Autogenous Cortical Bone Grafts in the Reconstruction of Segmental Skeletal Defects

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ABSTRACT: The results of using segmental cortical autogenous bone grafts to reconstruct defects created by resection of tumors were analyzed in forty patients. Thirty-three patients had dual grafts while seven had a single fibular graft. Dual grafts were used for major bones (humerus, femur, and tibia without fibula) while single grafts were used for the radius and for the tibia when the ipsilateral fibula was intact. Thirty patients had good or excellent results; seven, fair; and three, poor results. In twenty-five patients primary union was achieved within twelve months and in two, in twenty months, while twelve patients required a second, supplementary cancellous graft at the site of non-union to obtain stability. One patient required removal of an infected graft and had a poor result.

Stress fractures of the grafts occurred in eighteen of the forty patients after union had occurred. The stress fractures healed in fifteen of these patients: in six with no treatment (the fracture was identified retrospectively), in seven with external immobilization, and in two after bone-grafting of the ununited fracture. There were three persistent non-unions of stress fractures despite bone-grafting, internal fixation, and electrical stimulation, and these account for two of the three poor results.

The length of the defect did not affect the incidence of non-union but it did affect the number of fatigue fractures. The shorter grafts (7.5 to twelve centimeters) were associated with a 33 per cent incidence of non-union (four non-unions of twelve grafts) while the longer grafts (twelve to twenty-five centimeters) had a 32 per cent rate of non-union (nine non-unions of twenty-eight grafts). The incidence of fatigue fractures in the longer grafts (58 per cent) was much greater than that in the shorter grafts (17 per cent).

The grafts decreased in density during the first six months but gradually regained their mass and were generally comparable to normal cortical bone at two years. As the patients became functional, most (55 per cent) of the grafts became more dense than normal, some (34 per cent) remained the same, and a few (11 per cent) became less dense. Similarly, some (32 per cent) hypertrophied, most (58 per cent) remained the same size, and a few (9 per cent) atrophied. There was little morbidity (three of forty patients) associated with graft procurement.

In twelve patients an additional graft was implanted experimentally, labeled with tetracycline, and subsequently removed at the time of a secondary procedure. These grafts were analyzed to determine if human grafts were repaired in the same fashion as grafts in experimental animals. The studies showed that human grafts are repaired in the same fashion, but that the sequence takes approximately twice as long as it does in the dog.

There is almost unanimous agreement that autoge-
nous cortical bone grafts furnish the best method for reconstructing significant skeletal defects. Numerous substitutes (various types of allografts, xenografts, and prosthetic devices) have been proposed because of the often-cited disadvantages of autogenous segmental cortical grafts—that is, morbidity and disability at the site where the graft was removed and inadequate graft material for prevention of late fatigue fractures. It has been believed that segmental, autogenous free cortical bone grafts incorporate very slowly at best, that their ability to hypertrophy is "nil and perhaps absent", and that spontaneous fractures are common and defeat the purpose of the grafts. More recently, autogenous cortical grafts with microvascular repair have been advocated to provide a viable graft to ensure union, incorporation, and subsequent hypertrophy. During the past two decades, the majority of major segmental skeletal defects created by tumor resection at the University of Florida have been reconstructed by free segmental autogenous cortical bone grafts. An analysis of the results of these procedures was carried out in an attempt to answer the following questions: (1) How often did the grafts become incorporated and provide the desired stability? (2) What were the disabilities at the sites of graft procurement? (3) What were the functional results in these patients? (4) What factors influenced union and fatigue failure? (5) Were human autogenous cortical grafts repaired in the same fashion as such grafts in experimental animals?

The answers to these questions were sought in order to permit future comparisons of the effectiveness of this method of reconstruction by living autogenous grafts with that of microvascular repair, allografts, and prosthetic devices.

Materials

The age, sex, diagnosis, anatomical site and size of the defect, type and source of graft, type of stabilization, use of primary and supplementary junctional grafts, ultimate stability, length of follow-up, and functional results are shown in Table I. Other patients seen during this period of time whose defects were reconstructed by segmental grafts were not included in the study because of: (1) the use of allogeneic grafts; (2) insufficient follow-up due to death from metastasis or unavailability for review; (3) subsequent amputation due to local recurrence; (4) defects caused by non-neoplastic problems; or (5) large defects that were not segmental in configuration. All of the patients in this study were free of recurrence at the time of review. Thirteen of our patients (noted by an asterisk in Table I) were part of a previous study whose purpose was to emphasize surgical selection, technique, and tumor control rather than the fate of the grafts. It should be noted that twelve of the forty patients were followed for less than three years, so there is still some risk of a late fatigue fracture. There were twenty male and twenty female patients, with an age range of ten to sixty years. Nine patients had open and thirty-one had closed physies at the time of grafting. Table II shows the time to primary union of graft junctions, site and treatment of junctional non-unions, site and treatment of fatigue fractures, subsequent quality of the grafts, complications of obtaining the grafts, and comments on each patient.

