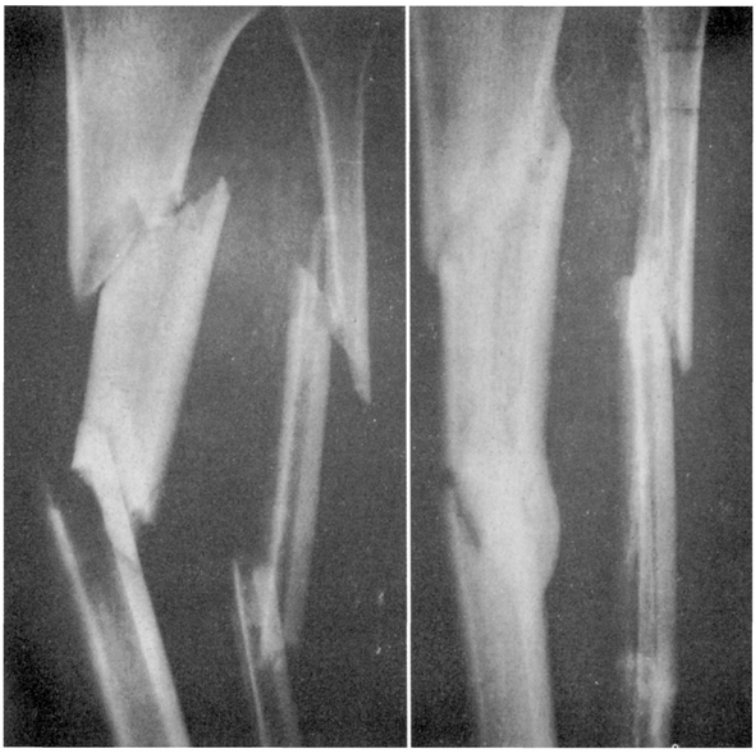

FIG. 35

Illustrating the 'callus pathway' in the intact tissues on the side of the distal fracture which was concave in the original deformity.

comminuted fracture of the tibia the interest centres round the distal tibial fracture. The concave side of the deformity (*i.e.*, the side on which the soft parts are least torn) is the side of the interosseous septum. The radiograph at six months has been made with an oblique orientation to show the full width of the interosseous space which is not revealed in routine anteroposterior and lateral views. It will be seen that the callus has bridged the fracture in the attachment of the interosseous septum, and that there is no callus on the opposite side of the bone. A similar state of affairs in seen in Fig. 158, page 206.

The function of fibrous tissue in offering a pathway for callus to bridge a fracture is suggested in the examples shown in Figs. 22, 23, 35, and 158; if the

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intermuscular septa arising from the linea aspera of the femur were elevated during the operation for plating they would occupy the position of the bridge of callus in these illustrations.

Primary Bone Grafting in the Treatment of Fractures

If we accept the idea that the delayed union of fractures in cortical bone is decided at the time of the injury by the extent of the tearing of ' callus-pathways,' the immediate use of bone grafts might seem a logical way of establishing a callus-pathway across the ' physiological gap ' which can exist between bone ends which are in perfect anatomical coaptation. We must ask ourselves whether primary bone grafting is quite such a logical procedure as it may appear on first consideration.

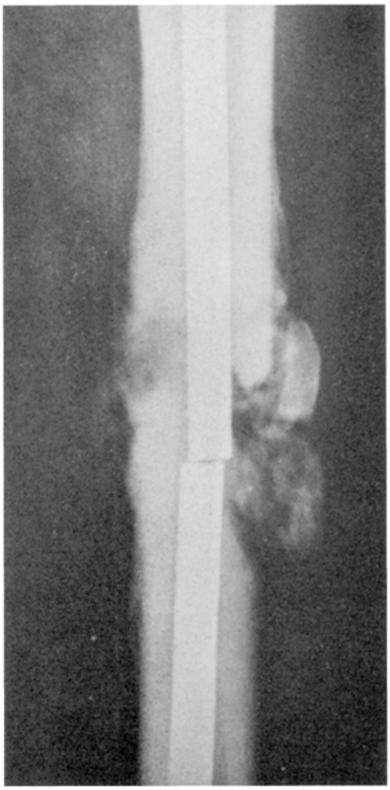

FIG. 36

Failure of autogenous iliac bone-graft to induce union of a fracture when inserted at the time of the primary operation. Non-union was revealed ten months later when the intramedullary nail fractured by fatigue.

