STUDY OF SOME METHODS OF BONE-GRAFTING.

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IN the following article no attempt is made to settle finally the vexed question as to which method of dealing with ununited fractures is the best, because the number of cases at the author's disposal is not sufficient to warrant dogmatic statements; moreover, it is probable that in this, as in other branches of surgery, each method has its own special indications, nor is any one adapted to all cases. It is hoped that a study of the following groups of cases treated by various methods may be helpful in illustrating the advantages and limitations of the different types of operation.

The cases recorded were all sooner or later in wards under the writer's care, with the exception of two, which are published by kind permission of Sir Harold Stiles, as they illustrate well the fate of grafts in the form of bone-chips. Owing to various administrative changes, most of the cases had been operated on at least once before coming under the writer's care, while some of the later ones were operated on by her assistants, but no cases are recorded whose progress had not been personally followed.

They have been chosen not as typical of the work at Bangour, but to illustrate special difficulties which confront the surgeon who deals with non-union following septic fractures, and the drawbacks and advantages of the various methods available. For this reason a large proportion are cases where several attempts had to be made before a successful result was attained, and in a few it was not attained while the patient was still in the hospital. In the writer's experience, it is by his failures that a surgeon and his friends learn most, and one failure is often more instructive than half a dozen successes; mere tables of good results are of little value to the student, however desirable from the patient's point of view. The surgeon who approaches a new field wishes to know the possible pitfalls, and unfortunately in bone-work they are many.

The guiding principles in all these cases seem to be :—

1. Wide opening-up of vascular bone, so as to give as many osteophytes as possible access to the seat of fracture.
2. The preliminary counteraction of all deforming tendencies, which are usually due to the simultaneous involvement of the soft parts.
3. The protection of the bone from undue stress subsequent to the operation. This is attained best, in the writer's view, by the application of a plaster-of-Paris cast at the time of operation, which eliminates the risk of slipping of the support, or interference with the position by patient or nursing staff. It enables the patient to get about freely at an early period, even with lower-limb injuries. It exerts an even pressure, and so interferes but little with nutrition of the parts and the shape of the muscles.
4. As soon as the ends of the bone are tied together by soft callus, so that they cannot get separated by soft parts, stimulation of the bone by local heavy massage and use of the limb in a support which will prevent deformity.

The operative methods available for dealing with an ununited fracture, which has no chance of spontaneous union owing to the intervention between the bone-ends of some other tissue, are :—

1. *Rawing the ends*, preferably with stepping, so as to secure some mechanical safeguard against separation of the ends and to increase the surface of contact. This usually needs to be reinforced by the use of some form of ligature, either wire or strong catgut, which is best passed through holes drilled in the bone-ends.
2. The use of numerous *small bone-grafts*, as sources of osteoblasts, to supplement the osteogenetic powers of the bone-ends. These chips of bone may be derived from the

neighbourhood of the fracture, or from some other bone, the iliac crest being the best source of vascular cancellous bone.

3. *A sliding graft*, i.e., a slice of bone from the surface of one fragment, which is slid across the gap and brought in contact with a specially-rawed area on the surface of the other fragment.

4. An *intramedullary peg-graft*, usually derived from some other bone.

5. An *inlay graft* from some other bone, usually the tibia, which provides a considerable length of dense bone adapted for this form of 'internal splint'.

6. *Plating*. This method provides an internal splint of great mechanical strength, but of a substance foreign to the organism, and therefore liable to cause irritation, and possibly to be ultimately extruded.

7. *Grafts of ivory or boiled bone*, either human or animal, which may be used either as intramedullary or lateral grafts.

THE TWO-STAGE OPERATION.

We will deal in turn with each method, referring to its special advantages and drawbacks, and illustrating these as far as possible by case records; but before discussing the first method, the writer wishes to draw attention to the great benefits of what may be

called the *two-stage operation* in dealing with ununited fractures, more especially those due to war injuries. By this is meant the use of a preliminary operation at which as much scar tissue as possible is excised, particularly that over the bone-ends, including the sclerosed portions of bone, while all contractures and other static deformities are overcome, often with the assistance of a plaster cast to maintain correction. If primary healing occurs, a second operation, at which the actual graft is introduced, is done two weeks later. The advantages of this are two-fold:—

a. *It prevents mechanical strain* on the bone-graft, which, when of more than slight degree, is a fruitful source of non-union. This strain is usually due to the anchoring effect of scar tissue, or to shortening of the muscles, which has been allowed to occur while the fracture was ununited. Unless the scar tissue has been freely excised and the muscles have been stretched by a plaster splint, the bone-graft is not able to resist them, no matter what mechanical means, in the form of

FIG. 160.—Pte. S.
Ununited radius with much
radial deviation of hand.
Before operation.

carpentry or wire ligatures, are adopted to reinforce it. Though wire does not itself yield early, yet it cuts through the bone as if that were cheese, and therefore fails to maintain its support. Indeed, the writer has found that wherever the strain is greater than can be borne by thick iodine-tannic catgut, then, if wire is used, the bone will be cut. This is a serious drawback to the use of wire, because, as it is usually applied one inch or more from the end of the bone, it isolates that length from its blood-supply; and by so much lengthens the gap to be bridged at a subsequent operation. As wire has the additional disadvantage

FIG. 161.—Same case
as Fig. 160, after second
operation (lateral tibial
graft into radius).

of being a foreign body, liable in itself to cause rarefaction of bone and irritation, and certain to prolong any flare-up of the original sepsis, there seems no reason for its use.

b. The second advantage of the two-stage operation lies in its connection with the *prevention of flares-up of sepsis*. The organisms to which these are due lurk in the scar tissue, especially that part which has invaded the ends of the bone, and therefore, the more radically the scar is excised, the fewer of these organisms are left. As it is usually impossible to resect the scar without cutting into it, it follows that a few organisms are likely to be set free, and if at the same time a piece of isolated tissue like a graft is left with them it may form a pabulum for them, so that an infection will result, which otherwise could have been stamped out by the vascular tissues of the neighbourhood. Secondly, the dissection necessary to freshen the ends of the bone satisfactorily, with the inevitable opening up of scar tissue, makes complete hæmostasis difficult; whereas this is not so at the second operation, when the bone can be exposed with little disturbance of surrounding tissues: the occurrence of a hæmatoma seriously imperils the success of a graft operation.