The most frequent lesion was a Stage-IA, intraosseous, potentially malignant or low-grade malignant tumor (Table III). Seven patients had resections of Stage-II high-grade malignant lesions, with five of them receiving chemotherapy at various points in the post-operative course (Table II).
Figs. 2-A and 2-B: Case 36. A twenty-eight-year-old woman had a single fibular reconstruction of a 14.5-centimeter defect of the tibial shaft resulting from resection of a Stage-IA chondrosarcoma.

Fig. 2-A: A series of lateral roentgenograms made six, eight, ten, and sixteen months after grafting. A segment of the contralateral fibula was secured as a graft within the distal part of the medullary canal by a transfixing wire. Proximally the graft was impaled into the cancellous proximal part of the tibia and held with a screw. Supplementary cancellous grafts were used to promote cross union with the ipsilateral fibula. The proximal tibiofibular joint was fused.

At eight months union was evident distally but at ten months a non-union was evident proximally. At sixteen months, supplementary secondary grafts and additional screw fixation at the site of the non-union had been in place for three months postoperatively.

Fig. 2-B

A subsequent series of lateral roentgenograms. At eighteen months, the proximal non-union was healed and clinically stable. The patient walked with a patellar tendon-bearing orthosis. At twenty months a fatigue fracture was evident distally. The fracture was ununited at twenty-nine months despite the application of a long plaster cast and electromagnetic stimulation. Onlay cancellous grafting and plate fixation was employed at thirty months, and the fracture finally united at thirty-three months after the resection.
The locations of the defects that were reconstructed are shown in Table IV. The distal part of the femur and proximal part of the tibia were the most common locations, and when an articular surface was resected arthrodesis of the knee was accomplished by segmental grafting to achieve a stable extremity. The next most common location was the proximal part of the humerus. There were four other locations in six patients (two, distal part of the tibia; two, tibial shaft; and one each, distal part of the radius and femoral shaft) with large cortical reconstructions of various configurations.

**Methods**

In order to enhance union, rigid immobilization was sought with internal fixation. Intramedullary fixation was chosen for defects in the femur or unsupported tibia to maximize stability of the reconstruction until solid fusion occurred (Figs. 1, 3, 5, and 6). In the humerus, where the defect commonly included the entire proximal part, intramedullary fixation was not possible. In these patients, the dual fibular grafts were fixed to the distal part of the humerus by cross-bolting and were bolted to themselves proximally. The proximal grafts then were either fixed with screws to the scapula to achieve arthrodesis or juxtaposed to the glenoid to form an arthroplasty (Fig. 4). In these patients, the grafts themselves furnished the stability. When a single graft was used, the graft usually acted as the fixation device, and only secondary fixation at the ends of the grafts was used rather than a defect-spanning device (Figs. 2-A and 2-B).

In addition to the stability provided by the intramedullary device or the graft itself, supplementary fixation at the junction of the graft and host was achieved in various ways. Where a fibular graft abutted cortical bone, it was secured by a Steinmann pin passing from the medullary canal of the fibula into a hole drilled longitudinally into one cortex of the host (Figs. 1, 3, and 5). When a fibular graft abutted cancellous bone, it was fixed by shaping the graft to a tapering point and impaling it without additional metallic devices (Figs. 1, 3, and 5). When a fibular graft was onlaid to a cortex of the host, it was secured by screws or cross bolts (Figs. 2-A, 2-B, and 4). When hemicortices of the femur or tibia were used as grafts, they were secured by inlaying them into cancellous metaphyses and securing them with screws (Figs. 1 and 5). Where they joined cortices, they were onlaid and fixed with screws or wires (Fig. 1), inlayed and fixed with crossed Kirschner wires, or simply impaled between the cortex and the intramedullary device (Fig. 5). When a single fibular graft was used, it was fixed at either end with screws or bolts or was transfixed with a Steinmann pin (Figs. 2-A and 2-B).

