THE JOURNAL OF BONE & JOINT SURGERY

JB&JS

This is an enhanced PDF from The Journal of Bone and Joint Surgery

The PDF of the article you requested follows this cover page.

Reconstruction of Posttraumatic Disorders of the Forearm

Jesse B. Jupiter, Diego L. Fernandez, L. Scott Levin and Robert W. Wysocki
J Bone Joint Surg Am. 2009;91:2730-2739.

This information is current as of November 2, 2009

Reprints and Permissions Click here to **order reprints or request permission** to use material from this article, or locate the article citation on jbjs.org and click on the [Reprints and Permissions] link.

Publisher Information The Journal of Bone and Joint Surgery
20 Pickering Street, Needham, MA 02492-3157
www.jbjs.org

Selected Instructional Course Lectures

The American Academy of Orthopaedic Surgeons

Mary I. O'Connor
Editor, Vol. 59

Committee
Mary I. O'Connor
Chairman

Frederick M. Azar
Paul J. Duwelius
Kenneth A. Egol
Paul Tornetta III

Ex-Officio
Dempsey S. Springfield
Deputy Editor of The Journal of Bone and Joint Surgery for Instructional Course Lectures

James D. Heckman
Editor-in-Chief,
The Journal of Bone and Joint Surgery

Printed with permission of the American Academy of Orthopaedic Surgeons. This article, as well as other lectures presented at the Academy's Annual Meeting, will be available in March 2010 in Instructional Course Lectures, *Volume 59. The complete volume can be ordered online at www.aaos.org, or by calling 800-626-6726 (8 A.M.-5 P.M., Central time).*

AMERICAN ACADEMY OF ORTHOPAEDIC SURGEONS

Reconstruction of Posttraumatic Disorders of the Forearm

By Jesse B. Jupiter, MD, Diego L. Fernandez, MD, L. Scott Levin, MD, and Robert W. Wysocki, MD

An Instructional Course Lecture, American Academy of Orthopaedic Surgeons

Forearm Kinesiology

Forearm rotation is the most important contribution to the rotational mobility of the upper limb[1]. The two-bone unit with its proximal and distal radioulnar joints, and its rotational axis connecting the centers of the two, have been viewed as a single bicondylar joint. When combined with rotational motion of the shoulder, forearm rotation permits the hand to be positioned through an entire 360° arc of motion. With the shoulder fully abducted, nearly all of the rotational motion of the upper limb occurs through the forearm[1]. Activities such as accepting objects in the palm of the hand require nearly full forearm supination, while many other functional tasks require some degree of pronation. It has been suggested that, in addition to rotation along the axis of the forearm articulation, the distal aspect of the ulna moves in both adduction and abduction planes with forearm rotation, although some believe that this perceived motion may be due to axial rotation of the humerus[2,3].

The interosseous membrane, which is considered to be better described as a ligament, also contributes to the longitudinal stability of the forearm[4-7]. The central band contributes to the axial stability of the forearm, while the dorsal oblique band adds to the stability of the proximal radioulnar joint and the distal membranous portion functions as a secondary stabilizer of the distal radioulnar joint[7].

Malunion

When the forearm is considered to be a joint, diaphyseal fractures constitute intra-articular lesions and therefore require accurate anatomic reduction to ensure full function. The same principle applies to surgical reconstruction of malunited forearm fractures.

Surgical management of a diaphyseal malunion is a challenge because, despite the achievement of osseous union, correction of deformity, and relief of pain, complete and symmetrical restoration of forearm rotation is difficult to obtain[8]. This is due to the associated derangement of the proximal and distal radioulnar joints and the interosseous membrane[9,10]. Shortening of a single forearm bone with or without angular deformity automatically affects the articular anatomic relationships of either the proximal or the distal radioulnar joint. Loss of the physiological bow of the radius limits pronation, and reduction of the interosseous space associated with angular or translational deformity can lead to osseous impingement and secondary contracture of the interosseous membrane, further reducing forearm rotation[10] (Fig. 1-A).

Diaphyseal malunion in adults may be due to insufficient reduction,

Look for this and other related articles in *Instructional Course Lectures*, Volume 59, which will be published by the American Academy of Orthopaedic Surgeons in March 2010:

- **"The Management of Complex Fractures and Fracture-Dislocations of the Hand," by Jesse Jupiter, MD, Hill Hastings, MD, and John T. Capo, MD**

Disclosure: The authors did not receive any outside funding or grants in support of their research for or preparation of this work. Neither they nor a member of their immediate families received payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity.

usually with nonoperative treatment, or may be an iatrogenic deformity after an attempted osteotomy. The deformity may include one or both bones of the forearm. The clinical scenario presents as restriction of forearm rotation, pain and instability of the radioulnar joints during pronation and supination, and often a cosmetic problem. Symptoms may be decreased by correcting all components of the deformity, including length discrepancy, angulation, rotation, and the bow of the radius[9].

In children over ten years of age and adults, restoration of normal anatomy and neighboring joint relationships following posttraumatic deformity can be achieved only with corrective osteotomies. This together with the appropriate soft-tissue release improves forearm rotation, while realignment of the radioulnar joints provides stability. Because there are no generally valid normal values, the contralateral, healthy forearm is used for preoperative planning. Fluoroscopy, computed tomography scans, and cross-sectional magnetic resonance imaging are used to assess rotational malalignment while three-dimensional plastic models based on the computed tomography scans are used to assess complex deformities[11-13].

Pathomechanics of Forearm Malunions and Clinical Correlation with Forearm Rotation

The influence of ulnar and radial malalignment on rotational motion has been demonstrated experimentally on cadaver forearms[14-17]. The amount of angulation directly correlates with the restriction of pronation and supination. Deformities in the distal third of the forearm, but not those in the middle or proximal third, decrease pronation[14]. Angulations of up to 10° in the middle third of the radius or ulna, or both, do not limit rotation, but deformities of 20° restrict forearm rotation by at least 30% and angulations of >20° result in even greater restrictions[14,15]. Rotational deformities may also displace and decrease the pronation-supination arc of motion[18,19].

