

Infected nonunions of diaphyseal fractures of the forearm

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Abstract

Background There are no reported series that specifically deal with repair of infected nonunions of the diaphysis of the forearm bones. We sought to determine whether a standardized treatment protocol we have utilized for 15 patients from 1989 to 2005 results in a high union rate, resolution of infection, and a good functional outcome.

Methods The study cohort included nine male and six female patients who presented to a University hospital setting with an infected nonunion of the diaphysis of the radius or ulna. Every patient had a minimum of 2-year follow-up. The average patient age was 45 years (range 17–79). Eight of the patients had fractures involving their dominant arm. Thirteen patients had initially fractured both the radius and ulna, but two of these patients had subsequently healed one of the bones. One patient had an

isolated radius fractures, and one patient fractured the ulna alone. All patients underwent a protocol that combines aggressive surgical debridements as necessary, definitive fixation after 7–14 days, tricortical iliac crest bone grafting for segmental defects, leaving wounds open to heal by secondary intention, 6 weeks of culture-specific intravenous antibiotics, and early active range of motion (ROM) exercises. We sought to report our success rate of nonunion repair, number of re-interventions, complication rate, final ROM, and the ability to eradicate the infection using this treatment regimen.

Results At most recent follow-up (average 5 years, range 2–15 years), all patients had united and resolved their infections. One case was considered a failure, although he did go on to unite a one-bone forearm and was free of infection at most recent follow-up. All but three patients, including the one failure, had at least 50° of supination/pronation and 30–130° of flexion/extension arc. Excluding the one failure that united his one-bone forearm at 46 months, the average time to union was 13.2 weeks (range 10–15 weeks).

Conclusions The results of this study indicate that our standard protocol for treatment of infected nonunion of the shafts of the radius and ulna is reliable at obtaining fracture union with a good functional result, while also resolving the infection.

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Introduction

With the widespread use of AO/ASIF techniques and improved implant designs the nonunion rate of diaphyseal forearm fractures has markedly decreased over the past

half-century [1, 2]. Emphasis on anatomic reduction and strict adherence to these techniques has reduced the rate of nonunions in the forearm to less than 3% [2, 3]. Factors that have been shown to predispose patients to nonunions involving the shafts of the radius and ulna are open injuries, highly comminuted fractures, significant soft-tissue injury, inadequate surgical fixation, and infection [4–7].

Infection rates following ORIF of diaphyseal forearm fractures have ranged from 2 to 6% in the literature, with more recent series demonstrating rates in the higher end of this figure [2, 3, 6–8]. Darouiche looked at the statistics of implant-associated infections in 2004 and demonstrated that 5% of the 2 million fracture-fixation devices implanted in the United States become infected. The combined medical and surgical cost of each of these infections is estimated to be \$15,000 [9]. The ability to prevent or effectively eradicate infections following surgical fixation should therefore be a high priority, and standardized treatment protocols that are cost-effective need to be instituted when this problem does arise.

While infected nonunions in the forearm are rare, the problem is complex due to the presence of bone necrosis, segmental bone loss, sinus tract formation, fracture instability, and scar adhesion of the soft tissues [5, 7]. Only a very small number reports exist specifically dealing with infected nonunions of the diaphyseal radius and ulna, and none of these have included more than four patients [10–14]. The few series in the literature looking at the forearm either deal solely with aseptic nonunions, or they lump all etiologies of forearm nonunion together [7, 15–22]. A number of other studies look at infected nonunions of long bones all together [24, 25]. In the only series specifically dealing with this clinical entity the final outcome was one-bone forearms in all patients [13].

The main goals in the treatment of infected diaphyseal nonunions of the forearm are to eradicate all infection, adequately restore bone length and shape, achieve bone union, and attain an optimal functional outcome. To achieve these goals we have developed and utilized a protocol that combines aggressive debridement, definitive fixation following 7–14 days, tricortical iliac crest bone grafting as needed for segmental defects, leaving wounds open to heal by secondary intention, 6 weeks of culture-specific intravenous antibiotics, and early active range of motion (ROM) exercises. The purpose of the study was to review the results of this protocol utilized for 15 patients at our institution from 1989 to 2007.