Finally, a number of the junctions between a cortical graft and a cortex of the host had supplementary cancellous grafts packed about them at the time of the initial procedure, in an attempt to enhance the likelihood of union (Figs. 2-A and 2-B).

In twelve of the patients in whom later procedures were pre-planned, a short segment of graft was taken as an extra and was placed in the reconstruction site, where it could be retrieved during the subsequent procedure to study the repair of human cortical bone grafts (Fig. 4). This extra was laid along the reconstruction site but was
not an integral part of it and thus bore no stress. These
grafts were labeled with tetracycline during the postopera-
tive period, and were collected during subsequent proce-
dures at various intervals. The specimens were embedded,
undecalciﬁed in methacrylate, sectioned on a milling
machine, analyzed microradiographically and by ﬂuo-
rescent microscopy, and quantitated by methods previously
described to assess the amount and pattern of repair in
dogs.7,11

Roentgenograms were made at regular intervals post-
operatively to assess union. If there was no evidence of
union at a particular graft-host junction, the site was surgically
explored and onlay-grafted with supplementary au-
togenous cancellous bone before the patient was allowed
to resume function (Figs. 2-A and 2-B). If there was subtle
or no false motion at the site of non-union, no additional
internal ﬁxation was used. If false motion was clearly
present, immobilization was secured by an onlay plate.

Fatigue fractures of grafts were treated by external
immobilization with casts or braces (Figs. 3 and 5). If they
failed to unite, they were treated with onlay autogenous
cancellous bone grafts (Figs. 2-A and 2-B).

At the time of analysis, the size and density of the
grafts were assessed roentgenographically. The preopera-
tive size of the graft was compared with its immediate
postoperative size to determine whether it was the same,
smaller by 10 per cent or more, or larger by 10 per cent or
more (Fig. 1). At the same time, the quality of the graft
was assessed to determine if it was of the same density, of
less density, or of increased density (Fig. 1). These esti-
mations of density were done subjectively. If the changes
were subtle or questionable, the graft status was recorded
as unchanged.

The functional results were categorized as excellent
(unlimited activity within the limits of the reconstruction);
good (limited vigorous activity but no external supports or
aids required for activities of daily living); fair (activities
of daily living with external supports); or poor (limited ac-
tivities of daily living due to instability despite external
supports). The term excellent is not meant to infer that a
fused joint is the equivalent of a normal, moving, painless
joint, but rather that the function, when judged as a result
of fusion, is all that could be expected.

Forty patients whose segmental defects of the major
long bones were reconstructed with autogenous cortical
bone grafts with a follow-up of two years or more form the
clinical population of this study. Table II shows the details
of the source of the combinations of grafts, while Table V
shows the numbers of patients with each of the three major
conﬁgurations. All twenty-ﬁve of the dual ﬁbular-
hemicortical grafts were used at the knee, while only three
of the dual ﬁbular grafts were used at this location. Of the
other ﬁve dual ﬁbular grafts, three were used in the prox-
imal part of the humerus; one, in the femoral shaft; and
one, for a tibial shaft reconstruction. The seven single
ﬁbular grafts were used for the proximal part of the
humerus (two), the distal part of the tibia (two), the distal
part of the femur (one), and the middle of the tibial shaft
(one).

Primary stability of the site of reconstruction was
achieved in thirty patients by intramedullary rod ﬁxation.
The details of the various devices are shown in Table VI.
The type of supplementary fixation at the abutting junctions of the graft and host depended on the type of graft (fibular or hemicortical) and the site (metaphyseal cancellous bone or diaphyseal cortical bone). When a fibular graft abutted diaphyseal cortical bone, fixation was usually provided by a Steinmann pin passed from the medullary canal of the fibular graft into a longitudinal hole prepared in the cortex of the host. When a hemicortex of the tibia or femur was used as a graft, the graft usually was onlayed and secured with a unicortical screw. Table VII shows the numbers of times that these and other methods of supplementary fixation were used.

**Results**

The incidence of non-union and the influence of the type of junction, the length of the defect, and initial supplementary grafting on the incidence of non-union is shown in Table VIII.

Primary union (in less than twelve months after operation) of all four graft junctions occurred in 60 per cent (fifteen of twenty-five) of the patients with dual fibular-hemicortical grafts, in 75 per cent (six of eight) of the patients with dual fibular grafts, and at both ends in 57 per cent (four of seven) of the patients with single fibular grafts. In two additional patients with dual fibular-hemicortical grafts, delayed union (more than twelve months after operation) was achieved without secondary procedures. Thus, union occurred in 67 per cent (twenty-seven of forty) of the patients without secondary procedures, while in 33 per cent (thirteen of forty) of the patients one or more junctions of a graft to the host bone failed to unite.