Diaphyseal Deformity and Instability of the Distal Radioulnar Joint

Instability of the distal radioulnar joint can occur with angulation, malrotation, and length discrepancy of one or both forearm bones[19]. The loss of the normal spatial orientation of the joint surfaces prevents anatomic healing of acutely torn ligament restraints. This is true for fractures localized to the distal third of the radius[20,21]. If the fracture heals with a skeletal deformity, instability, subluxation, or complete dislocation with incompetence of the triangular fibrocartilage complex may occur[21]. Palmar subluxation of the distal part of the ulna is associated with dorsally angulated diaphyseal malunion. Conversely, malreduced Galeazzi fractures with persistent palmar angulation and pronated rotational malalignment are associated with dorsal displacement of the distal part of the ulna and complete loss of active supination.

Associated Disorders of the Proximal Radioulnar Joint

Chronic dislocation of the radial head can result from an unreduced Monteggia fracture with persistent angulation of the ulna or be associated with a forearm malunion with a discrepancy between the lengths of the radius and the ulna. An angulated metaphyseal malunion of the proximal part of the radius leads to incongruity of the radial head in the sigmoid notch and results in severe limitation of pronation. In general, valgus malalignment of the proximal part of the radius results in lateral subluxation of the radial head, creating substantial incongruity of both the proximal radioulnar joint and the radiocapitellar joint.

Surgical Techniques

Types of Osteotomies

A transverse osteotomy is preferred to treat a “simple” rotational or translational deformity. Moderate lengthening with angular correction in the plane of the osteotomy can be achieved with oblique osteotomies[22,23]. Rotational correction with oblique osteotomies is limited because rotation automatically induces a change in angular alignment and opens the osteotomy on one side, reducing the contact surface. For complex diaphyseal malunions, for which angular, rotational, and length adjustments are to be made, the single-cut osteotomy oriented in the combined oblique plane of deformity based on a mathematical analysis of the malalignment has been proposed[24]. Further refinements for planning and performing the single-cut osteotomy by applying a geometrical methodology were reported by Meyer et al.[25]. For an exact calculation of the true angle of deformity, Nagy recommended the use of tables that readily provide these values on the basis of projected angles of the deformity on anteroposterior and lateral radiographs[26]. During the performance of a single-cut osteotomy, the decision to create a closing or opening wedge osteotomy depends on the amount of length discrepancy of the involved bone. In patients with extreme bowing of the radius or a malunited segmental fracture, a double-level osteotomy may be required to restore alignment of the anatomic axis. Classically, step-cut osteotomies, although technically more demanding, have been used to lengthen long bones, thereby avoiding the need for bone-grafting. An isolated rotational deformity is corrected with a transverse osteotomy[27]. Osseous defects created by lengthening require bone-grafting except in children, in whom rapid periosteal bone-healing readily fills the bone gap.

Deformity characterized by >4 cm of shortening of one forearm bone, such as occurs following physeal trauma, is better addressed with progressive distraction/osteogenesis techniques that employ external fixation.

Preoperative Planning

The contralateral, normal forearm is used as a guide for preoperative planning as the correctional osteotomy should reproduce the osseous geometry of the normal side. Exact anteroposterior and lateral radiographs of both the radius and the ulna, including the proximal and distal joints, should be obtained. This may be difficult, especially when limited forearm rotation prevents the patient from placing the forearm in neutral rotation. In these cases, the correct position for exposure must be determined under an image intensifier. The distal epiphysis is used as the reference for the radius, and the humeroulnar joint is used for the ulna.

The contours of the healthy and deformed bones in both projections are drawn on separate sheets of tracing paper (Figs. 1-B and 1-C). The location of maximal deformity is determined by simple superimposition of the drawings. The angular deformity in both planes is measured with use of the values of these projected angles; the true angle of deformity and the orientation of the deformity in space are calculated with use of established tables[19]. In contrast, rotational deformity is determined by inspecting the relationship of the bicipital tuberosity to the radial styloid and the relationship of the coronoid process to the ulnar styloid. The exact degree of radial and ulnar torsion is measured by comparing the computed tomography or magnetic resonance images of the two forearms. The bicipital tuberosity and the square section of the radius at the level of the Lister tubercle are used to determine radial torsion, whereas the trochlea and the ulnar styloid are most commonly used for the ulna[12,28]. Rotational malalignment of the radius of >30° and rotational malalignment of the ulna of >20° should be corrected, since these values exceed the physiological limits of individual variations[6].

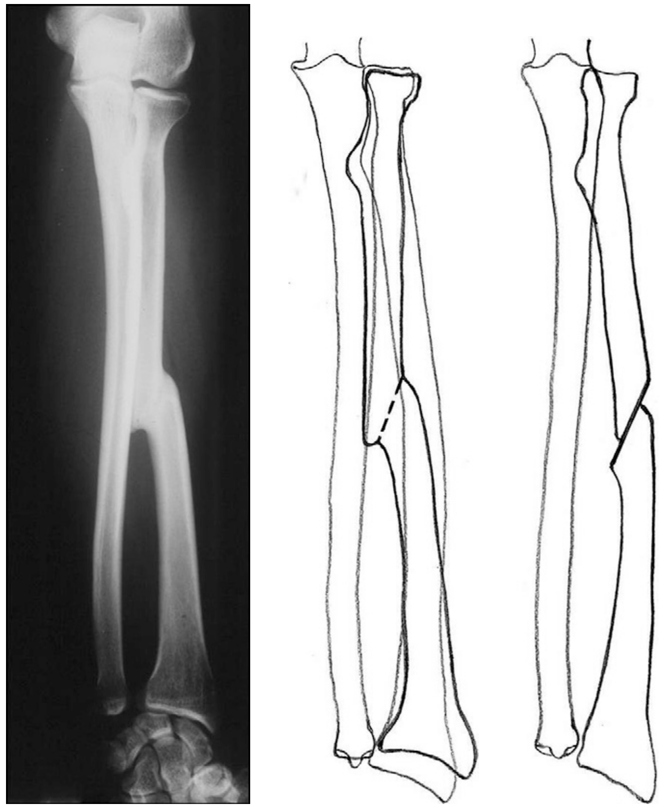

Fig. 1-A Fig. 1-B Fig. 1-C

Fig. 1-A A radiograph of a malunited midshaft left radial fracture after closed treatment. There is reduction of the interosseous space, radial shortening resulting in a positive ulnar variance of 4 mm, and dissociation of the distal radioulnar joint. The patient had complete loss of pronation, unrestricted supination, and pain at the distal radioulnar joint. He also had a negative ulnar variance of 4 mm in the normal forearm. **Fig. 1-B and 1-C** Tracings of the anteroposterior radiographs of the two forearms have been superimposed (Fig. 1-B), and an oblique osteotomy (Fig. 1-C) was chosen to permit a lengthening of 8 mm, which was necessary to restore congruency of the distal radioulnar joint. The amount of lateral displacement of the proximal fragment indicates that a formal release of the interosseous membrane will be necessary.