Materials and methods

After obtaining approval from our Institutional Review Board, a retrospective chart review of all patients treated

for infected nonunions of diaphyseal fractures of the forearm was performed. The above-mentioned treatment protocol was universally instituted for patients who presented with this clinical problem since 1989, and the cohort therefore consisted of patients presenting to our institution after that time. Inclusion criteria consisted of adult patients (age >18 years) with nonunited, infected diaphyseal forearm fractures with a minimum of 2-year follow-up. All patients were treated by a single surgeon at one of our university hospitals from 1989 to 2005.

Nonunion was defined as an unstable fracture with a lack of progressive healing following three consecutive radiographs, or the persistence of an obvious nonunited fracture a minimum of 4 months from injury. Patients were determined to have an infected nonunion based on clinical, laboratory, and radiographic criteria. Clinical indicators included: erythema or warmth around the incision sites, purulent discharge or palpable abscess, a draining sinus tract, localized pain, gross motion at the fracture site, and systemic signs of infection. Routine laboratory studies including white blood cell (WBC) count and erythrocyte sedimentation rate (ESR) were measured. Radiographs were examined for persistent radiolucent lines or obvious gap at the fracture site, osteolysis, implant loosening or failure, and periosteal reaction.

There were a total of 15 consecutive patients treated by a single surgeon in this study. Included are nine men and six women with an average patient age of 45 (range 19–79 years). The dominant arm was involved in 8 of the 15 patients. The injury mechanisms included: seven falls, five motor vehicle collisions (MVC), two crush injuries, and one boat propeller accident. Eleven of the injuries were open fractures. All had previously undergone open reduction and internal fixation. Thirteen patients had initially fractured both the radius and ulna, but two of these patients had subsequently healed one of the bones. One patient had an isolated radius fractures, and one patient fractured the ulna alone. Fourteen patients had documented infections at the nonunion site, and one other patient had clinical and radiographic signs of an infected nonunion but cultures failed to demonstrate an organism.

Six patients were active smokers, and two patients had histories of drug and alcohol abuse. Six patients were involved in either litigation or worker's compensation claims. Three patients had multiple comorbidities, including two with insulin-dependent diabetes mellitus. Two patients had been treated for psychiatric disorders. Fourteen patients had initially been treated at an outside institution. The average time from injury to presentation to us was 8 months. The average number of previous operative procedures prior to presenting to us was 5.2, with a range of 2–16.

Treatment protocol

After the patients are identified as likely having an infected nonunion they are taken-off of antibiotics for 10–14 days if they are actively being treated. Following this “antibiotic holiday” they are taken to the operating suite for a thorough debridement including removal of hardware. Previous surgical incisions are utilized when possible. Avascular scar is resected along with any established sinus tracts. Great care is taken to sharply debride any inflammatory or fibrous tissue in the wound. Deep cultures are obtained, and bone specimens sent to pathology for analysis. Any necrotic bone is debrided until punctate bleeding of the bone ends is visualized. A 2.5-mm drill is utilized to drill the intramedullary canal in both the proximal and distal segments. The wound is copiously irrigated and left open. The patient is then placed in a posterior splint for stabilization.

Consultation with the infectious disease service was obtained for every patient, and they were initially placed on broad spectrum intravenous antibiotics. A removable posterior long-arm splint is fabricated the day of initial debridement. On the first post-operative day superficial, gentle soap and water washes of the open wound are initiated and performed three times per day in the patient’s room using the faucet. Most patients initially require intravenous analgesics prior to wound care, however after the first 3 days only oral analgesics or none at all are required. Repeat surgical debridements are performed every 48–72 h until a clean surgical bed is achieved. If a specific bacteria is identified from the operative cultures, organism-specific antibiotics are initiated as per the infectious disease team.

The patient returns for definitive fixation once a clean wound is obtained, typically at 7–14 days from the initial debridement. The hip area is prepped and draped as well as the involved extremity if a defect is present at the nonunion site and a bone graft anticipated to be necessary. When needed, an autologous tricortical iliac crest bone graft is harvested that is approximately 5 mm greater in size than the defect that is measured. The fracture and graft are then reduced and stabilized with a 3.5-mm titanium dynamic compression or limited contact dynamic compression plate and screws (Synthes Paoli, PA, USA). Great care is taken to restore length and alignment of the bone or bones involved prior to fixation. Lag screws are placed when possible across the fracture site. At times a neutral screw is placed to secure the structural autograft when used. Compression across the fracture site is obtained with the plate when a lag screw across the fracture site is not possible. Local tissue is loosely approximated to cover the plate and bone, but the wound is once again left open.