Of the thirteen patients with a non-union, seven (54 per cent) had a non-union at a single site after dual grafting; five (38 per cent), at both sites at the same end of the defect after dual grafting; and one (8 per cent), at one end of a single graft. There was a total of seventy-three grafts in the forty patients with 146 graft-host junctions. With eighteen sites of non-union in the forty patients who had 146 potential sites of non-union, this yielded an incidence of non-union of 12 per cent. Seventeen of the eighteen non-unions occurred at a site of cortical-cortical bone junction. One occurred after placement of a single fibular graft at a cortical-cancellous junction. In the twenty-eight patients treated with dual grafts, there was not one non-union at the fifty-six sites of cortical-cancellous junction.

There was no significant difference in the incidence of non-union between the various graft configurations. In the dual fibular-hemicortical grafts the incidence was 32 per cent (eight of twenty-five); in the dual fibular grafts, 25 per cent (two of eight); and in the single fibular grafts, 43 per cent (three of seven). The incidence of non-union was greater for patients with lesions about the knee that were primarily stabilized by an intramedullary rod (eleven of thirty, or 35 per cent) than in those with lesions of the upper extremity in whom the grafts provided the primary stability (two of ten, or 20 per cent). The size of the defect,
and hence the length of the grafts, did not influence the incidence of non-union. The grafts that were less than twelve centimeters in length had a 33 per cent (four of twelve) incidence of non-union while those grafts that were twelve centimeters in length or longer had a 32 per cent (nine of twenty-eight) incidence. Non-union occurred with equal frequency in patients with and without supplementary grafting of the junctions. Those with supplementary grafting at the time of the primary operation had a non-union rate of 32 per cent (seven of twenty-two), and those without initial supplementary grafts had an incidence of 33 per cent (six of eighteen).

Twelve of thirteen patients with non-union underwent secondary grafting procedures, and eleven of the non-unions healed within two to eight months postoperatively. One non-union required a second graft and plating of the non-union site, but union was achieved within twenty-four months. In one patient non-union was associated with an infection, a sequestrum developed and was treated by sequestrectomy, and the patient died from the malignant lesion twenty months postoperatively, without union. Thus, twelve of the thirteen non-unions healed with secondary grafting, giving an ultimate over-all rate of union of 97.5 per cent.

The incidence of stress fractures, their location, the effect of the intramedullary rods, the size of the defect, and their ultimate fate are shown in Table IX. Fatigue failures or stress fractures occurred in 45 per cent (eighteen of forty) of the patients. They were observed much more frequently in grafts that were longer than twelve centimeters (57 per cent versus 12 per cent in shorter grafts). Stress fractures occurred only after union of both graft junctions; conversely, if a non-union developed in a junction, no stress fracture was evident until that junction had united. The range in time of development of fatigue fractures was from six to thirty-nine months, with an average of twenty-one months. Thirty-three per cent (six of eighteen) of these patients were asymptomatic, and the fracture was recognized only retrospectively on follow-up roentgenograms. Sixty-six per cent (twelve of eighteen) of the patients had an identifiable episode of sudden pain, and roentgenograms showed a recent stress fracture. Seven of these twelve fractures, when treated non-operatively, healed within two to six months (Fig. 5). Thus, 72 per cent (thirteen of eighteen) of the patients with stress fractures had healing with no treatment or with external immobilization.

Five patients (28 per cent) in whom the stress fractures failed to heal when treated non-operatively were then treated with onlay bone grafts, internal fixation, and external immobilization. Two fractures healed, but three did not. Of the three patients without union, one had two iliac-bone grafts and one free fibular pedicle graft without evidence of union; one was subsequently treated with electrical stimulation without union; and the third had no further treatment. All three patients preferred to accept their disability rather than undergo further attempts at securing union.
### Table