If a flare-up occurs after the preliminary excision of scar, the surgeon has good warning that the time is not ripe for grafting, while the infection usually pursues a mild course, there being no interference with drainage and no foreign material to keep it up. In such a case it is difficult to know when it will be safe to put in a graft. If there is sufficient skin available to allow of a second excision after a period of heavy massage, has failed to evoke a flare, the graft may safely be proceeded with. Fortunately, few such cases occur; and it is probable that heavy massage to the bone-ends, by inducing a repeated mild auto-inoculation, would enable the patient to destroy the remaining infectious organisms, especially as their original lurking-place, the heavy bed of scar, which had been slowly formed in the original virulent infection, has been removed.

As a post-operative infection is generally fatal to the vitality of part or all of the graft, and is the commonest cause of non-union after grafting, it is most desirable to avoid it; and it is well worth the patient's while to undergo the moderate discomfort of a second anæsthetic, especially as this procedure shortens the length of the second operation, which otherwise is apt to be tedious.

Most surgeons who have had to deal with the late effects of war injuries have drawn attention to the impossibility of judging by ordinary methods when the original infection is extinct, and not merely quiescent, no known time-limit being in itself a guarantee.

The writer has not met a case where this procedure was adopted and where a flare-up occurred after the grafting, and it was more particularly used in cases with a history of severe and prolonged sepsis, or where a previous grafting operation had been spoiled by infection; this speaks strongly for the procedure, even on a small series of cases.

FIG. 163.—Same as Fig. 162, after second operation (lateral tibial graft into ulna).

FIG. 162.—Pnsr. B. E. Ununited ulna after first operation (trimming ends). Arrows mark a previous graft united at one end only, owing to sepsis.

The following two cases illustrate the points raised above :—

Case 1.—Pte. S., age 34. (*Figs. 160 and 161.*)

April 9, 1918. Gunshot wound, with gap fracture of radius. *Aug. 19:* First bone-graft operation at previous hospital. Suppuration for seven months. Sequestrum removed. *June 19, 1919:* Admitted to Bangour. *Aug. 27:* Excision of scar—correction of deformity, both pronation and radial deviation—plaster cast. *Oct.:* Bone-grafting, large tibial graft applied to raw posterior surface of radius, tied by tannic catgut. Plaster dressing. Primary healing. Good function finally, but only after several tendon-transplantation operations.

Case 2.—Pnsr. B., age 25. (*Figs. 162 and 163.*)

Aug., 1918: Wounded. *Dec.:* Healed. *June, 1919:* First bone-graft operation, followed by flare-up. *Jan., 1921:* Admitted to Bangour with severe scarring and ununited fracture of the ulna. Graft had united to the lower fragment. Excision of scar and trimming of bones. Graft from tibia, 5 in. long, to surface of ulna, and another, 1 in. long, between its ends. Plaster case in which a window was cut three days later. Primary healing, and bony union in due course.

There is no doubt that the method of applying a strong lateral graft to act as an internal splint, and then using other fragments, which require no stability but only a large raw surface, to fill the space between the actual ends of the bone, gives excellent results. In the case of a large bone like the humerus, it is often useful to put the central graft into the medulla of one or both fragments, to prevent its displacement, which is more apt to occur where there is not a second bone acting as a splint, as there is in the forearm.

Method 1.—STEPPING BONE.

The method of rawing the ends of the bone and stepping them so that the raw surfaces fit together in an L-shaped manner is obviously inapplicable to a single bone in the forearm or leg, where the second bone splints it and keeps the ends apart. It can be used in such a case if the second bone is divided and stepped also, and this is a desirable procedure in a certain type of forearm injury, which will be discussed later. Stepping is particularly applicable to ununited fractures of the humerus, for the inevitable shortening is not a serious disability, unless it reaches extreme limits. In the case of the femur, shortening beyond 2 inches is a serious handicap, so that the method is only applicable to certain cases.

The great advantage of this method is that it can be utilized in the presence of infection, e.g., during the removal of sequestra, so that by the time healing has occurred union is also firm, and the patient is saved the long waiting period which otherwise would be necessary before any grafting operation was safe. In the arm, the cases where non-union occurs usually have scar tissue through its whole thickness, involving the main vessels and nerves, so that the radical excision advised above can seldom be carried out. It is therefore usually wise, when removing the scar or sequestra, to freshen and step the ends of the humerus without stripping periosteum more than possible, and then to ligature the ends with strong catgut, which serves to hold them together while a plaster-cast is applied, but comes away quickly if there is suppuration. If the cast is strongly reinforced in the axilla, large windows can be cut for the dressing, or indeed a whole lid, so that sepsis is no bar to its application. On the contrary, the rest which it offers by fixation is a most valuable factor in promoting healing.

The following cases illustrate the advantages of this method. They had all active or recent sepsis, and it is almost certain that other methods, such as grafting or plating, would have failed to secure union, and would assuredly have resulted in much more severe suppuration.

In connection with the subject of stepping bones, it may be well to say a word as to the advisability of shortening one bone of the forearm where the other is ununited. The dangers of this procedure are: (1) Non-union may result in the second bone, especially as the fragments are difficult to control when both bones are loose. (2) The second bone may become infected if a flare-up occurs. (3) There may be slack in the muscles which might interfere with their function. This last is a purely theoretical objection, as the

muscles adapt themselves with extraordinary rapidity ; but the two former ones are real and grave. They can be guarded against largely by shortening the healthy bone as a separate operation through an incision planned to avoid scar tissue ; unfortunately, if the fractured bone is not exposed at the same time, it is usually impossible to get sufficient overlap of its fragments to allow of subsequent apposition after trimming ; however, it is often sufficiently useful to reduce the gap between the ends without actually annihilating it.

There is one great indication for shortening the forearm which, in the writer's opinion, can be satisfactorily dealt with in no other way, namely, contracture of the radial tendons, and loss of skin and soft parts in cases of ununited radius, to such an extent that the skin would not meet over a bone-graft, while correction of the extreme radial deviation of the hand would not be possible. In such cases some surgeons lengthen the tendons, which are stretched like a bow-string across the defect in the bone ; but as the sutured tendons and the graft lie under a wide skin scar, adhesions are almost certain to impair their function, even if the skin does not actually slough away over them. On the other hand, if the ulna be shortened, the skin on the radial side will be so much relaxed that it is usually possible to excise the scar altogether, while the tendons attain a normal tension. It is extraordinary what good function the tendons have in some of these cases where they run through a mass of scar, so long as their sheaths are not opened by the surgeon. Non-union of the ulna only is very rarely an indication for shortening the radius.