Post-operatively wound care with soap and water washes is continued until closure is obtained by secondary intention. Early active ROM exercises are begun immediately under the supervision of an occupational therapist. A peripherally inserted central catheter is placed, and culture-specific antibiotics given for a total of 6 weeks. Aggressive outpatient occupational therapy is continued until maximal ROM is obtained. The patient is monitored closely for evidence of persistent or recurrent infection and osseous healing during regular office visits.

Results

A total of 15 consecutive patients have been treated by a single surgeon for infected nonunions of diaphyseal forearm fractures utilizing this protocol. The average follow-up was 5 years (range 2–15). All patients eventually achieved infection-free union, although one patient required multiple procedures and was eventually converted to a one-bone forearm. The remaining 14 patients all united and had no evidence of infection after initial fixation in the protocol. Excluding the one failure that united his one-bone forearm at 46 months, the average time to union was 13.2 weeks (range 10–15 weeks). No patients, other than this failure, required prolonged antibiotic courses beyond the 6 weeks given during their treatment under this protocol.

Intra-operative and radiographic findings in all patients demonstrated atrophic nonunions. Cortical bone destruction with a moth-eaten appearance was observed in all cases (Fig. 1c). Dense fibrous tissue was always present at the nonunion site with surrounding inflammatory tissue. Twelve patients had segmental defects at the fracture site and required a structural autograft to restore proper length. Tricortical iliac crest graft was used in all 12 cases in which this was found. The average gap measured 2.1 cm, with a range of 1–7 cm (Figs. 2, 3).

All cases were noted to have inadequate fracture fixation at the time of revision, and consequently hardware was removed universally. The plates used at index procedures were often tubular or pelvic reconstruction plates, or the implant chosen was simply deemed to be too short to provide adequate stability by the senior author (Fig. 1a, b). Often times there were less than six cortices of fixation on either side of the plate in the face of a short implant. Gap was universally noted at the fracture site, indicating a lack of adequate compression or possibly bone resorption. In several of the cases where both bones were initially involved, one side healed where the fixation was adequate while the other with inadequate fixation became infected and went on to nonunion.

Deep wound cultures were positive in 14 patients. The most common scenario was a polymicrobial infection

Fig. 1 **a** Anteroposterior (AP) and lateral radiograph of an infected nonunion of the radius demonstrating hardware failure with use of a 3.5-mm reconstruction plate for fixation. **b** Intra-operative photograph after hardware removal demonstrating a nonunion with necrotic, infected bone

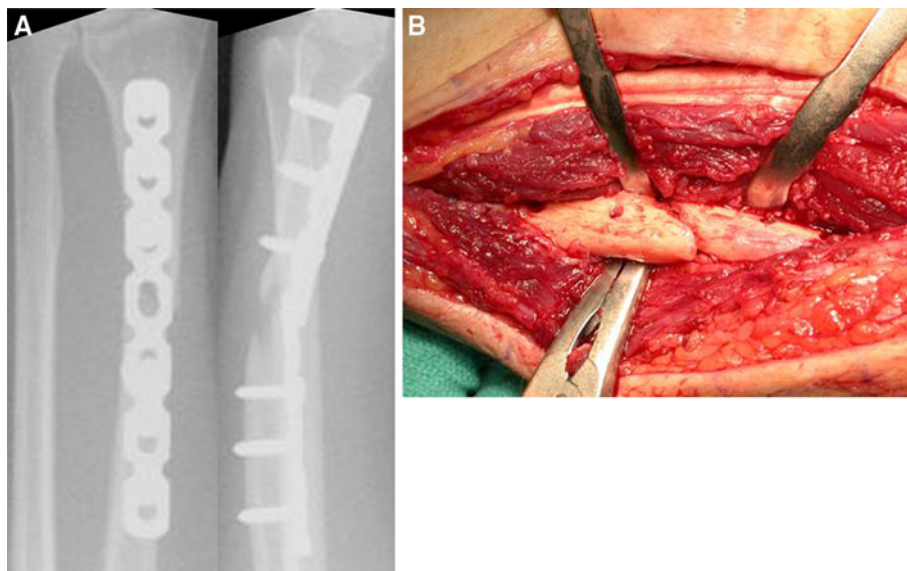


Fig. 2 **a** Anteroposterior radiograph of a 34-year-old man (Patient 9 in Table 1) with a Grade II open left radius and ulna fracture from a boat propeller accident 2 years prior. All previous hardware had been removed. The radiograph shows a segmental gap in the radius after debridement of the infected nonunion site. Intra-operative cultures