<table>
<thead>
<tr>
<th>Case</th>
<th>Type of Graft</th>
<th>Time to Primary Union (Mos.)</th>
<th>Non-Union</th>
<th>Fatigue Fractures</th>
</tr>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Junction</td>
<td>Treatment</td>
</tr>
<tr>
<td>27</td>
<td>Fibula</td>
<td>6</td>
<td>Prox.</td>
<td>Bone graft, 6 mos.</td>
</tr>
<tr>
<td>29</td>
<td>Fibula</td>
<td>6</td>
<td>Prox.</td>
<td>Union, 4 mos.</td>
</tr>
<tr>
<td></td>
<td>Tibia</td>
<td></td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Tibia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>33</td>
<td>Fibula</td>
<td>6</td>
<td>Prox.</td>
<td>Bone graft, 6 mos.</td>
</tr>
<tr>
<td>34</td>
<td>Fibula</td>
<td>6</td>
<td>Prox.</td>
<td>Union, 6 mos.</td>
</tr>
<tr>
<td></td>
<td>Tibia</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>35</td>
<td>Fibula</td>
<td>6</td>
<td>Prox.</td>
<td>Bone graft, 9 mos.</td>
</tr>
<tr>
<td>36</td>
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<td>6</td>
<td>Prox.</td>
<td>Union, 4 mos.</td>
</tr>
<tr>
<td>37</td>
<td>Fibula</td>
<td>8</td>
<td></td>
<td></td>
</tr>
<tr>
<td>38</td>
<td>Fibula</td>
<td>6</td>
<td></td>
<td>Union, 4 mos.</td>
</tr>
<tr>
<td>39</td>
<td>Fibula</td>
<td>6</td>
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</tr>
<tr>
<td></td>
<td>Tibia</td>
<td></td>
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</table>

* Cyclophosphamide.

Of the thirty patients with intramedullary rod fixation, there were thirteen (43 per cent) with fatigue fractures, while in the patients in whom the grafts provided the primary stability the incidence of fatigue fracture was five of ten (50 per cent). Among the patients with rods, the incidence of failure was five (31 per cent) of sixteen patients with the fluted rod and eight (57 per cent) of fourteen with the other devices.

There were twenty-five fibular grafts reinforced by a Steinmann pin within the entire length of the medullary canal of the graft. Eight (33 per cent) sustained fatigue fractures. Nine (30 per cent) of twenty-four fibular grafts without Steinmann-pin reinforcement failed. Of the twenty-five hemi-cortical grafts, six (24 per cent) failed. Thus, there was no difference between a hemi-cortical and fibular graft, nor did the presence of an intramedullary Steinmann pin decrease the incidence of fatigue failure.

Fifteen of the eighteen patients with stress fractures showed no change in the size of the graft at the time of fracture. In seven of these patients, the graft that had the fracture then hypertrophied around the fracture site. In eight patients there was no residual increase in graft size after the fracture. Only three patients showed a decrease in the size of the graft at the time of the failure, and all three grafts hypertrophied minimally as the fracture healed.

Two patients deserve special mention. One (Case 6) had a fracture of the hemi-cortical portion of a dual fibular-hemi-cortical graft twenty-four months postoperatively that healed after it was reinforced with additional iliac-bone grafts. A fracture of the fibular graft developed, and at the time of writing it was being treated with an electromagnetical stimulation device. While six patients sustained simultaneous stress fractures of dual grafts, this was the only patient to date who had more than one episode of stress fracture. The second patient (Case 7) sustained a traumatic fracture of the unsupported radial graft which healed in a cast in four months without problems.

Fifteen of the eighteen patients with stress fractures
had healing. Once the fracture healed, the patients returned to unrestricted activity without repeated fractures, with the one exception already noted.

The density and dimensions of the grafts were studied by evaluating each graft individually. A total of seventy-three grafts were evaluated in the forty patients. Table X shows the increases or decreases in density and size. Almost twice as many (forty-one compared with twenty-four) increased in density as remained the same. Only a few (eight of seventy-three) decreased in density. Conversely, almost twice as many (forty-two compared with twenty-four) stayed the same in size as increased. Again, only a few (seven of seventy-three) decreased in size. When the grafts were followed serially, the majority decreased in density during the first six to ten months and then progressively increased with time. There was no cor-