In the case of the leg, the shortening is usually undesirable, but occasionally, with a septic ununited fracture of the tibia with malposition of the fragments, it may be wise to divide the fibula obliquely, so as to let it shorten, in order to get the fragments of tibia into line and contact ; if spontaneous union does not then occur, it will be much easier to get satisfactory union later by a sliding graft than if the ends were separated by much scar and were lying at an angle to one another. *Case 3*, recorded below, illustrates the advantage of this method. The following are cases where shortening of the ulna seemed advisable and gave a good result. In *Case 5*, the shortening allowed a contracture of the flexors of the wrist to be overcome, and the median nerve to be sutured across a gap, without reproducing the contracture by the need of flexing the wrist, which would otherwise have occurred.

FIG. 164.—Sgt. C. Ununited radius with much deviation—before operation.

FIG. 165.—The same patient as Fig. 164, after operation. Ulna shortened: sliding graft of radius. (The figure has been reversed in photographing.)

CASES WHERE FOREARM WAS SHORTENED FOR UNUNITED FRACTURE OF RADIUS.

Case 3.—Sgt. C., age 28. (Figs. 164, 165.)

March, 1918 : Wounded, gap fracture of left radius. *May :* Wound healed. *July :* Admitted to Bangour, with 1-in. gap in left radius and much deviation of hand. *Sept. :* Ulna shortened and united by step and autogenous bone-peg. Ulna united, but radius did not. *March, 1919 :* Radius

exposed, sclerosed bone removed, leaving gap of 1 in. ; a 4-in. sliding graft taken from upper fragment and laid across gap, whilst piece cut to make trough in lower fragment was placed in the gap. *June* : Union fair. Ultimate result excellent.

Case 4.—Rfm. G., age 30. (Figs. 166, 167.)

1919 : Wounded. *July*, 1919 : Admitted. Muscle contraction of fingers, radius had a 2½-in. gap with extreme deviation of hand. *Oct.* : Excision of wound scar. *Jan.*, 1920 : Ulna shortened by 2½ in., with shortening of extensor ulnaris tendon. *June* : Bone-graft from tibia to radius, which on account of sclerosed ends had not united. Plaster worn for ten weeks, at end of which radius was firmly united with hand in good position.

FIG. 166.—Rfm. G. Ununited radius; extreme deviation of hand—before operation.

The radius practically never unites unless it is exposed and freshened at the same time that the ulna is shortened. This procedure is, in the writer's opinion, seldom justifiable, on account of the risk of infecting the ulna from scar tissue, and also because the fragments are much more difficult to control when both bones are quite free; for although the radius is always ununited, yet its ends are much steadied by the scar tissue, and it forms a fulcrum in dealing with the ulna.

Case 5.—Pte. N. (Figs. 168, 169, 170.)

August, 1917 : Wounded.

March, 1918 : Admitted, the skin wound having just healed. Gap fracture of radius with fixed pronation and extreme radial deviation, median paralysis, contracture of wrist and fingers in flexion. *March* : Ulna shortened by 1½ in. over an autogenous intramedullary peg. Supination attained later by a series of plasters. *July* : Median nerve sutured. *Sept.* : Radius still ununited, ends refreshed, and sliding graft brought across the gap. Union unsatisfactory, so that radius became angulated. *Feb.*, 1921 : Useful function, but *x* rays indicated a false joint in the radius. This occurred because the sliding graft used was too small to stand the strain. Nerve recovered completely.

FIG. 167.—Same case as Fig. 166, after operation. Lower end of ulna removed; tibial graft.

The following case is instructive as showing the danger involved in shortening the forearm; it also illustrates one of the disadvantages of wires, but shows that a good result can be attained in the most difficult case, if surgeon and patient do not allow themselves to be discouraged by a previous failure.

Case 6.—Pte. Mc.G., age 35. (Figs. 171 and 172.)

Oct., 1917 : Wounded. Healed six months later. *Oct.*, 1917 : Admitted, gap fracture of radius with septic wound leading down to it. *Jan.*, 1918 : Sequestra removed, healed in ten weeks. *May* : Ulna shortened by ¾ in. and fixed by medullary peg. Ulna did not unite because the peg slipped out of place. *Oct.* : Ends of radius freshened and tied with tendon sutures. Union did not occur. *Feb.*, 1919 : Radius united by step-cut operation, primary healing, but non-union. *May* : Both bones exposed, stepped, and wired. Plaster. *July* : Inlay graft from tibia to radius, which was tied in place by wire. Non-union of graft at upper end. *Dec.* : Wires removed, ends of bone refreshed; plaster. Feeble union. *Feb.*, 1920 : Ulna treated by a sliding graft. *July* : Both bones firmly united.

The interesting points about this case are :—

1. That the methods of fixation which are commonly supposed to give mechanical stability failed to do so, but did interfere with callus formation.

FIG. 168.—Pte. N. Ununited radius; much deviation and contractures—before operation.

FIG. 169.—Same case as *Fig. 168*, after first operation. Ulna shortened; intramedullary peg.

FIG. 170.—Same as *Fig. 168*, after second operation. Small sliding graft of radius.

FIG. 171.—Pte. McG., after tibial graft of radius. Wire and necrosed upper end of tibial graft have been removed; wire of first operation still on ulna.

FIG. 172.—Same case as *Fig. 171*, later. Radius now united; sliding graft of ulna uniting well. Note increase of callus on radius since removal of wire.

2. That union was finally attained by very simple methods when the bones were extensively rawed, and fixed just enough to prevent displacement till a cast was applied; there was then no interference at all for four weeks, after which a second cast was most carefully applied and worn another four weeks. In these cases, where some factor has prevented primary union of a fracture, it seems to take about eight weeks for any union to stand strain; in other words, the rules which can be applied to most simple fractures do not hold with these cases.

STEPPING FOR UNUNITED FRACTURE OF HUMERUS.

Case 7.—Pte. N., age 28.