revealed *Pseudomonas aeruginosa*. **b** AP radiograph showing definitive fixation of the ulna and radius with placement of a tricortical iliac crest bone graft in the radius. **c** AP and lateral radiographs at final (4-year) follow-up shows union of both bones with complete consolidation of tricortical graft in the radius

including one staphylococcus species found in five patients. When a single organism was isolated four patients grew oxacillin-sensitive *Staphylococcus aureus* (OSSA), 3 methicillin-resistant *Staphylococcus aureus*, and 2 *Pseudomonas aeruginosa*. One patient did not have positive cultures, but both clinically and radiographically had an infected nonunion. This patient had a persistent draining wound with development of a sinus tract for over 6 months from initial surgery at an outside institution. Intra-operative findings were consistent with an infected nonunion. The

surgical pathology demonstrated necrotic bone with inflammatory and fibrous tissue, but no bacteria visualized.

Twelve patients obtained functional ROM of the elbow, with at least 50° of supination/pronation and 30–130° of flexion/extension arc (Table 1). The one patient failure that was converted to a one-bone forearm had severe limitations in forearm rotation as expected. Another patient with limited supination/pronation and pain was a polytrauma patient who suffered from complex regional pain syndrome (CRPS) of the involved extremity upon presentation to us.

Fig. 3 Clinical photographs and radiographs of Patient 1 from Table 1 at 15-year follow-up from her infected nonunion of the ulna demonstrating full range of motion, union and hardware removal, and cosmetic result of the scar over the ulna



Table 1 Patient data with final range of motion of the elbow

Patient	Age	M/F	Mechanism	Fracture	Open	Union (weeks)	Flexion/extension	Pronation	Supination
1	33	F	Fall	Ulna	No	10	0–140	80	90
2	47	M	Crush injury	Both bones	Yes	15	0–130	50	60
3	41	M	Fall	Both bones	No	13	45–90	10	15
4	79	M	MVC	Both bones	Yes	14	0–130	70	90
5	38	M	MVC	Both bones	Yes	13	30–130	50	60
6	47	M	Fall	Radius	Yes	12	0–130	50	50
7	25	F	Fall	Both bones	Yes	15	10–130	50	60
8	51	F	Fall	Both bones	No	12	10–135	60	70
9	34	M	Boat accident	Both bones	Yes	14	30–130	50	55
10	37	F	MVC	Both bones	Yes	15	25–130	0	15
11	59	M	Crush injury	Both bones	Yes	15	30–130	50	55
12	32	M	MVC	Both bones	Yes	Failure	45–100	0	0
13	19	F	MVC	Both bones	Yes	12	20–130	60	70
14	61	M	Fall	Both bones	Yes	13	30–130	50	55
15	63	F	Fall	Both bones	No	12	0–135	70	90

MVC motor vehicle collision

Post-operatively she underwent intensive occupational therapy and pain blocks with persistent limitations. It should be noted that she had a traumatic brain injury (TBI) from her accident. She was also receiving worker's compensation and was involved with litigation following her

MVC. The third patient with poor ROM had initially suffered a Bado IV Monteggia fracture and an ipsilateral shoulder dislocation. The three patients who fell below our cutoff for functional ROM tended to have the greatest number of prior surgical procedures (12/patient average).

There were a total of seven complications in this series, two of which occurred in one patient. This patient suffered from persistent infection resulting in delayed union. He finally united a one-bone forearm after 46 months without any recurrent infection. Only one wound required a split-thickness skin graft, while all the others healed by secondary intention. The average time to wound healing was 4.1 weeks. No patient required flap coverage. One patient developed ulnar impingement and underwent ulnar shortening with resolution of her symptoms. There was one case of cellulitis at the iliac crest donor site that resolved with a short course of oral antibiotics. One patient developed painful hardware and underwent removal with improvement in symptoms. One patient had elective hardware removal without sequelae.

The one failure was in a 32-year-old male initially injured in a MVC during which he was intoxicated and found to have cocaine in his system. He sustained a both-bone forearm fracture on the right, a left distal radius fracture, and a sternal fracture. He had a previous history of gastro-esophageal reflux disease, active tobacco use, illicit drug use, and alcoholism. He developed an early infection with OSSA and was non-compliant with follow-up appointments and therapy. He underwent several irrigation and debridements following the index ORIF and was finally fixed and grafted at 5 months out. He was doing well until he fell off a bike and refractured 7 months later. He subsequently underwent repeat ORIF with development of recurrent OSSA infections and was finally converted to a one-bone forearm. At 46-month follow-up he was without evidence of infection.