I have never been able to satisfy myself that a bone graft in a fresh fracture is any different from a fragment of the fracture itself. A bone graft, being totally ischæmic, will be even more ischæmic than the comminuted fragments already present in the fracture because many of these will possess some vascular connections. A suggestion of this possibility, which I have observed on several occasions, is indicated by the two following case histories :

Case 1. The patient was a man of fifty years of age with comminuted fracture of the midshaft of the femur, with gross initial displacement, which was treated by open exposure of the fragments and insertion of a Kuntscher nail. The surgeon performing the operation felt he could improve the situation by replacing the loose comminuted fragments of dense cortical bone by slices of autogenous spongiosa of iliac bone because these might fuse into the fracture quicker than cortical bone (Fig. 36). In due course clinical union was considered to be safe and the patient was permitted to take full weight on the limb. Sudden pain was experienced ten months after the injury and fatigue fracture of the nail was discovered, with return of mobility in the fracture, and with clear radiological evidence that the grafted fragments of cancellous bone had not incorporated into the fracture.

Case 2. This was a patient of twenty-four years of age (Fig. 37) who was operated on nine days after the fracture. A four-hole plate was applied, augmented with chips of fresh autogenous iliac bone. Rigid fixation was obtained but because the plate was short

FIG. 37

Autogenous iliac bone-graft, seen on lateral aspect of fracture, B, applied at time of primary operation for plating the tibia. Three months later fracture was un-united and mobile. Appearances three months after application of a second iliac graft and removal of loose plate, C, and appearances one year later, D.

a long leg plaster was applied in addition. Three months later, when the second plaster was removed, the fracture had become mobile.

It is my belief that an autogenous graft of cancellous bone is incorporated into a fracture with most uniform success when a delay of several weeks has elapsed between the fracture and the operation. By that time the ends of the bones, and the periosteum, have achieved maximum vascularity and the volume of cortical bone rendered ischæmic at the time of the fracture is at a minimum. Sandwiched between a hyperæmic periosteum and the denuded surface of hyperæmic bone, the bone graft has an optimal chance of incorporation (page 248). If inserted when the fracture is fresh the graft merely denudes the fracture of more periosteum, which increases the volume of ischæmic bone in the fracture, and in some cases the fragments of graft become invested in fibrous tissue and fail to incorporate in the fracture.

Blood Supply and Fracture Repair

Throughout this review of the factors which influence the healing of fractures I have tried to show that mechanical elements are of secondary importance to biological factors. In the treatment of a fresh fracture we can control only the secondary factors, such as accurate reduction and rigid fixation. The full deployment of biological factors in the repair of a fracture depends on augmentation of existing blood supply at the fracture site. The augmentation of blood supply is a process which takes time ; it proceeds at a rate determined by the living tissues in response to the stimulus of fracture. Operative interference at the fracture site can never enhance this process of increasing vascularisation and only too often operative interference isolates the bone fragments from their original blood supply and puts them in a position where the stimulus to hyperæmia cannot take effect.

Cancellous bone usually has a profuse supply of blood and therefore the mechanical factors of accurate reduction and rigid fixation (enhanced by the addition of compression) can be guaranteed to secure union in about four weeks (as judged in arthrodesis of the knee clinically and by the histology of biopsy specimens). When both fragments of a fracture possess an intact supply of blood, both can participate actively in the process of union, and I hold the view that in these circumstances union can take place in the presence of a slight ' hinge ' movement. In fractures where one of the fragments has been deprived of its supply of blood, as in sub-capital fractures of the neck of the femur, the only factors available to encourage union are mechanical. In this special instance we are dealing with conditions which are the same as in bone grafting. When one fragment is ischæmic the ' host ' bone has to revascularise the ischæmic fragment before it can become incorporated, and to do this close apposition and rigid fixation are absolutely necessary. One can summarise these ideas thus :

1. If both fragments are alive, rigid immobilisation is not essential for union.
2. If one fragment is ischæmic, rigid immobilisation is essential for union.
3. If both fragments are ischæmic, rigid immobilisation is futile.

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It is when we consider the treatment of fractures in cortical bone (as in the shafts of long bones) that the mechanical elements in treatment are of secondary importance. In cortical bone the supply of blood to the ends of a bone fragment in a fresh fracture is restricted by the small calibre of the Haversian canals which traverse the dense mass of ivory bone. At the moment when a fracture of cortical bone is sustained the proportion of living elements, which ultimately are responsible for the healing of the fracture, is small when compared with the proportion of inert mineral matter which is responsible for the strength of the tubular bone. The density of the ivory bone is an obstacle to repair, but in the course of normal fracture healing the vascular channels enlarge and the dense cortical bone becomes permeated with enlarged vascular channels. Until the cortical bone has become porous there seems no hope of it being able to participate in osseous union. If the ends of the bones are stripped of periosteum by open operation the ability of the Haversian canals to enlarge is seriously impeded and the ends of the bones remain dense long after adjacent parts with intact vascular connections have become porous (Fig. 24, p. 24). Thoughts like this encourage the idea of delay before engaging in the operative treatment of fractures (see p. 41).