May, 1918: Wounded. *Sept.:* Admitted. Septic wound leading down to comminuted fracture of humerus. Ulnar paralysis. Arm in straight Thomas splint. *Oct.:* Removal of small sequestra, large fragments with periosteal attachments left in place. *Dec.:* Further sequestra removed; arm and chest put up in plaster, with windows for dressings. *April, 1919:* Fracture exposed; further sequestrum and much scar tissue removed from between the fragments. Fragments shaped like steps and united by wire, which had subsequently to be removed. In attempting to flex the elbow, the olecranon was fractured. *July:* Fracture united. Ulnar nerve sutured.

FIG. 173.—Cpl. R. After operation. Humerus stepped; united.

Case 8.—Pte. J.

Ununited comminuted fracture of lower end of right humerus with fixed elbow. Step-cut operation, the fragments being tied together with tendon sutures. Some sequestra were removed. The elbow was forcibly straightened and the hand supinated, whilst the lower humeral fragment was held in a lion forceps. Put up in plaster case which included the chest and forearm. Plaster removed in six weeks. After ten weeks the fracture was firm and the elbow had a range from 90° to 130°. Rotation of hand for about half a circle.

Case 9.—Cpl. R.
(Fig. 173.)

Septic comminuted fracture of middle of humerus. *May, 1920:* Step-cut operation on humerus with removal of sequestra; some pus was present. Fragments drilled and tied with tannic catgut. *Sept.:* Humerus well united. Sequestrum removed. *Oct.:* Tendon transplantation for musculospiral paralysis.

In this, as in the other cases quoted above, any attempt to restore the normal length of the limb by grafting would have meant an indefinite postponement of recovery, while waiting for the sepsis to subside; or, if attempted early, would almost certainly have been doomed to failure.

The following case illustrates the failure of plating before the sepsis was quiescent, while stepping gave union under the same conditions. Incidentally, the reaction caused by the plating induced a paralysis of the musculospiral, which cleared up after union had occurred.

FIG. 174.—Pte. M. After operation. Humerus stepped; united.

Case 10.—Pte. M., age 22. (*Fig. 17.*)

May, 1918: Wounded. *June:* Fragments of bone removed from humerus. *Feb., 1919:* Further sequestra removed. *April.* Humerus plated, wound left open and treated by Carrel-Dakin method. Musculospiral paralysis appeared. *Aug.:* Plate removed because the wound had not healed. *Feb., 1920:* Step-cut operation with catgut fixation. Plaster-cast including chest and forearm. Slow after-progress with removal of sequestra. Gradual improvement of musculospiral paralysis. *Feb., 1921:* Union.

FIG. 175.—Pte. P. Ununited humerus, before operation.

FIG. 176.—Same case as *Fig. 175*, after operation. Humerus stepped; united; some bowing, but good function.

Case 11.—Pte. P. (*Figs. 175, 176, and 177.*)

This fifth case showed a similar course, except that the sepsis was less active and union occurred much earlier.

The skiagrams show that there was some forward bowing after union, but this gave no disability. In this case there was no interference with the forearm branches of the musculospiral, but those to the outer and inner heads of the triceps had been destroyed, with the corresponding segment of humerus, by the bullet; the long head worked, but this loss and adhesions of the biceps interfered somewhat with the function of the limb.

This illustrates a point which should never be lost sight of in these cases of

FIG. 177.—Same case as *Fig. 175*. Photograph to show amount of shortening.

ununion fracture, namely, that the injury severe enough to cause non-union has usually done irreparable damage to other structures besides the bone, and the repair of the latter alone is seldom sufficient to restore usefulness to the limb.

The sixth case of this series failed to get union by the stepping operation, but sufficient stability and shortening were obtained to enable the musculospiral nerve to be sutured easily. A bone-graft operation was intended to be done when the sepsis was likely to be quiescent, but the man has failed to return for this so far.

Case 12.—Pte. C. R., age 28.

Sept., 1918 : Wounded. Fracture of humerus, with musculospiral paralysis. *July*, 1919 : Removal of sequestra. Distal fragment impacted into proximal, and tied by tendon sutures. These slipped whilst plaster was being applied. *Oct.* : Step-cut operation ; ends of bone drilled and tied together. Non-union persisted. *May*, 1920 : Musculospiral nerve sutured. *July* : Patient transferred and lost sight of.

SHORTENING TIBIA.

The following case shows that the method of shortening and stepping a bone may occasionally be applicable to the bones of the lower limb, though the serious disability entailed by much shortening usually contra-indicates it there. In a case like the following, where the presence of deep sequestra necessitated an extensive operation, while the sepsis would delay any grafting operation, the other procedure is valuable, as well as much speedier.

FIG. 178.—Pte. C. Ununited tibia, before operation.

Case 13.—Pte. C., age 20.
(Figs. 178, 179.)

Sept., 1918 : Wounded, comminuted fracture of tibia and fibula. *Oct.* : Admitted, open gap fracture of tibia with overlapping fracture of fibula. Plaster case from groin to toes. *June*, 1919 : Union of fibula divided and fragments allowed to overlap further. Tibia cleaned, lower end impacted into upper. *Nov.* : Allowed to walk with leg-iron. *July*, 1920 : Wound healed, can walk without support. Shortening of $1\frac{1}{4}$ in.

In the above case, the extensive destruction of soft parts over the site of fracture, and the virulence of the sepsis, would have jeopardized the vitality of any graft.

The case also illustrates the advantages of the ambulatory treatment of such injuries in plaster, for from the moment the cast was

FIG. 179.—Same case as Fig. 178, after operation. Pointed lower fragment of tibia wedged into cavity in upper end, after freeing fibula ; union.

applied the daily dressing became painless ; the man was able to benefit by fresh air and bodily exercise and social intercourse ; and the nursing of the case was reduced to a minimum, which was an important consideration in those days of overworked staff. In fact, although the man had a most tedious and disabling lesion, yet he was able almost to lead the life of a normal individual.

Method 2.—SMALL BONE-GRAFTS.