Discussion

Most reports on the treatment of infected nonunions refer to the lower extremity, particularly the tibia [23–25]. Infected nonunion in the upper extremity is a rare event, and only a few cases have been reported as either individual case reports [10–12, 14], in association with forearm nonunions that were not infected [7, 15–22], or in conjunction with infected nonunions of other long bones [23–25]. Only one report has dealt specifically with infected nonunion of the forearm [13]. In this case series of four patients, the authors discuss their results with transfer of a vascularized fibular graft to create a one-bone forearm. They fixed the graft to the ulna proximally and the radius distally with internal fixation. In three of the cases it was necessary to use adjunctive external fixation, and one patient required additional supplemental bone grafting [13].

In most reports, the method of treating infected forearm nonunions is not precisely delineated, and the number of cases is so small that it is difficult to draw conclusions about the efficacies of the treatment modalities, which have

also varied widely [10–14, 16, 19, 20]. Ring et al. have reported on a large series of nonunions of diaphyseal forearm fractures. Their retrospective review consisted of a total of 35 patients, of which 11 had deep infections. The main emphasis of the paper was dealing with segmental defects with bridge-plating and adjuvant autologous bone graft. The size of the defects in their series was comparable to our study, measuring an average of 2.2 cm (range 1–6 cm). All patients were treated with cancellous autograft, and no patient required a vascularized bone graft or even structural cortical autograft. They did not provide a detailed description of their treatment protocol for the infected patient subset, and never commented on whether the infection was completely eradicated following treatment [7]. In a similar study of forearm nonunions, the authors also had a mixed cohort of septic and aseptic nonunions but treated them with compression plating and structural autologous bone graft. They demonstrated an excellent union rate (30/31 patients), but once again gave no specific mention to the treatment of the infected patient subset [22].

The combination of dynamic compression plating, tricortical iliac crest bone graft, and open wound healing in forearm nonunions with active infections has not been reported. As mentioned previously, this specific clinical problem with proposed solutions has only been discussed in case reports [10–12], a case controversy article [14], and a series of 4 patients resulting in a one-bone forearm [13]. The open technique of bone grafting for patients with large segmental defects of bone secondary to chronic osteomyelitis has been described previously. The authors of these studies emphasized that delayed secondary closure of the skin was essential. They also stated that stable skeletal fixation was an integral component of the method. These authors simply used autologous bone graft, and avoided the high morbidity of vascularized bone transfer as well [21, 26, 27]. In a large study of patients who underwent reconstruction of skeletal defects with vascularized bone transfer there was a 52% nonunion rate and 16% rate of infection recurrence in the subset of patients with osteomyelitis. The authors cautioned against the use of such grafts in the setting of chronic infection [28]. Even so, we do feel that in the face of defects over 7 cm vascularized bone grafts might be necessary to attain union. Using metal cages packed with morsellized bone graft could be another alternative for such large diaphyseal defects [29].

We were ultimately able to obtain infection-free union in all patients, and functional ROM in all but three. We feel that even with three patients with limited ROM, our outcomes were far superior to those reported by Dell and Sheppard who converted all four of their patients to one-bone forearms [13]. Upon examination of our three patients with limited motion, there were significant extraneous factors that likely

contributed to the final outcome. One patient was in a MVC and suffered a TBI. She had CRPS of the involved extremity following the accident that was not responsive to therapy and peripheral pain nerve blocks. She was also receiving worker's compensation and involved in litigation. Another patient involved in a fall from a carnival ride sustained a Bado IV Monteggia fracture and an ipsilateral shoulder dislocation. This complex injury pattern may have contributed to the limited ROM. He was also on worker's compensation. Finally, the third patient who had a prolonged course likely due to non-compliance and smoking was converted to a one-bone forearm. Upon examining these three patients together, they tended to have the highest number of previous surgical procedures ($N = 12$). This may have also contributed to limited ROM secondary to excessive scarring.