Conservative versus Operative Treatment

In discussing the pros and cons of the operative treatment of fractures I shall defer the obvious argument of operative sepsis to the chapter on fractures of the tibia, because it is here that infection is most likely, the tibia being a subcutaneous bone and very frequently compound.

I shall here confine attention to matters which I think are just as important as sepsis, though less obvious, and will consider these under two headings: (1) the harmful effects of operative treatment and (2) the harmful effects of conservative treatment.

The *harmful effects of operative treatment* stem from the depression of osteogenic activity in the fragments of a fracture. Operative exposure increases the volume of ischæmic bone which is always present, even if only in small amount, in any fracture of cortical bone. The extent of this sequel to operation is commonly overlooked because early ischæmia in long bones is not detectable in radiographs. Even in fractures of the femoral neck where ischæmia of the femoral head is anticipated, we know that extreme ischæmia can be present for more than one year without definite radiological evidence. Urist, Mazet, and McLean (1954) investigated operative and conservative treatment in 100 successfully united tibiæ and in eighty-five cases of non-union in the tibia, and I cannot do better than quote extracts which summarise their views. Every surgeon would do well to ponder these statements before embarking on open treatment:

> 'The effect of open operations on fresh fractures is to increase the volume of damaged bone which has to be absorbed and replaced before the fracture can unite and permit full weight-bearing.'
>
> 'Comminuted fractures of the human adult tibia should be considered non-operable because the trauma added by surgery exceeds the normal capacity for bone regeneration in this area of the skeleton.'

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'In fractures with contact between the bone ends, internal fixation has either no effect or no adverse effect on the healing time. It is never a stimulus to bone repair.'

'If a fracture is short and oblique rather than long and spiral and if two or three screws are inserted in order to achieve strong fixation there will frequently be enough necrosis of the bone around the metal to cause disintegration of the entire area of the fracture.'

'The very good results in the majority of non-comminuted fractures could be used as evidence in favour of internal fixation, but the argument is weakened by comparison with the equally good results in matched fractures treated by closed methods.'

'Open reduction and internal fixation of extensively comminuted fractures always prolongs healing and never encourages it.'

The *harmful effects of conservative treatment* of fractures of the shafts of long bones all stem from delayed union and are all related to residual deformity and stiffness of joints.

In both operative and conservative methods of primary treatment we must take into consideration the complications of bone grafting operations if these become necessary as secondary measures.

In comparing the harmful effects of conservative and operative methods it is interesting to consider the three following propositions: (1) that operative treatment is potentially harmful to all fractures,[1] but conservative treatment is harmful only to a few; (2) that the few fractures which are harmed by conservative treatment would have been less harmed had they been operated; (3) that the failures of operative and of conservative methods are not equally capable of being salvaged by secondary procedures. It is this last which is the critical point.

Reviewing fractures of the shafts of the long bones in accordance with ideas suggested by the foregoing propositions, I have come to the conclusion that only in two sites are the failures of conservative treatment worse than the failures of operative treatment; these are (1) middle and upper thirds of the femur (*not* the lower third) and (2) shafts of the radius and ulna.

In the upper half of the shaft of the femur the result of delayed consolidation under conservative treatment is invariably late deformity, because conservative methods, if they have to be used for weeks on end, eventually fail to control alignment in fractures at, or above, the midshaft. To apply a bone graft to a femur in the presence of late angulation and mal-alignment is a formidable procedure. The only method of internal fixation which I consider justifiable when grafting the shaft of the femur is an intramedullary nail, and in order to insert this it is necessary to break down the fracture and expose the medullary canal. If this major procedure is to be done without a delay of many months it will have to be done through tissues which are indurated and slightly œdematous; this renders the wound prone to operative sepsis and more so if the operating time is prolonged by unforeseen technical difficulties. If, on the other hand, the original

[1] I am considering fractures of the shafts of long bones. I do not, of course, include fractures in such bones as the patella, olecranon, and neck of femur where conservative treatment is obviously futile.

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fracture has been treated by a Kuntscher nail, and if delayed consolidation has later become evident, the introduction of a subperiosteal graft of iliac bone is a procedure of the utmost simplicity and safety, because it can be postponed until the patient has a fully mobile knee and healthy soft tissues.