The following cases illustrate the value and limitations of the use of small chips of bone from the iliac crest, sown between the bone-ends to fill in a gap. The advocates of this method point out that it gives the maximum of raw bone surfaces, and therefore, presumably, the maximum escape of living osteoblasts, on whose activity the success of all bone-grafting operations depends; moreover, the bone used is of a very vascular type. The opponents of the method point out that it provides no primary mechanical stability, as does the intramedullary peg, and they assert that these small fragments become isolated and tend to absorb after a time, even if at first they increase in size by new growth of bone. The following cases show that they may survive for periods of one or two years, and during that time produce a great improvement in the limb, which one can scarcely believe will be lost later. In the cases quoted, the grafts formed considerable masses of bone, but did not cause bony union of the shafts between whose fragments they were placed. This suggests that the mean view is the just one in this as in most controversies, so that while these grafts have their value as a source of new bone, yet they need to be supplemented by the addition of an inlay or peg graft, if a bony ankylosis is desired. These iliac grafts are indicated for large gaps in thick bones, for which a bridging graft of equal diameter cannot be obtained, and also to replace the enlarged end of a bone, where a joint is flail from its destruction.

FIG. 180.—Pte. B. Flail elbow; loss of humeral condyles and olecranon.

FIG. 181.—Same case as Fig. 180, after first operation (chips from ulna sown in gap).

All the three following cases had a loss of at least 2 in. of the humerus: in one the lower end, in the second 1 in. above the elbow, and in the third at the middle of the shaft. In each case the limb was flail and quite useless before the operation. In each, after operation, a mass of bone formed and filled the gap; and though the union remained fibrous, being short it was stable, so that the strain was reduced to a minimum, which much simplified the further plastic procedures that were undertaken. In the case of the flail elbow, after repair of the triceps tendon, the joint remained movable and useful for light work, which the man, being a clerk, preferred to an ankylosis. One of the humerus cases also regained control of the limb even while the union was fibrous.

Unfortunately, the skiagrams of the conditions before operation got broken at an early stage.

FLAIL ELBOW TREATED BY CHIPS OF BONE FROM ULNA.

Case 14.—Pte. B. (Figs. 180, 181.)

April, 1918: Wounded, comminuted fracture of lower end of humerus, treated by immediate resection of the condyles of the humerus, resulting in a flail elbow. *July:* Scar tissue excised, bones forced together and sutured by periosteum. Elbow kept in successive windowed plasters till *Dec. Jan., 1919:* Ends of bone sawn off, divided up into small chips, and planted round. Kept in plaster till *June.* Much lateral mobility remains. *Sept.:* Triceps tendon reconstituted by turning up a flap from ulnar periosteum. *Jan., 1920:* Bones refreshed, humerus placed in front of ulna and fixed by a nail through the skin. *May:* Lateral mobility cured; can lift a chair and put hand to mouth.

UNUNITED HUMERUS TREATED BY CHIPS OF BONE FROM ILIAC CREST.

FIG. 182.—Capt. L. After first operation (wired).

FIG. 183.—Same case as Fig. 182, after second operation (chips from iliac crest sown in gap).

FIG. 184.—Same case as Fig. 182, 8 months later. Fibrous union, but limb stable (chips survive).

FIG. 185.—Same case as Fig. 182. Still fibrous union; chips survive 9 months after operation.

Case 15.—Lieut. A.

April, 1918: Wounded. Fracture of humerus with musculo-spiral paralysis. Loss of $2\frac{1}{2}$ in. of humerus. *Aug.:* Foreign body removed and abscess drained. *Jan., 1919:* Ends of humerus refreshed and wired, more débris being removed. *Sept.:* Ends of bone refreshed and the gap filled by chips from the iliac crest. *June, 1920:* Non-union persists. Intramedullary graft from tibia, together with further chips from iliac crest. (Further progress unknown.)

Case 16.—Capt. L. (Figs. 182, 183, 184, 185.)

Oct., 1917: Bomb wound, 2 in. blown away from left humerus. *March, 1918:* Bone-ends refreshed. One separated fragment used as an intramedullary graft. *Oct.:* Non-union. Bone-ends freshened and tied with kangaroo tendon. Plaster. *June, 1919:* Humerus step-cut and wired. *Oct.:* Non-union; wire removed; bones refreshed and gap filled with chips from iliac crest. *June, 1920:* Still some movement at fracture, but fair voluntary control of limb. Tendon transplantation for musculospiral paralysis.

Method 3.—SLIDING GRAFT.

The sliding graft is one of the simplest, and in many cases a most satisfactory one. Its advantages are that, coming from the very bone to which it is to be applied, it corresponds exactly in structure to the host, i.e., in the proportion of cancellous to ivory bone, etc.; moreover, it is quickly applied in its new bed, so that there is no fear of its suffering from cooling or excessive handling.

The disadvantages are that it is not nearly the calibre of the missing part which it has to replace, nor can it usually be taken large enough to withstand strain. For this reason it should not be relied upon alone where any but the shortest gap has to be bridged.

The sliding graft is most effective in dealing with non-union of the tibia when the ends of the bone are almost in contact; if they are first freshened and placed in line, and then the Albee's saw is run continuously down from one fragment to the other, a graft will be cut from the longer fragment which fits exactly into a groove in the shorter one, the piece of bone removed from this latter being utilized to lie beside the other at the gap between the bone-ends, so that the two together practically restore the original calibre of the bone.

FIG. 186.—Dvr. H. Ununited ulna, after first operation (trimming ends).

FIG. 187.—Same case as Fig. 186, after second operation (intramedullary graft from tibia).

The radius is another bone which adapts itself to sliding grafts, especially when the gap has been obliterated by shortening the ulna. The graft is best sliced up with a very wide gouge, which peels it up like a wood-shaving, the curve of the gouge just preventing splintering. A corresponding area on the shorter fragment is rawed by the gouge, and then the graft tied to both fragments by iodine-tannic catgut ligatures (Nos. 2 or 3).

The ulna being a less vascular bone than the radius, with usually a considerable thickness of sclerosed bone at the common site of non-union in the upper third, it is less often suited to the sliding graft. Two of the following cases, however, show that it can be useful. The case quoted above (Sgt. C., *Case 3*) shows the excellent result which can be obtained on the radius.

Successful cases of sliding graft of the tibia are common in every orthopaedic hospital, and illustrate no special point to make them worth recording.

Case 17.—Dvr. H. (*Figs. 186, 187.*)

Sept., 1917: Wounded. *Feb., 1918:* Ununited fracture of ulna. Operation for cleaning ends of bone. *May:* Graft from tibia driven into lower fragment, and wedged against side of upper

fragment. *Aug.*: Non-union between upper end of graft and upper fragment. *Dec.*: Sliding graft from lower fragment and first graft, over the gap—united by catgut. *April, 1919*: Good union, good function.