To decide whether an opening or a closing-wedge osteotomy is suitable, the ulnar variances of the malunited and healthy sides are compared. If a single-cut closing-wedge osteotomy is performed, the wedge should include the true angle of correction. The base of the wedge is measured in millimeters and is included in the preoperative drawing. In an opening-wedge osteotomy, a variable amount of lengthening can be achieved with use of an interpositional bone graft, preferably a compression-resistant corticocancellous graft from the iliac crest. This graft, which may be triangular or trapezoidal in shape, should also include the true angle of deformity.

Techniques for Diaphyseal Osteotomies

We prefer the Henry approach for exposure of the entire radius[29]. Proximal extension of this approach allows the surgeon to perform an anterior elbow joint arthrotomy to treat associated pathological conditions of the proximal radioulnar joint. Subperiosteal detachment of the supinator muscle and protection of the motor branch of the radial nerve are necessary for proximal osteotomies, whereas temporary release of the pronator teres may be needed for a midshaft malunion. The interval between the flexor and extensor carpi ulnaris is used to expose the ulna.

When both the radius and the ulna are malunited, the ulna should be realigned first. The radial realignment can then be “fine-tuned” to correct length and angular discrepancies to obtain accurate congruency of the radioulnar joints.

The site of the osteotomy (the apex of maximal deformity) is determined in the operating room on the basis of the distance from the distal or proximal end of the bone as measured on preoperative radiographic images. Before the osteotomy is performed, two Kirschner wires are placed to mark the exact anteroposterior and lateral planes proximal and distal to the osteotomy. A plate (usually a six or eight-hole 3.5-mm compression plate) is temporarily fixed to the proximal fragment and is contoured to achieve the desired correction. In the middle third of the radius, shaping the plate to reconstruct the physiological radial bow is of paramount importance.

The plate is then removed, and the base of the wedge is marked. If the angular deformity has markedly reduced the interosseous space, the scarred interosseous membrane should be released and partially resected prior to the osteotomy to facilitate reduction of the osteotomy. If a closing-wedge osteotomy is planned, the converging cuts are oriented in the plane of the true deformity. The osteotomy is closed with an intact periosteal hinge, and the plate is reapplied and is fixed to the distal fragment with one screw. The quality of the reduction is checked with fluoroscopy, and the amount of passive rotation is determined. If there is no substantial increase compared with the preoperative range of motion, a release of the interosseous membrane is performed. If, despite these measures, a reasonable improvement in rotation is not obtained, the radius should be derotated to achieve a balanced arc of rotation with at least 50° of pronation and 50° of supination. If bone graft is needed, interpositional corticocancellous bone blocks are preferred. If additional morselized grafts are used, they should not be placed adjacent to the interosseous membrane, as doing so increases the risk of creating a radioulnar synostosis. Associated subluxation of the distal radioulnar joint with malunion of the radial shaft (a healed Galeazzi fracture) usually does not require open reduction of the joint. Restoration of radial length and angular deformity should result in adequate congruity and stability of the joint.

Early active and passive-assisted range-of-motion therapy is begun on the second postoperative day. If passive motion does not reach 60% of that on the contralateral side by four weeks postoperatively, dynamic splinting for pronation and/or supination is begun. Strengthening is started at six to eight weeks after the surgery, and full weight-bearing and sports are allowed once solid bone-healing has been confirmed.

Techniques for Posttraumatic Chronic Radial Head Dislocations

Chronic radial head dislocations are less common in adults than they are in children, but they may be seen in a patient with a neglected initial subluxation associated with a complex high-energy forearm injury or in one with bipolar fracture-dislocations[30-33]. The most important factor responsible for the chronic dislocation is insufficient reduction leading to posttraumatic ulnar shortening (Fig. 2-A), not the loss of ligamentous restraints such as the anular ligament and the proximal part of the interosseous membrane. The discrepancy between the lengths of the radius and ulna is readily assessed by comparing radiographs of the affected and contralateral forearms. Open reduction of the radial head with simultaneous radial shortening is performed through a proximally extended Henry approach. The elongated capsule of the lateral elbow compartment is exposed between the brachioradialis and brachialis muscles after isolating and protecting the radial nerve. The proximal part of the radial shaft is exposed through subperiosteal detachment of the supinator muscle while the posterior interosseous nerve is visualized. The radius is shortened by the difference between the lengths of the ulnae on the affected and healthy sides (Fig. 2-B). The plate is temporarily fixed with two screws into the proximal fragment. The predetermined transverse segment of bone is removed, and the plate is reapplied under compression. After the radius is shortened, the radial head usually reduces without tension against the capitellum. The elbow should be examined in full flexion, extension, and rotation to prove that the radial head is stable. Then, the capsule is closed, with resection of any excessive capsular tissue. Reconstruction of an anular ligament is not necessary if spontaneous reduction is maintained through a passive range of motion.

Discussion

Several outcome studies have shown that satisfactory functional improvement can be expected after surgical correction of forearm malunions sustained in childhood[34-37]. Trousdale and Linscheid reported that the results in adult patients treated within a year after the initial injury were substantially better than those in adults who were treated later[38]. In a recent report by Nagy et al., seventeen patients with a malunited forearm fracture were divided into three groups according to the clinical problem and the presentation of the deformity: (1) limitation of pronation, (2) limitation of supination, and (3) distal radioulnar joint instability[19]. Ten patients had osteotomies of both the radius and the ulna, and seven had an osteotomy of the radius alone. The interosseous membrane was released in nine patients. Bone-healing was uneventful in all cases, and no complications, infections, refractures, or synostoses occurred. Sixteen of the seventeen patients reported subjective improvement, whereas one patient needed a repeat osteotomy to treat a residual symptomatic deformity and then had improvement as well. Patients with limited supination had better functional improvement after the osteotomy than did those with limited pronation. Stability of the distal radioulnar joint was restored after skeletal realignment of the radius without adjuvant ligament reconstruction, and release of the interosseous membrane did not impair function, including strength and stability.