<table>
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<tr>
<th>Quality of Graft Density</th>
<th>Complications at Donor Site</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Increased</td>
<td>No change</td>
<td>Wound skin slough, treated with skin graft</td>
</tr>
<tr>
<td>Increased</td>
<td>No change</td>
<td>Pulmon. metast., 10 mos.; thoracot., doxorubicin and methotrexate, 1 yr.</td>
</tr>
<tr>
<td>Decreased</td>
<td>Atrophied</td>
<td>Scar neuraoma</td>
</tr>
<tr>
<td>No change</td>
<td>No change</td>
<td>Doxorubicin and Cytoxin*, 1 yr. postop.; angulation of grafts secondary to mult. fracts.</td>
</tr>
<tr>
<td>Increased</td>
<td>No change</td>
<td>Pulmon. metast., 8 mos.; chemother., thoracot., doxorubicin, Cytoxin*; died, 2 yrs.</td>
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<tr>
<td>No change</td>
<td>No change</td>
<td>Wound skin slough healed, 4 mos.</td>
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<table>
<thead>
<tr>
<th>Pathological Process</th>
<th>No. of Patients</th>
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<tbody>
<tr>
<td>Giant-cell tumor</td>
<td>14</td>
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<tr>
<td>Chondrosarcoma</td>
<td>10</td>
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<tr>
<td>Osteogenic sarcoma</td>
<td>7</td>
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<tr>
<td>Parosteal osteosarcoma</td>
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<tr>
<td>Malignant fibrous histiocytoma</td>
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<tr>
<td>Recurrent chondroblastoma</td>
<td>2</td>
</tr>
<tr>
<td>Recurrent chondromyxofibroma</td>
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<table>
<thead>
<tr>
<th>Site of Reconstruction</th>
<th>No. of Patients</th>
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</thead>
<tbody>
<tr>
<td>Distal part of femur</td>
<td>22</td>
</tr>
<tr>
<td>Proximal part of tibia</td>
<td>7</td>
</tr>
<tr>
<td>Proximal part of humerus</td>
<td>5</td>
</tr>
<tr>
<td>Distal part of tibia</td>
<td>2</td>
</tr>
<tr>
<td>Femoral shaft</td>
<td>1</td>
</tr>
<tr>
<td>Tibial shaft</td>
<td>2</td>
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<tr>
<td>Distal part of radius</td>
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TABLE V

<table>
<thead>
<tr>
<th>Graft</th>
<th>No. of Patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dual fibular-hemicortical of tibia or femur</td>
<td>25</td>
</tr>
<tr>
<td>Dual fibular</td>
<td>8</td>
</tr>
<tr>
<td>Single fibular</td>
<td>7</td>
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</table>

relates between the age of the patient and change in density or dimensions of the graft. Analysis of the nine patients (sixteen grafts) with open physes revealed that three grafts hypertrophied, five decreased in size, and eight had no change. Those with closed physes showed twenty-one grafts with increased size, two with decreased size, and thirty-four with no change. All of the grafts that hypertrophied showed modest changes in size — that is, no more than a 20 per cent increase. The same was true of those that decreased in size.

Complications were divided into donor-site and graft-site categories. Two patients had peroneal-nerve injuries at the site of fibular graft procurement, one of which completely resolved postoperatively and one of which did not. There were no other significant complications at the donor site. There was no ligament instability at the knee or valgus deformity of the ankle. There was no weakness or restriction of motion about the foot or ankle.

There were five significant complications at the site of graft implantation. In two patients deep infection developed, in one at three months postoperatively and in one at eleven months postoperatively. Both were treated with antibiotics, and one healed without further intervention. The other patient required a sequestrectomy of the site at eleven months postoperatively. Three patients had a significant skin slough over the graft site, but all responded to local debridement and skin grafts.

TABLE VI

<table>
<thead>
<tr>
<th>Primary Stabilization</th>
<th>No. of Failures</th>
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<tbody>
<tr>
<td>Type</td>
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<td>Intramedullary device</td>
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<tr>
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<tr>
<td>Küntsccher rod</td>
<td>9</td>
</tr>
<tr>
<td>Fluted rod</td>
<td>3</td>
</tr>
<tr>
<td>Rush rod</td>
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<tr>
<td>Total</td>
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<table>
<thead>
<tr>
<th>Graft per se</th>
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<td>With Barr bolt</td>
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<td>With screws</td>
<td>2</td>
</tr>
<tr>
<td>Total</td>
<td>10</td>
</tr>
</tbody>
</table>

In the five patients who received chemotherapy, no significant effect on wound-healing or graft repair was discernible.

Table XI shows the results of the investigation of the patients who had marker pieces of graft removed from the graft site. The average interval to biopsy was six months, with a range of three to twelve months. There was an average of 13.3 per cent porosity seen in these grafts, with a range from 3.4 to 32 per cent, and an average of 9.6 per cent new bone, with a range of 1 to 30 per cent.