This case shows that even a large intramedullary graft does not necessarily give mechanical stability, while union was ultimately obtained by a small sliding graft, which appeared to fulfil better the essential condition of wide exposure of raw bony surfaces.

The next case is similar, except that the first sliding graft failed to give union, probably because too small a fragment was used; whereas, when the operation was repeated and a large slice used, good union resulted.

Case 18.—Pte. C. (*Figs. 183, 189.*)

FIG. 188.—Pte. C. Union after intramedullary graft from tibia (false joint).

FIG. 189.—Same case as *Fig. 188*, after sliding graft, taken partly from surface of previous graft; good union.

July, 1916: Wounded. *Feb., 1917*: Healed. *May*: Admitted, ununited fracture of ulna. *Sept. 17*: Sequestra removed and scar excised. *Nov.*: Intramedullary graft from tibia to ulna. *June, 1918*: Non-union between upper fragment and graft; small sliding graft from upper fragment placed across gap. *Feb., 1919*: Union still weak. Long sliding graft from the upper fragment placed on deep surface of gap. *May*: Good union.

The following case, where the precaution of first excising the scar was omitted, had severe recurrences of sepsis, yet united by means of a sliding graft; probably a large tibial graft in such a case would have acted as a foreign body, and come away without giving union.

Case 19.—Pte. M.

Oct., 1918: Wounded. *Nov.*: Admitted. Ununited fracture of ulna. *Nov.*: Sequestra removed, and bones refreshed and tied together with catgut. *Sept., 1919*: Sliding graft. No preliminary excision of scar. Slight suppuration. *Jan., 1920*: Small sequestrum removed. *Sept.*: Firm union.

The following case is another in which the sepsis was very persistent, the precaution of excision of the scar having also been omitted; intramedullary grafting and wiring both failed, while a sliding graft ultimately succeeded, although the sepsis was not yet quiescent.

Case 20.—Pte. II., age 24.

Aug., 1917 : Wounded. *Aug.*, 1918 : Healed. *May* : Admitted, ununited fracture of radius, mal-union of ulna. *June* : Sequestra removed from radius. *Jan.*, 1919 : Ulna shortened by $1\frac{1}{2}$ in., ends tied with wire. *June* : Wire removed, non-union. *Oct.* : Sliding graft of radius. Suppuration. *March*, 1920 : Good union.

The following case exhibited an interesting mal-union of the forearm bones, which was successfully dealt with by excision of the head of radius, to allow rotation, and sliding graft of ulna after correction of the deformity. It appeared from the history that

FIG. 190.—Pte. McK. Ankylosed elbow ; mal-union of radius and ulna after manipulation.

FIG. 191.—Same case as Fig. 190, after first operation. Excision of head of radius and stepping ulna.

ankylosis of the elbow had occurred in the extended position, and that a surgeon had attempted manipulation under anæsthesia, which had resulted in flexion at the fracture of radius and ulna in upper third of the forearm, which also remained fixed in supination. This deformity interfered with the pull of all the forearm muscles, which rapidly improved after it had been corrected, so that it would not have been wise merely to correct the supination, as some surgeons who saw the case advised. This case also illustrates the danger of keeping compound fractures of the forearm long in the straight position. The Thomas splint is excellent for immediate application, to allow drainage ; but as soon as the sepsis is subsiding the elbow should be flexed, if necessary under anæsthesia, and usually the limb can be satisfactorily fixed in plaster, with windows for the wounds. If the manipulation is done at an early date, and the precaution taken of splinting the fracture with gutter-splints before it is begun, the joint will yield rather than the fracture ; if it does not, it is best left for open operation after the fracture has united.

FIG. 192.—Same case as Fig. 190, after second operation. Sliding graft of ulna ; union, elbow in good functional position ; good rotation of forearm.

Case 21.—Pte. McK., age 29. (*Figs. 190, 191, 192.*)

April, 1918 : Wounded. *Feb.*, 1919 : Healed. *March* : Admitted. Fracture of radius and ulna in upper third of forearm united at right angles. *July* : Removal of head of radius, wedge

removed from site of ulnar fracture, ends of bone stepped and tied with kangaroo tendon; muscle placed between the radius and other bones. *Oct.*: Weak union of ulna with ankylosis of elbow. Sliding graft of ulna. Humerus and ulna separated through open incision. Good union of ulna followed, but the upper part of graft was extruded. Elbow movements remained limited, but rotation of forearm was good.

The following case represents the course and treatment of an uncomplicated sliding graft of the tibia. These cases are among the simplest and most satisfactory with which

we have to deal, and it is unnecessary to record more than one in detail. The difficulties which may be encountered are: firstly, backward bowing, which is most safely corrected by a preliminary operation, with excision of scar tissue and the application of plaster in the corrected position; secondly, lack of active bone when the upper fragment consists of the head of the tibia only, so that the upper end of the graft is apt to lie loose in a cavity and become surrounded by clot which, when it organizes, will produce a fibrous union; in such a case it is best to supplement the sliding graft by one from the other tibia, so that the cavity is obliterated by pieces of bone; thirdly, if the patient walks too early without support, he is apt to break the graft, and spontaneous union is rare after such an accident.

FIG. 193.—Pte. T. After operation. Sliding graft of tibia; small fragment also placed in gap; good union of both.

Case 22.—Pte. T. (*Fig. 193.*)

July, 1918: Wounded. *Oct.*: Healed. *May, 1919*: Admitted, with gap fracture of tibia. *Aug.*: Sliding bone-graft of tibia. Plaster. Walked with plaster on until *Oct.* *Nov.*: Outside leg-iron fitted. Good result.

Method 4.—INTRAMEDULLARY GRAFTS.

The idea of the intramedullary graft is to fix the two fragments of bone in contact and in perfect alignment by means of a bone peg driven into each medullary cavity.

Ideal as this seems in theory, its practical application is by no means so simple. Firstly, it is often impossible to get the ends of the bone far enough apart to allow of the introduction of the peg into both fragments; this difficulty has been circumvented by some surgeons by putting the peg into the side of one fragment, which, however, is not certain to give the stability which is theoretically obtainable in the other way. The method of driving the graft in from one end of the bone, through the skin, while overcoming this drawback, has considerable technical difficulties.