The same argument applies to the conservative treatment of fractures of both bones of the forearm: delayed consolidation after conservative treatment is invariably associated with malposition of the radial and ulnar fragments and bone grafting is a formidable procedure necessitating realignment of the fractures in tissues which are often slightly œdematous. If both radius and ulna have to be grafted there is often the special difficulty of closing the skin wounds without tension. On the other hand, if the fractures of the radius and ulna had originally been plated the insertion of subperiosteal grafts of iliac bone by the Phemister technique would have been a relatively minor and safe procedure because it could be carried out through soft tissues which were more or less completely rehabilitated.

This argument in favour of operative treatment (that it facilitates subsequent bone grafting should this become necessary) does not apply with the same force to those fractures where satisfactory alignment can be held by conservative methods. The fractures of long bones which can be held in adequate alignment by conservative treatment are the tibia, the lower third of the femur, and the humerus.

To appreciate fully the argument that the form of the initial treatment of a fresh fracture must be assessed in relation to it facilitating the performance of a bone graft if this should become necessary at a later date, it is necessary to mention the type of bone graft envisaged. The greatest advance in fracture treatment in this century has come from improvements in the technique of bone grafting and not from improvements in the technique of handling the fresh fracture. The type of bone graft which I believe has revolutionised the treatment of fractures is the application of slices of autogenous iliac bone to the surface of the delayed union without disturbing the tissue between the ends of the bones. We owe to Phemister (1947) the first full account of how this simple procedure induces the fibrous union to convert to bone. So important do I consider this technique that I have devoted considerable space to describing how I believe it is best carried out in relation to fractures of the tibia (p. 248).

Delayed Operations on Fractures

When balancing the indications for conservative and operative treatment in a particular clinical problem, there are occasions when the surgeon may feel that if he is to operate he must do so urgently if he is to get a good result. This idea makes him unwilling to try conservative treatment lest he should be driven to open reduction after a delay which might prejudice the result. The phrase ‘ the timing of the fracture healing process ’ has often been bandied about but no definite facts have been adduced and there is a general tendency to recommend early intervention.

In fractures of the shaft of the tibia, if open operation is to be undertaken, it certainly is a matter of considerable urgency because the overlying skin becomes œdematous and unfavourable for surgery in twenty-four to forty-eight hours.

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In sites where adequate soft parts cover the fracture and the dangers associated with a subcutaneous bone like the tibia do not exist, there is much to be said for delay before operation. J. E. M. Smith (1959) investigated the results of early and late operation on fractures of the radius and ulna and found that there were seventeen instances of non-union out of seventy-eight fractures operated within the first six days, and no cases of non-union in fifty-two fractures operated after the first seven days. In a larger series of fractures of the forearm bones the experience of Smith and Sage (1957), on the other hand, does not confirm this observation.

Adly Guindy,[1] working in my clinic, has repeated this investigation of the time elapsing between fracture and internal fixation, in relation to successful osseous union, in the case of thirty-eight fractures of the shaft of the femur treated by intramedullary nailing. His findings, though admittedly on a very small number of cases, support the idea that delayed interference is beneficial; six patients required bone-grafting out of twenty-four operated within the first week of the injury (25 per cent.) whereas only one patient out of fourteen operated more than one week after the injury required a bone-graft (7 per cent.). In the cases operated by internal fixation more than one week after the injury the amount of callus in the radiograph at three months was greater than in those operated within the first week after injury.

While absolute proof is still lacking that it is better to delay operation than to intervene urgently, at least it has been shown that no harm is done by delayed intervention. This observation would seem to be consistent with ideas on the blood supply of the fractured cortical bones, because it suggests that to delay intervention might give time for reactive hyperæmia to start in the ends of the bones. If operative intervention is performed urgently it may obstruct the action of blood to already partially ischæmic bone ends and delay their invasion by the hyperæmic process which precedes healing.

If delayed intervention is postponed too long (*i.e.*, more than two or three weeks) this will increase the technical difficulties of the operation by obscuring the detail of the bone ends and making it impossible to match them for a hair-line fit. In transverse fractures of the shaft of the femur which defy manipulative reduction due to gross swelling of the thigh, a delay long enough to absorb effused blood and lose some muscle bulk greatly facilitates the operation. This type of fracture frequently occurs in athletic young men whose bulky thigh muscles offer a serious obstacle to exposure of the fragment. In these cases I now rarely operate before the expiry of two weeks. Easy operations have fewer complications than difficult operations.

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