Free Vascularized Fibular Grafting for Reconstruction of the Forearm Axis

General Reconstructive Options

The management of diaphyseal skeletal defects of the forearm is a complex,

The Journal of Bone & Joint Surgery · jbjs.org
Volume 91-A · Number 11 · November 2009

Fig. 2-A

Fig. 2-B

Fig. 2-A A radiograph of a forearm with a chronic radial head dislocation after an open both-bone forearm fracture. The ulna became infected and required multiple reoperations, which resulted in ulnar shortening. A tracing of a radiograph of the contralateral, normal forearm was used to plan an angular correction together with open reduction of the radial head. **Fig. 2-B** Radiographs made at two years show maintenance of radial head stability and uneventful healing of the radial osteotomy site.

often multistage process, and vascularized fibular transfer has proven to be an effective reconstructive procedure in this setting[39-44]. Defects of <6 cm can be successfully treated with cancellous autograft or allograft, although this approach is less predictable in the presence of infection or following radiation therapy[44,45]. Alternatively, external fixation with bone transport works well and can be used to treat gaps of up to 3 cm, but the external fixation usually must be in place for several months and is fraught with complications such as infection and stiffness[46,47]. An additional reconstructive option for segmental bone loss is the creation of a one-bone forearm, but this eliminates all forearm rotation and should be considered to be a final salvage option[48,49].

Free bone transfer with microsurgical anastomoses is technically challenging and is associated with some donor site morbidity but has several distinct advantages[50-52]. Vascularized grafts heal rapidly, and periosteal new bone formation begins early irrespective of graft length. In contrast, nonvascularized grafts must undergo revascularization and creeping substitution before they are fully consolidated[53,54]. Because of its size and cortical nature, use of a free vascularized fibular graft is the treatment of choice for large segmental defects of the forearm[50,55,56]. Up to 26 cm of the fibula on a single vascular pedicle is available for reconstruction[57].

In the presence of associated soft-tissue defects in the forearm, a skin paddle of up to 10 × 20 cm can be transferred with the fibula. This skin pedicle is based on the peroneal artery, and a 6 × 7-cm graft based on each septal perforator can be transferred with the fibula as an osteoseptocutaneous flap for single-stage reconstruction of combined skeletal and soft-tissue defects in the forearm[44,50,55,58-61]. The skin paddle also serves as a means of monitoring the vascular status of the graft[60].

Osteoseptocutaneous Free Vascularized Fibular Flaps

The vascular pedicle of the vascularized fibular osteoseptocutaneous flap is the peroneal artery[55,56]. The artery has two venae comitantes and lies in the posterior compartment of the leg between the tibialis posterior and flexor hallucis longus muscles.

Clinical and cadaver evidence suggests that the best location for the skin paddle is at the junction of the middle and distal thirds of the fibula, 8 to 12 cm proximal to the ankle mortise, where the most consistent supramalleolar septocutaneous perforator is located[62].

Preoperative angiography of the lower limb is not recommended routinely but is recommended for patients with atherosclerosis or symptoms of vascular insufficiency. Angiography of the recipient upper extremity, especially when there has been trauma or previous surgery, is indicated to establish the pedicle length that will be needed. An abnormal result of the Allen test should also prompt angiography. When planning the length of the fibular graft, one should err on the side of a longer graft. Achieving an appropriate final length is critical for alignment of the distal radioulnar joint, and it is much easier to trim excess bone than to make up for a residual deficit in length.

The procedure is preferably done with the patient under general anesthesia because of its anticipated duration, but use of a supplementary regional blockade of the donor or recipient limb can assist with postoperative pain control. The patient is placed in the lateral decubitus position, with the affected upper extremity down and lying on an arm-board and the

Fig. 3-A   Fig. 3-B   Fig. 3-C

Fig. 3-A A coronal T1-weighted non-fat-suppression magnetic resonance scan of a fifteen-year-old boy with Ewing sarcoma of the ulna who underwent a wide resection that resulted in a 14-cm ulnar defect and a 4 × 6-cm soft-tissue defect. **Fig. 3-B** An osteoseptocutaneous fibular flap (including the fibula, soft tissue, and skin) was used to reconstruct the defect. **Fig. 3-C** A radiograph of the forearm after the vascularized fibular graft had healed.

contralateral donor leg up. The arm should be prepared to the axilla, and a sterile tourniquet is used. The donor leg should be prepared to the groin, with sufficient space left for a skin-graft harvest from the proximal part of the thigh, if necessary.

A two-team approach with simultaneous preparation of the recipient site and harvest at the donor site is recommended. The radial artery should be utilized when possible, as it is usually not the primary source of blood flow to the hand. Two recipient veins should be identified and prepared as well.

Although up to 26 cm of viable fibular bone can be harvested, it is preferable to leave 8 to 10 cm of the fibula distally to maintain ankle stability and 7 cm is left proximally for protection of the peroneal nerve. The specific surgical techniques of harvesting the osteocutaneous fibular transfer have been thoroughly described[50,58-61].

Before the vascular anastomoses in the forearm are performed, the fibular graft should be placed in its expected final position and a posteroanterior radiograph of the wrist in neutral rotation should be made to verify anatomic restoration of the forearm axis, ulnar variance, and congruity of the distal radioulnar joint. Stable fixation is then achieved with small-fragment compression plates. This can be done by either direct fixation with a compression plate of the site of a transverse osteotomy or conversion to a step-cut osteotomy. Standard microvascular anastomoses of one artery and two veins are done.