The functional results in our patients are recorded in Table 1, along with their present occupations. Twenty-seven (67.5 per cent) had excellent results; three (7.5 per cent), good; seven (17.5 per cent), fair; and three (7.5 per cent), poor results. All except the three patients with poor results resumed their former occupations or assumed more demanding ones.

Discussion

Animal studies have shown that only the intraosseal matrix of cortical bone grafts is replaced by living bone at the completion of their repair and that the grafts lose and regain half of their strength during the repair.

Fig. 5

Case 23. A 13.4-centimeter defect was created by resection of a malignant fibrous histiocytoma in a sixty-year-old man. The lateral roentgenogram on the left, made in May 1976, shows that union is consolidating at five months after grafting. In March 1977, a routine follow-up roentgenogram made at fifteen months shows an asymptomatic, healing stress fracture (C). In May 1978, the fracture is healed; there is modest hypertrophy of the graft; the patient is allowed unrestricted activity; and there have been no subsequent stress fractures.
period (one year in the dog)\textsuperscript{7,12}. Clinically, single fibular grafts have had a high failure rate when used to reconstruct segmental defects in large tubular bones\textsuperscript{1,2,32,36}. We thought, therefore, that in order to achieve functional res-

toration of the major tubular long bones (humerus, femur, and tibia), dual grafts of either the fibula or the fibula and hemicortical slabs of the tibia or femur would be required to provide enough stock in the defect to prevent late fatigue failure and the need for disabling external supports (Fig. 1). When defects in one bone of the forearm or in the tibia were supported by the remaining bone in the forearm or by the fibula, however, we thought that a single graft would be sufficient (Figs. 2-A, 2-B, and 6).

Analysis demonstrates that such reconstructions are a reliable method of managing intercalary defects of major bones. The term \textit{reliable} is taken to mean a high incidence of satisfactory, long-term stability despite the significant incidence of short-term complications. The incidence of morbidity and disability at the site of graft procurement is small (5 per cent). In the majority of patients stability is obtained within a year of operation, and the strength of the grafts returns to normal levels at two years. In patients with a non-union at one of the graft-host junctions, a secondary supplementary graft has a high (91 per cent) probability of success. During the two-year period required for completion of internal repair of the graft, there is significant weakening of the grafts and fatigue fractures are common. The majority of these fractures heal with non-operative care, and in many patients the callus further strengthens the graft. Once repair of the grafts has been completed, repeated stress fractures are not a significant problem.

The grafts show no dramatic change in size or density after repair and use. The lack of effect of the age of the patient on the repair process in this series is not surprising in view of the fact that only one of the nine patients (sixteen grafts) with open physes was less than fourteen years old. Dual grafts are adequate in volume to reconstruct the large tubular bones (humerus, femur, and tibia). A single fibular graft is not adequate in a tibia with an intact fibula, particularly when the defect exceeds twelve centimeters. Single fibular grafts should be reserved for bones of similar size (radius or ulna). When practical, intramedullary rod fixation to provide stability is desirable, particularly in the lower extremity.

Where the grafts abut cancellous bone union is almost certain, but where they abut cortical bone non-union is frequent. Union is best promoted by good supplementary

\begin{table}
\centering
\caption{Non-Unions}
\begin{tabular}{|c|c|c|c|c|c|}
\hline
Type of Graft & No. of Patients & Type of Non-Unions\textsuperscript{*} & \textsuperscript{Cortical-} & \textsuperscript{Cortical-} & Length of Graft\textsuperscript{*} & Subsequently Healed\textsuperscript{†} \\
 & & & \textsuperscript{Cortical} & \textsuperscript{Cancellous} & \leq 12 cm. & > 12 cm. & Yes & No & \\
\hline
hemicortical & & & & & & & & & \\
Dual fibular & 8 & 2/8 & 0/3 & 0/2 & 2/6 & 1/4 & 1/4 & 2/2 \\
Single fibular & 7 & 2/6 & 1/1 & 2/3 & 1/4 & 2/4 & 1/3 & 3/3 \\
Total & 40 & 13/40 & & 4/12 & 9/28 & 7/22 & 6/18 & 12/13 \\
\hline
\end{tabular}
\textsuperscript{*} Number of non-unions/number of procedures.
\textsuperscript{†} Number of unions/number of non-unions after secondary grafting.
\end{table}
fixation at the graft-host junction rather than by additional onlay cancellous grafts at the sites of potential non-union. Supplementary fixation of a cortex-to-cortex junction is best provided by longitudinal pin fixation rather than unicortical screws or wires.