Secondly, the medulla of the forearm bones has so small a bore that the part of the graft which enters it has not much strength and is apt to break, even if the part between the bone-ends is left thicker, like a cricket-bail.

Thirdly, the area of raw bone from which osteogenesis is to spread is less in this method than in those where a large area on the side of the bone is freshened; indeed, as shown by repeated *x-ray* examination, the very place whence the maximum of early callus is formed, the medulla, is corked up by this method.

The graft also plugs the most vascular part of the bone, from which new vessels should develop to nourish the graft, the clot from the open medulla being probably the source of these. Many *x-rays* of intramedullary grafts show a zone of rarefaction around the implanted end of the graft, similar to that which is apt to develop round a wire or plate, suggesting that it interferes with the nutrition of the neighbouring bone, and acts almost like a foreign body.

The intramedullary graft is useful in maintaining apposition of the ends of the humerus or femur, but it is safest to supplement it by a lateral graft.

The advocates of the intramedullary method have numerous excellent results to show in its support; nevertheless they have always a certain number also where a false joint has formed at one end, and these appear to be in the very cases where there is special strain on the graft, which is the complication that the intramedullary graft was designed to overcome. The upper third of the ulna, where the upper fragment tends to be deflected outwards and backwards, is a notable instance of this. The following cases illustrate the point. In the writer's experience there is less tendency to false-joint formation with the lateral grafts.

A considerable number of cases have been recorded above where intramedullary grafts failed to give union, and some other method had to be resorted to later. These have given the writer an unfavourable impression of the intramedullary method, especially as the operations were nearly all carried out by, or under the immediate supervision of, surgeons who had considerable experience of the method in civilian surgery before the war.

The cases already referred to are: Pte. McG., *Case 6*; Pte. C., *Case 18*; Dvr. H., *Case 17*.

One case already described gave an excellent result, but in it the grafted bone was healthy, i.e., the ulna, when the forearm was being shortened: Pte. N., *Case 5*.

Method 5.—INLAY GRAFTS.

Inlay bone-grafts form, in the writer's experience, the most satisfactory method of dealing with an ununited fracture, where any considerable deficiency of bone exists.

In its original form, as described by Albee, the inlay graft was fitted with the accuracy of a cabinet-maker into its bed, which, though a simple process in theory, is by no means so when applied to actual bones with their natural irregularity, besides that acquired through the trauma. However, as we are not dealing with inert wood, where mechanical stability is of primary importance, but with living bone, which can and will modify its structure in accordance with outside conditions, other considerations are of more importance. Thus, the most accurate carpentry will not provide a union strong enough for satisfactory function if the blood-supply is deficient or the osteoblasts are so inactive that they do not weld the graft and host into one living whole; indeed, many grafts which give excellent *x*-ray appearances immediately after operation are found to absorb or break in course of time. On the other hand, a graft which only fits roughly into its bed, but is thick enough to stand the initial strain and consists of vascular active bone in a similar bed, will unite rapidly and firmly, while ultimately the lines of stress will modify the form of the new bone, so that an approximation to the normal type is attained. In other words, the essentials are: (1) That the graft be thick and vascular; (2) That it be applied to as large a raw area of the host as possible; (3) That the maximum area of cancellous bone be exposed, consistent with stability; (4) That the junctions of the graft with host be protected from all strain until callus unites them (usually four to six weeks), and then be subjected to small degrees of strain, such as muscular contractions against resistance (i.e., without movement), whereby the new bone is stimulated to grow and to harden.

These conditions can usually be attained by the use of grafts cut from the subcutaneous surface of the tibia, with its periosteum, which ensures the retention of the surface osteoblasts; the graft is applied to slots which have been cut on corresponding surfaces of the two fractured ends; the graft is held by ligatures of iodine-tannic catgut, which prevent displacement while a plaster cast is being applied. The plaster is worn for about four weeks, being merely split on one aspect if the limb should swell unduly; then it is valved for removal of the stitches and massage, and is retained for about another four weeks, or to whatever period is required for firm union. Periodic *x*-ray examination of cases with non-union suggests that early and excessive strain on the graft is, next to sepsis, the commonest cause of failure.

The following case records, with their skiagrams, show what satisfactory results can be obtained by a technique which is absolutely simple. The only special experience which it requires is in the use of the electric saw and in the application of plaster. A cast applied at the operation must be applied very evenly and over a thick layer of wool, which must also be evenly distributed; this precaution usually compensates for any swelling that may occur; in certain cases there may still be excessive swelling, but if the cast is split down the whole length (not merely a portion) of one aspect, i.e., the one where strain is least, then the œdema will rapidly subside and there will be no tendency to deformity. In the upper limb, if the digits are carefully left free so that the act of closing the fist can be carried out, this will provide a degree of function which stimulates bone-growth without straining the graft. In the lower limb, a cast which fits well enough to allow walking attains the same end. The writer has found the application of a plaster metatarsal bar very effective in preventing weakening of the footpiece of the cast with the consequent tendency to equinus. Even if the patient is foolish enough to walk out in the damp with the cast, a thick metatarsal bar will usually hold the foot firm.

The fact that the graft can act as a source of new bone seems proved beyond possibility of error by the following case, in which a wide gap in the ulna had been bridged by a piece of tibia, and good union had occurred at the ends of the graft; then the patient snapped the graft in its centre, far from the original ends of the ulna, yet union occurred within a few weeks by ensheathing and central callus. It does not appear from the *x* rays that the fresh callus could have had any other source than the graft, as the latter had not been in place long enough to have been reconstructed *in situ*, as most grafts seem to be ultimately.

Case 23.—Pnsr. R. (Fig. 194.)

Dec., 1918: Kicked by horse. *May, 1919:* Ulna plated. *Feb., 1920:* Admitted. Ununited fracture of ulna, screws having become loose. Man could not lift a weight. *Feb.:* Sliding graft of ulna, after removal of plate. *June:* Non-union. Tibial inlay graft. Bone-ends trimmed until

FIG. 194.—Pnsr. R. Graft uniting spontaneously by lateral and central callus.

a 2-in. gap was left, deep aspect of each fragment rawed for $1\frac{1}{2}$ in. Five-inch tibial graft tied in place with catgut. *Jan., 1921:* Returned with fracture of graft in its centre, the result of heavy work. Ends well united. Plaster applied for three weeks, after which callus union occurred on the deep surface of the graft, away from the ulna. Firm union after nine weeks.