Although patients are instructed to not bear weight on the donor extremity for six weeks, they are en-

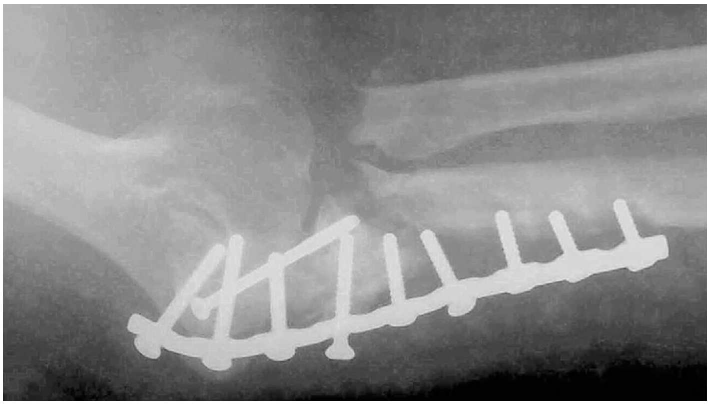

Fig. 4-A

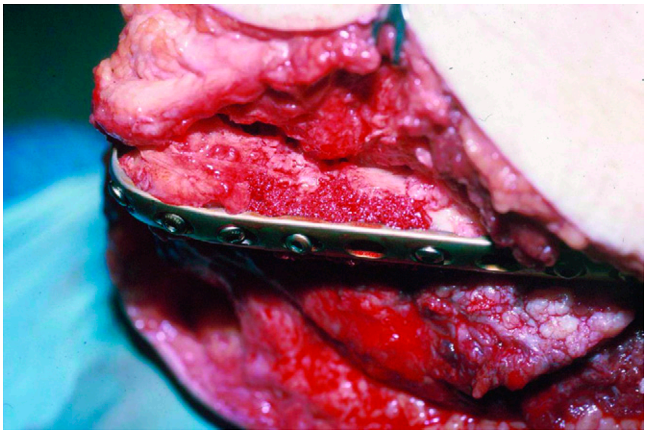

Fig. 4-B

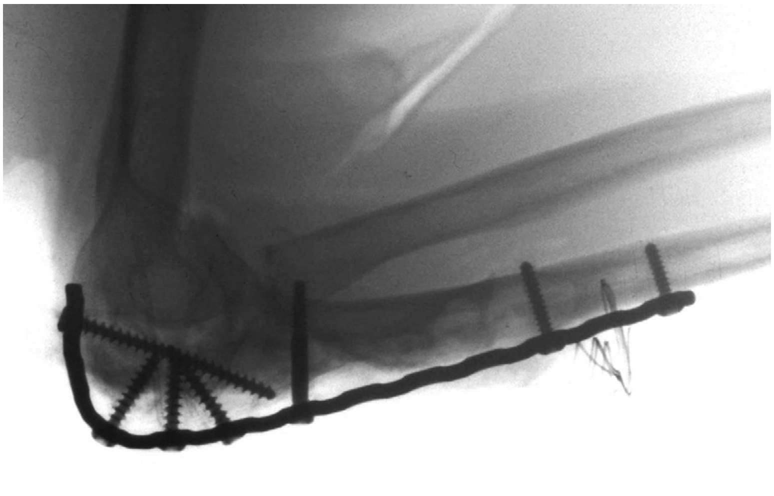

Fig. 4-C

Fig. 4-A A lateral radiograph of an atrophic nonunion of the proximal part of the ulna after internal fixation of a posterior Monteggia fracture-dislocation in a sixty-two-year-old woman. **Fig. 4-B** An intraoperative photograph depicting a plate well contoured to the bone with the defect filled with autogenous iliac crest cancellous bone graft. **Fig. 4-C** A postoperative lateral radiograph of the proximal part of the forearm shows the internal fixation and bone graft in place. The nonunion healed, and the patient regained all but a few degrees of elbow extension.

couraged to start early motion of the toes and ankle, focusing especially on passive stretching of the great toe, which is prone to the development of a flexion contracture. The forearm and elbow are immobilized in a sugar tong splint or long arm cast until there is radiographic evidence of union.

Results

The reconstruction of defects due to trauma, infection, and tumor have been reported to have encouraging results, with times to union of approximately four months[63-66]. Adani et al. reported that eleven of twelve patients with a posttraumatic forearm defect, ranging from 6 to 13 cm in length, had successful union at a mean of 4.8 months[39]. Two patients required additional bone-grafting to achieve consolidation, and an osteoseptocutaneous flap was used in four patients. We previously used an osteoseptocutaneous fibular flap to treat nine patients with a large defect of the radius and an associated soft-tissue defect[50] (Figs. 3-A, 3-B, and 3-C). The mean radial defect was 7.9 cm, and the soft-tissue defect averaged 11.8 × 5.9 cm. All cutaneous flaps survived, and all but one patient obtained osseous union at both host-graft junctions. There were no donor site complications. Kumar et al. treated seven patients (five with a tumor and two with an infection) with application of a free vascularized fibular flap to the forearm[67]. The mean time to union was 3.8 months. There were two nonunions, one of which was converted to a one-bone forearm and the other of which was not treated. Safoury treated eighteen patients with application of a free vascularized fibular graft to the forearm to bridge a posttraumatic segmental defect (mean, 17 cm) and reported a 100% rate of union at a mean of four months[68].

Donor site morbidity is not frequent after treatment with a fibular flap, but gait analysis has shown decreased walking velocity in comparison with control values[68,69]. Ankle valgus is a potential problem in children, and screw stabilization of the distal tibiofibular syndesmosis has been recommended[43,70]. Ankle malalignment or instability has not been a problem in adults[71]. Decreased motion and strength of the great toe have also been observed. We believe that avoiding tight closure of the flexor hallucis and peroneal muscles and the skin interval helps to prevent this problem. Complications at the recipient site include nonunion, fracture of the graft, and thrombosis of the vascular pedicle[41,50].

Diaphyseal Nonunions of the Forearm

Contemporary treatment of diaphyseal fractures of the radius and ulna with stable plate-and-screw fixation has led to nonunion rates of <5%[72-75]. When nonunion occurs, it is generally the result of a complex injury, a complication such as infection, or inadequate internal fixation[72,73,76-78]. Hypertrophic nonunions, characterized radiographically by abundant callus formation, are the result of inadequate mechanical stability of the fracture, usually after nonoperative treatment or treatment with an intramedullary device[79]. Atrophic nonunions, characterized radiographically by tapering of the bones at the fracture without callus formation, lack both the biological capacity to heal and adequate mechanical stability. These nonunions are related to loss of bone at the time of débridement of an open fracture, an infection, or an unexplained lack of healing capacity by the patient (Figs. 4-A, 4-B, and 4-C).

The treatment should restore the length and alignment of the diaphyseal segment, which in turn restores the radioulnar articulations and forearm rotation[9]. Successful treatment is based on stable plate fixation combined with use of intercalary structural grafts, autogenous cancellous grafts, or a vascularized fibular graft[50,80-85].