In the thirteen patients who had a non-union, seven had dual grafts and the non-union was at one of the four junctions of one graft while union occurred at the other end of that graft and at both ends of the other graft. Thus, the non-union did not produce a clinically unstable extremity but rather delayed the time until we thought it safe for the patient to resume activity with the extremity. From this experience, we believe that such non-unions are not caused by inadequate immobilization (since the other graft united) but by the avascular abutting cortices denuded by the removal of the graft on the one hand and the dissection necessary to resect the tumor on the other.

Neither intramedullary rods across the defect nor Steinmann pins within the fibular grafts were effective in preventing fatigue fractures. Since the incidence of fatigue fractures was significantly higher in the longer grafts, this suggests that stabilization by an intramedullary rod is not sufficient to prevent minor deformations of the grafts and that the amount of deformation is related to the length of the graft. The devices did maintain stability and allowed union with little disability in 72 per cent of the fatigue failures. Of the five fatigue fractures that failed to heal when treated non-operatively, four had clinically detectable false motion at the time of the fracture despite an intact intramedullary device.

All intramedullary rods but one were left in place with the assumption that since the grafts do not replace the complete volume of the resected bone, the rods add additional support to the reconstruction. It is notable that of the thirty rods, five sustained a late fatigue fracture within the extent of the grafts. Only one rod, however, was removed. All rod failures occurred prior to the use of the fluted rods. Thus, the optimum method for a successful reconstruction of an intercalary defect by autogenous cortical bone grafts seems to be achieving stability of the defect by intramedullary fixation, using two cortical grafts, fixing the grafts rigidly end-to-end with pin fixation or onlaying them with side-to-side bolt fixation, and protecting the grafts for two years until they have united and undergone internal repair.
AUTOGENOUS CORTICAL BONE GRAFTS IN RECONSTRUCTION OF SKELETAL DEFECTS

this group of patients, 75 per cent (thirty of forty) table, painless extremity and resumed active use of table, painless extremity and resumed active use of limited extremity without protective devices within one month. The seven patients who had fair results were in three patients with an unstable, painful extended fractures: one with a sequestrectomy and two with ununited fractures. These seven patients had fair results with moderate degrees of pain, were excluded from tabulation and resumed their life-style but they redressed the extremities they had not been able to support during the period for which the reconstructions were done, thirty

The analysis of the retrieved graft specimens confirmed pathologically what was suggested clinically in terms of cortical bone repair. The mechanisms described quantitatively and qualitatively in dogs were seen in this human material. Early revascularization of the haversian canals; excavation of the matrix from the osteons, with an increase in porosity and a decrease in radiodensity and strength; and, following union, a gradual rebuilding of the osteons with a resultant increase in porosity and return of strength were noted. The external dimensions of the grafts remain about the same during this process, perhaps augmented a modest amount by a thin sheath of new bone that adds no more than 20 per cent to their size. The decrease in density that occurs initially is the result of the revascularization. The maintenance of the size of the graft is the result of the involutionality of the interstitial lamellae to resorption, and the subsequent reformation of the osteons is triggered by stress transmitted to the graft only after union has occurred. The outstanding difference between dogs and humans is the temporal sequence of the events. Union in dogs is achieved in three to four months, while in humans it takes six to eight months; maximum porosity in dogs is seen from three to six months postoperatively, while in humans it is seen from six to twelve months postoperatively; and in dogs maximum weakness is present from the third to the sixth month, while in humans it is present from the sixth to the twelfth month. Fatigue failures in dogs occur from three to nine months postoperatively, while in humans they occur from six to eighteen months postoperatively, and resumption of normal strength in the graft in dogs is seen at one year, while in humans it is seen at two years. Thus, everything observed in dogs is seen in humans, but it takes twice as long.

Whether this time difference is a reflection of the difference between species or of the differences between the stressed graft used in the dog and the non-stressed graft used in this study is not certain. Given the time difference in generalized bone repair and metabolism between humans and dogs, it would seem more likely to be a difference between species.

From these observations, the principles of segmental cortical bone-grafting can be formulated rationally. Rigid immobilization of the grafts in a stable extremity is required to achieve union. The grafts must be protected throughout the prolonged reparative phase until their roentgenographic appearance indicates that the repair process is sufficient for the extremity to resume function. Adequate stress must be transmitted to the grafts during this period to stimulate the repair. Enough grafts must be used to provide functional replacement in the major tubular bones.

References