The following case illustrates the value of a strong tibial graft as a source of bone in one of the most disabling injuries with which the orthopaedic surgeon has to deal, i.e., a flail shoulder in which about the upper half of the humerus has disappeared. In the case quoted, if an attempt had been made to fix the upper end of the shaft in the remains of the glenoid, the limb would have been shortened beyond use; moreover, it is unlikely that any form of ankylosis could have been attained, with so much strain on the union. Here a tibial graft resulted in a fibrous ankylosis without excessive shortening, and such as restored useful function to the limb, even though far short of the normal.

Case 24.—Sgt. McC., age 22. (Figs. 195, 196, 197.)

Nov., 1916 : Wounded left shoulder, bone freely removed. May, 1917 : Healed. July : Admitted. Flail shoulder, with about 4 in. missing from upper end of humerus. July : Graft from tibia, $3\frac{1}{2}$ in. long, driven into humerus. Arm in abduction splint. Aug. : Upper end of graft had slipped out of glenoid ; replaced, arm and chest put up in plaster. May, 1918 : Good function ; can lift arm to occiput and carry moderate weights.

FIG. 195.—Sgt. McC. Flail shoulder ; loss of 4 inches from upper end of humerus.

FIG. 196.—Same case as Fig. 195, after operation. Bone-graft from tibia (slipped out of glenoid).

FIG. 197.—Same case as Fig. 195, one year after operation : shoulder stable ; graft much thicker ; much new bone formed.

The following two cases illustrate the course of uncomplicated forearm fractures treated by inlay grafts from the tibia.

Case 25.—Pnsr. M., age 22. (*Fig. 198.*)
Oct., 1918 : Wounded. *Feb.*, 1919 : Healed. *May*, 1920 : Admitted. Non-union of ulna just above the middle ; ulnar deviation of hand and inability to lift. *Sept.* : Inlay tibial graft, 5 in. long, applied to the deep surface of ulnar fragments. Four months later union firm and function good.

FIG. 198.—Pnsr. M. Lateral graft from tibia to ulna ; firm union.

Case 26.—Pte. S., age 22.
July, 1916 : Wounded. *Feb.*, 1917 : Healed. *Jan.*, 1917 : Admitted with gap in middle of radius. *March* : Bone-graft from tibia to radius 4 in. long, tied to deep surface of radius by fine wire. Wound broke down several times. *Dec.*, 1918 : Wound healed finally. *March*, 1918 : Firm union, good function.

In this latter case, it is likely that the wire helped to keep alive the sepsis and induced the bone necrosis noted above. It is astonishing that the flares were so mild, considering the short period for which wounds had been healed before the operation. This was one of the earliest cases done at Bangour, before the prophylactic and diagnostic value of heavy massage had been realized and become a routine.

In the space at our disposal it is impossible to give in detail all the cases which are instructive, but it is hoped that the study of those recorded above may impress on the reader the common difficulties and sources of error. They have been chosen among the ones which presented difficult problems, or in which some procedure, commonly recommended, had failed, either from its being unsuitable to the type of case, or from errors in the execution. While some of them are depressing reading, as records of repeated failure, yet they show that in almost all cases success can ultimately be attained, if the patient and surgeon both possess patience and determination.

Method 6.—PLATING.

Of the use of plates the writer cannot speak from personal experience. A certain number of failures after this method have come for further treatment, and union has been attained by the methods described above. Although all methods result in some failures, the following considerations appear to the writer to weigh seriously against the use of metal plates :—

1. After gunshot injuries there is the ever-present fear of a recrudescence of sepsis, and this risk is increased by the presence in the tissues of a foreign material, such as a plate ; if a flare-up should occur, it will not subside till the metal is removed, which probably entails a second operation ; whereas a certain number of bone-grafts unite even in the presence of sepsis ; and if they do not, the dead bone tends to break up and come away spontaneously without much delay.

2. Metal tends to cause an area of rarefaction in the bone immediately surrounding it, which is well shown by *x* rays, so that screws are apt to become loose, and the very mechanical stability, which was the chief recommendation of the metal, is annihilated.

This effect is most marked in the presence of strain, i.e., in the very cases where other methods are difficult.

3. Non-union is usually associated with sclerosis of the bone at the site of fracture, and mere fixation of such avascular ends is usually insufficient to induce the formation of sufficient callus. When a vascular graft is applied and the atrophic bone trimmed away, then absolute fixation is found to be unnecessary; indeed, a wire or plate is apt to interfere with the vitality of the graft.

4. Even when plates are used, it is usually necessary to supply some outside support also; whereas, when plaster is applied, the temporary fixation of catgut is enough to prevent slipping while the cast is being put on, so that the strength of the metal is no advantage, while, as noted above, it does not always retain a good hold after the month at the end of which the plaster is removed.

Method 7.—GRAFTS OF IVORY OR BOILED BONE.

Of heterogenous grafts and those of ivory or dead bone the writer has no personal experience. Many of the arguments used against metal apply to them, and as there is always in the patient's tibiae and iliac crests a supply of living bone of various types, it is difficult to see the indication for these extraneous materials.

One final point is worthy of careful attention, i.e., that in cases of non-union after gunshot injuries the condition of the bone is only one factor in the patients' disability, not always the most important one. Usually several muscles have been shot away with the bone which leaves the gap; often a nerve is cut or compressed; more often still the severe sepsis which may have helped to prevent bony union has left tough adhesions in or around the joints. If these conditions are not treated adequately, the most perfect bone operation will merely have put the patient to much inconvenience and some suffering without improving the function of the limb. For instance, non-union of the radius in the lower third is nearly always accompanied by loss of the extensors of the thumb, and without them the thumb is almost useless, and accordingly the whole limb almost functionless; in the upper-third fractures it is the posterior interosseous nerve which has suffered, and unless its muscles are restored by some form of tendon-transplant, the hand is valueless. Similarly, severe fractures of the tibia are apt to interfere with the tibialis anticus, one of the most important muscles of the lower limb. These remarks may seem unnecessary, as the logic of the matter is obvious on paper; but it is extraordinary how often this aspect of a case is overlooked in practice, unless a routine of examination for the joints, muscles, nerves, and blood-vessels is carried out in every case of injury to a limb.