Ring et al. reviewed the experience with thirty-five diaphyseal atrophic nonunions treated over a fifteen-year period by two surgeons using 3.5-mm compression plates and autogenous cancellous bone-grafting[78]. A segmental osseous defect, averaging 2 cm (range, 1 to 6 cm) in length, was present in each case. Twenty of the original fractures had been open injuries, and a deep infection had developed in association with eleven of them. The nonunion involved the radius alone in sixteen patients, the ulna alone in eleven, and both bones in eight. The 3.5-mm plates had an average of nine holes, and autogenous cancellous bone graft was used to fill the defect in each patient. All fractures healed within six months without additional intervention. Two patients required a subsequent resection of the distal end of the ulna for the treatment of arthritis of the distal radioulnar joint. After an average of forty-three months, the average final arc of forearm rotation was 121° and the average grip strength was 83% of that on the contralateral side. According to the criteria of Anderson et al.[73], five patients had an excellent result; eighteen, a satisfactory result; eleven, an unsatisfactory result (three because of associated elbow injuries and eight because of wrist stiffness); and one, a poor result (due to residual deformity).

Overview

The assessment and management of adverse sequelae of traumatic injury to the forearm can be exceedingly complex. The loss of forearm rotation has a substantial impact on effective function of the entire upper limb. The problems can include diaphyseal deformity, bone or soft-tissue loss, or a failure to heal—either alone or often in combination. Careful preoperative planning is essential to accurately define the extent and location of the clinical problem, establish a precise surgical plan, and better inform the patient regarding the risks and goals of the procedure.

Jesse B. Jupiter, MD
Hand and Upper Limb Service,
Massachusetts General Hospital,
Yawkey Building, Suite 2100,
55 Parkman Street, Boston, MA 02114.
E-mail address: jjupiter1@partners.org

Diego L. Fernandez, MD
Department of Orthopaedic Surgery,
University of Berne, Lindenhof Hospital,
Bremgartenstrasse 19,
CH-3012 Berne, Switzerland.
E-mail address: diegof@bluewin.ch

L. Scott Levin, MD
Penn Orthopaedic Institute,
Hospital of the University of Pennsylvania,
2 Silverstein, 3400 Spruce Street,
Philadelphia, PA 19104.
E-mail address: scott.levin@uphs.upenn.edu

Robert W. Wysocki, MD
Department of Orthopaedic Surgery,

Rush University Medical Center,
1725 West Harrison, Suite 1042,
Chicago, IL 60612.
E-mail address: robertwysocki@mac.com

Printed with permission of the American Academy of Orthopaedic Surgeons. This article, as well as other lectures presented at the Academy's Annual Meeting, will be available in March 2010 in *Instructional Course Lectures,* Volume 59. The complete volume can be ordered online at www.aaos.org, or by calling 800-626-6726 (8 A.M.-5 P.M., Central time).

References

1. Kapandji IA. Physiologie articulaire. Schémas commentés de mécanique humaine. 6th ed. Paris: Maloine; 2005. La prono-supination; p 104-15.

2. Rose-Innes AP. Anterior dislocation of the ulna at the inferior radio-ulnar joint. Case report, with a discussion of the anatomy of rotation of the forearm. J Bone Joint Surg Br. 1960;42:515-21.

3. Djbay HC. L'humerus dans la prono-supination. Rev Med Limoges. 1972;3:147-50.

4. Hotchkiss RN, An KN, Sowa DT, Basta S, Weiland AJ. An anatomic and mechanical study of the interosseous membrane of the forearm: pathomechanics of proximal migration of the radius. J Hand Surg Am. 1989;14:256-61.

5. Rabinowitz RS, Light TR, Havey RM, Gourineni P, Patwardhan AG, Sartori MJ, Vrbos L. The role of the interosseous membrane and triangular fibrocartilage complex in forearm stability. J Hand Surg Am. 1994;19:385-93.

6. Poitevin LA. Anatomy and biomechanics of the interosseous membrane: its importance in the longitudinal stability of the forearm. Hand Clin. 2001;17:97-110, vii.

7. Ofuchi S, Takahashi K, Yamagata M, Rokkaku T, Moriya H, Hara T. Pressure distribution in the humeroradial joint and force transmission to the capitellum during rotation of the forearm: effects of the Sauvé-Kapandji procedure and incision of the interosseous membrane. J Orthop Sci. 2001;6:33-8.

8. Stern PJ, Drury WJ. Complications of plate fixation of forearm fractures. Clin Orthop Relat Res. 1983;175:25-9.

9. Schemitsch EH, Richards RR. The effect of malunion on functional outcome after plate fixation of fractures of both bones of the forearm in adults. J Bone Joint Surg Am. 1992;74:1068-78.

10. Graham TJ, Fischer TJ, Hotchkiss RN, Kleinmann WB. Disorders of the forearm axis. Hand Clin. 1998;14:305-16.

11. Dumont CE, Nagy L, Ziegler D, Pfirmann CW. Fluoroscopic and magnetic resonance cross-sectional imaging assessments of radial and ulnar torsion profiles in volunteers. J Hand Surg Am. 2007;32:501-9.

12. Dumont CE, Pfirmann CWA, Ziegler D, Nagy L. Assessment of the radial and the ulnar torsion profiles with cross-sectional magnetic resonance imaging. A study of volunteers. J Bone Joint Surg Am. 2006;88:1582-8.

13. Jupiter JB, Ruder J, Roth DA. Computer-generated bone models in the planning of osteotomy of multidirectional distal radius malunions. J Hand Surg Am. 1992;17:406-15.

14. Sarmiento A, Ebramzadeh E, Brys D, Tarr R. Angular deformities and forearm function. J Orthop Res. 1992;10:121-33.

15. Matthews LS, Kaufer H, Garver DF, Sonstegard DA. The effect on supination-pronation of angular malalignment of fractures of both bones of the forearm. J Bone Joint Surg Am. 1982;64:14-7.

16. Tynan MC, Fornalski S, McMahon PJ, Utkan A, Green SA, Lee TQ. The effects of ulnar axial malalignment on supination and pronation. J Bone Joint Surg Am. 2000;82:1726-31.

17. Tarr RR, Garfinkel AI, Sarmiento A. The effects of angular and rotational deformities of both bones of the forearm. An in vitro study. J Bone Joint Surg Am. 1984;66:65-70.

18. Dumont CE, Thalmann R, Macy JC. The effect of rotational malunion of the radius and the ulna on supination and pronation. J Bone Joint Surg Br. 2002;84:1070-4.

19. Nagy L, Jankauskas L, Dumont CE. Correction of forearm malunion guided by the preoperative complaint. Clin Orthop Relat Res. 2008;466:1419-28.

20. Hughston JC. Fracture of the distal radial shaft; mistakes in management. J Bone Joint Surg Am. 1957;39:249-64.

21. Bowers WH. Instability of the distal radioulnar articulation. Hand Clin. 1991;7:311-27.

22. Merle d'Aubigné R, Descamps L. L'ostéotomie plane oblique dans la correction des deformations des membres. Bull Mem Arch Chirurgie. 1952;8: 271-6.

23. Saffar P. Ulna oblique osteotomy for radius and ulna length inequality: technique and applications. Tech Hand Up Extrem Surg. 2006;10:47-53.

24. Sangeorzan BP, Judd RP, Sangeorzan BJ. Mathematical analysis of single-cut osteotomy for complex long bone deformity. J Biomech. 1989;22:1271-8.

25. Meyer DC, Siebenrock KA, Schiele B, Gerber C. A new methodology for the planning of single-cut corrective osteotomies of mal-aligned long bones. Clin Biomech (Bristol, Avon). 2005;20:223-7.

26. Nagy L. Malunion of the distal end of the radius. In: Fernandez DL, Jupiter JB, editors. Fractures of the distal radius. A practical approach to management. 2nd ed. New York: Springer; 2002. p 289-344.

27. McNamara M, Munoz A. Alaskan three-dimensional osteotomy: surgical correction for long bone malunions. J Hand Surg Am. 2008;33:776-9.

28. Bindra RR, Cole RJ, Yamaguchi K, Evanoff BA, Pilgram TK, Gilula LA, Gelberman RH. Quantification of the radial torsion angle with computerized tomography in cadaver specimens. J Bone Joint Surg Am. 1997;79:833-7.

29. Henry AK. Extensile exposure applied to limb surgery. Edinburgh: Livingstone; 1945. p 59-65.

30. Bouyala JM, Bollini G, Jacquemier M, Chrestian P, Tallet JM, Tisserand P, Mouttet A. [The treatment of old dislocations of the radial head in children by osteotomy of the upper end of the ulna. Apropos of 15 cases]. Rev Chir Orthop Reparatrice Appar Mot. 1988;74:173-82. French.

31. Inoue G, Shionoya K. Corrective ulnar osteotomy for malunited anterior Monteggia lesions in children. 12 patients followed for 1-12 years. Acta Orthop Scand. 1998;69:73-6.

32. Hasler CC, Von Laer L, Hell AK. Open reduction, ulnar osteotomy and external fixation for chronic anterior dislocation of the head of the radius. J Bone Joint Surg Br. 2005;87:88-94.

33. Freedman L, Luk K, Leong JC. Radial head reduction after a missed Monteggia fracture: brief report. J Bone Joint Surg Br. 1988;70:846-7.

34. Blackburn N, Ziv I, Rang M. Correction of the malunited forearm fracture. Clin Orthop Relat Res. 1984;188:54-7.

35. Meier R, Prommersberger KJ, Lanz U. [Surgical correction of malunited fractures of the forearm in children]. Z Orthop Ihre Grenzgeb. 2003;141: 328-35. German.

36. Price CT, Knapp DR. Osteotomy for malunited forearm shaft fractures in children. J Pediatr Orthop. 2006;26:193-6.

37. van Geenen RCI, Besselaar PP. Outcome after corrective osteotomy for malunited fractures of the forearm sustained in childhood. J Bone Joint Surg Br. 2007;89:236-9.

38. Trousdale RT, Linscheid RL. Operative treatment of malunited fractures of the forearm. J Bone Joint Surg Am. 1995;77:894-902.

39. Adani R, Delcroix L, Innocenti M, Marcoccio I, Tarallo L, Celli A, Ceruso M. Reconstruction of large posttraumatic skeletal defects of the forearm by vascularized free fibular graft. Microsurgery. 2004;24:423-9.

40. Olekas J, Guobys A. Vascularised bone transfer for defects and pseudarthroses of forearm bones. J Hand Surg Br. 1991;16:406-8.

41. Heitmann C, Levin LS. Applications of the vascularized fibula for upper extremity reconstruction. Tech Hand Up Extrem Surg. 2003;7:12-7.

42. Giessler GA, Bickert B, Sauerbier M, Germann G. [Free microvascular fibula graft for skeletal reconstruction after tumor resections in the forearm—experience with five cases]. Handchir Mikrochir Plast Chir. 2004;36:301-7. German.

43. Bae DS, Waters PM, Sampson CE. Use of free vascularized fibular graft for congenital ulnar pseudarthrosis: surgical decision making in the growing child. J Pediatr Orthop. 2005;25:755-62.

44. Kremer T, Bickert B, Germann G, Heitmann C, Sauerbier M. Outcome assessment after reconstruction of complex defects of the forearm and hand with osteocutaneous free flaps. Plast Reconstr Surg. 2006;118:443-56.

45. Hurst LC, Mirza MA, Spellman W. Vascularized fibular graft for infected loss of the ulna: case report. J Hand Surg Am. 1982;7:498-501.

46. Emara KM. Ilizarov technique in management of nonunited fracture of both bones of the forearm. J Orthop Traumatol. 2002;3:177-80.

47. Grishin IG, Golubev VG, Goncharenko IV, Evgrafov AV, Kafarov FM. Transfer of free vascularized bone and skin-bone autografts: experiences in the application of external fixation apparatus. J Reconstr Microsurg. 1990;6:1-11.

48. Peterson CA 2nd, Maki S, Wood MB. Clinical results of the one-bone forearm. J Hand Surg Am. 1995;20:609-18.

49. Castle ME. One-bone forearm. J Bone Joint Surg Am. 1974;56:1223-7.

50. Jupiter JB, Gerhard HJ, Guerrero J, Nunley JA, Levin LS. Treatment of segmental defects of the radius with use of the vascularized osteoseptocutaneous fibular autogenous graft. J Bone Joint Surg Am. 1997;79:542-50.

51. Brown KL. Limb reconstruction with vascularized fibular grafts after bone tumor resection. Clin Orthop Relat Res. 1991;262:64-73.

52. Doi K, Tominaga S, Shibata T. Bone grafts with microvascular anastomoses of vascular pedicles: an experimental study in dogs. J Bone Joint Surg Am. 1977;59:809-15.

53. Moore JB, Mazur JM, Zehr D, Davis PK, Zook EG. A biomechanical comparison of vascularized and conventional autogenous bone grafts. Plast Reconstr Surg. 1984;73:382-6.

54. Enneking WF, Eady JL, Burchardt H. Autogenous cortical bone grafts in the reconstruction of segmental skeletal defects. J Bone Joint Surg Am. 1980;62:1039-58.

55. Stevanovic M, Gutow AP, Sharpe F. The management of bone defects of the forearm after trauma. Hand Clin. 1999;15:299-318.

56. del Pinal F, Innocenti M. Evolving concepts in the management of the bone gap in the upper limb. Long and small defects. J Plast Reconstr Aesthet Surg. 2007;60:776-92.

57. Jones NF, Swartz WM, Mears DC, Jupiter JB, Grossman A. The ‘‘double barrel’’ free vascularized fibular bone graft. Plast Reconstr Surg. 1988;81:378-85.

58. Minami A, Usui M, Ogino T, Minami M. Simultaneous reconstruction of bone and skin defects by free fibular graft with a skin flap. Microsurgery. 1986;7:38-45.

59. Chen ZW, Yan W. The study and clinical application of the osteocutaneous flap of fibula. Microsurgery. 1983;4:11-6.

60. Yoshimura M, Shimamura K, Iwai Y, Yamauchi S, Ueno T. Free vascularized fibular transplant. A new method for monitoring circulation of the grafted fibula. J Bone Joint Surg Am. 1983;65:1295-301.

61. Harrison DH. The osteocutaneous free fibular graft. J Bone Joint Surg Br. 1986;68:804-7.

62. Beppu M, Hanel DP, Johnston GH, Carmo JM, Tsai TM. The osteocutaneous fibula flap: an anatomic study. J Reconstr Microsurg. 1992;8:215-23.

63. Sellers DS, Sowa DT, Moore JR, Weiland AJ. Congenital pseudarthrosis of the forearm. J Hand Surg Am. 1988;13:89-93.

64. Witoonchart K, Uerpairojkit C, Leechavengvongs S, Thuvasethakul P. Congenital pseudarthrosis of the forearm treated by free vascularized fibular graft: a report of three cases and a review of the literature. J Hand Surg Am. 1999;24:1045-55.

65. Zaretski A, Amir A, Meller I, Leshem D, Kollender Y, Barnea Y, Bickels J, Shpitzer T, Ad-El D, Gur E. Free fibula long bone reconstruction in orthopedic oncology: a surgical algorithm for reconstructive options. Plast Reconstr Surg. 2004;113:1989-2000.

66. Minami A, Kasashima T, Iwasaki N, Kato H, Kaneda K. Vascularised fibular grafts. An experience of 102 patients. J Bone Joint Surg Br. 2000;82:1022-5.

67. Kumar VP, Satku K, Helm R, Pho RW. Radial reconstruction in segmental defects of both forearm bones. J Bone Joint Surg Br. 1988;70:815-7.

68. Safoury Y. Free vascularized fibula for the treatment of traumatic bone defects and nonunion of the forearm bones. J Hand Surg Br. 2005;30:67-72.

69. Bodde EW, de Visser E, Duysens JE, Hartman EH. Donor-site morbidity after free vascularized autogenous fibular transfer: subjective and quantitative analyses. Plast Reconstr Surg. 2003;111:2237-42.

70. Germain MA, Mascard E, Dubousset J, Nguefack M. Free vascularized fibula and reconstruction of long bones in the child—our evolution. Microsurgery. 2007;27:415-9.

71. Lee EH, Goh JC, Helm R, Pho RW. Donor site morbidity following resection of the fibula. J Bone Joint Surg Br. 1990;72:129-31.

72. Chapman MW, Gordon JE, Zissmos AG. Compression-plate fixation of acute fractures of the diaphyses of the radius and ulna. J Bone Joint Surg Am. 1989;71:159-69.

73. Anderson LD, Sisk D, Tooms RE, Park WI 3rd. Compression-plate fixation in acute diaphyseal fractures of the radius and ulna. J Bone Joint Surg Am. 1975;57:1068-78.

74. Wright RR, Schmeling GJ, Schwab JP. The necessity of acute bone grafting in diaphyseal forearm fractures: a retrospective review. J Orthop Trauma. 1997;11:288-94.

75. Wei SY, Born CT, Abene A, Ong A, Hayda R, DeLong WG Jr. Diaphyseal forearm fractures treated with and without bone graft. J Trauma. 1999;46:1045-8.

76. Langkamer VG, Ackroyd CE. Internal fixation of forearm fractures in the 1980s: lessons to be learnt. Injury. 1991;22:97-102.

77. Jupiter JB, Ruedi T. Intraoperative distraction in the treatment of complex nonunions of the radius. J Hand Surg Am. 1992;17:416-22.

78. Ring D, Allende C, Jafarnia K, Allende BT, Jupiter JB. Ununited diaphyseal forearm fractures with segmental defects: plate fixation and autogenous cancellous bone-grafting. J Bone Joint Surg Am. 2004;86:2440-5.

79. Sage FP. Medullary fixation of fractures of the forearm. A study of the medullary canal of the radius and a report of fifty fractures of the radius treated with a prebent triangular nail. J Bone Joint Surg Am. 1959;41:1489-516.

80. Barbieri CH, Mazzer N, Aranda CA, Pinto MM. Use of a bone block graft from the iliac crest with rigid fixation to correct diaphyseal defects of the radius and ulna. J Hand Surg Br. 1997;22:395-401.

81. Dabezies EJ, Stewart WE, Goodman FG, Deffer PA. Management of segmental defects of the radius and ulna. J Trauma. 1971;11:778-88.

82. Grace TG, Eversmann WW Jr. The management of segmental bone loss associated with forearm fractures. J Bone Joint Surg Am. 1980;62:1150-5.

83. Miller RC, Phalen GS. The repair of defects of the radius with fibular bone grafts. J Bone Joint Surg Am. 1947;29:629-36.

84. Nicoll EA. The treatment of gaps in long bones by cancellous insert grafts. J Bone Joint Surg Br. 1956;38:70-82.

85. Dell PC, Sheppard JE. Vascularized bone grafts in the treatment of infected forearm nonunions. J Hand Surg Am. 1984;9:653-8.