The obvious shortcomings of the paper are its retrospective nature and the relatively small number of patients. The main strength is our average 5-year follow-up. This specific problem has been the focus of a recent case-controversy [14], and we would like to propose a treatment protocol that has been very effective in our hands. The main limitation to the use of this protocol is in patients that have either a devitalized or absent soft tissue compartment and may be better treated with an osteoseptocutaneous flap [16]. Such flaps were deemed unnecessary by the senior author in all cases since no patient had a large open wound upon presentation, and enough viable local muscle and fascia was present to obtain coverage of the plate and bone during surgery. Although not all patients in our series obtained full range or motion, every patient achieved bone union with concurrent resolution of infection. Only one patient required a skin graft and the remainder healed by secondary intention without sequelae and a good cosmetic result. We believe that our protocol is a viable option for the management of infected nonunions of the forearm, and offers an excellent chance for union and a good functional outcome.

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References

1. Knight RA, Purvis GD (1949) Fractures of both bones of the forearm in adults. *J Bone Joint Surg* 31-A:755
2. Chapman MW, Gordon JE, Zissimos AG (1989) Compression-plate fixation of acute fractures of the diaphyses of the radius and ulna. *J Bone Joint Surg* 71:159–169
3. Schemitch EHG, Richards RR (1992) The effect of malunion on functional outcome after plate fixation of fractures of both bones of the forearm in adults. *J Bone Joint Surg* 74:1068–1078
4. Moroni A, Rollo G, Guzzardella M, Zinghi G (1997) Surgical treatment of isolated forearm non-union with segmental bone loss. *Injury* 28:497–504
5. Rubin C (1983) Analysis of 81 cases of nonunion of forearm fractures. *Chin Med J* 96:29–32
6. Langkamer VG, Ackroyd CE (1991) Internal fixation of forearm fractures in the 1980 s: lessons to be learnt. *Injury* 22:97–102
7. Ring D, Allende C, Jafarnia K, Allende BT, Jupiter JB (2004) Ununited diaphyseal forearm fractures with segmental defects: plate fixation and autogenous cancellous bone-grafting. *J Bone Joint Surg* 86:2440–2445
8. Stern PJ, Drury WJ (1983) Complications of plate fixation of forearm fractures. *Clin Orthop* 175:25–29
9. Darouiche RO (2004) Treatment of infections associated with surgical implants. *N Engl J Med* 350:1422–1429
10. Hurst LC, Mirz MA, Spellman W (1982) Vascular fibular graft for infected loss of the ulna: case report. *J Hand Surg* 7:498–501
11. Meals RA (1989) The use of flexor carpi ulnaris muscle flap in the treatment of an infected nonunion of the proximal ulna: a case report. *Clin Orthop* 240:68–72
12. Malki A, Wong-Chung J, Hariharan V (2000) Centralization of ulna for infected nonunion of the radius with extensive bone loss. A modified Hey-Groves procedure. *Injury* 31:345–349
13. Dell PC, Sheppard JE (1984) Vascularized bone grafts in the treatment of infected forearm nonunions. *J Hand Surg* 9:653–658
14. Steinberg EL (2004) Case controversy: Infected nonunion of the ulna. *J Orthop Trauma* 18:470–472
15. Ring D, Jupiter JB, Gulotta L (2003) Atrophic nonunions of the proximal ulna. *Clin Orthop* 409:268–274
16. Jupiter JB, Gebhard HJ, Guerrero J (1997) Treatment of segmental defects of the radius with use of the vascularized osteoseptocutaneous fibular autogenous graft. *J Bone Joint Surg* 79:542–550
17. Harrington DK, Saleh M (1999) An open fracture of the ulna with bone loss, treated by bone transport. *Injury* 30:349–356
18. Barbieri CH, Mazzer N, Aranda CA, Pinto MM (1997) 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* 22-A:395–401
19. Kumar VP, Satku K, Helm R, Pho RWH (1988) Radial reconstruction in segmental defects of both forearm bones. *J Bone Joint Surg Br* 70-B:815–817
20. Dabezies EJ, Stewart WE, Goodman FG, Deffer PA (1971) Management of segmental defects of the radius and ulna. *J Trauma* 11:778–788
21. Calkins MS, Burkhalter W, Reyes F (1987) Traumatic segmental bone defects in the upper extremity. Treatment with exposed grafts of corticocancellous bone. *J Bone Joint Surg* 69:19–27
22. Baldy dos Reis F, Floppa F, Alvachian Fernandes HJ, Albertoni WM, Stahel PF (2009) Outcome of diaphyseal forearm fracture-nonunions treated by autologous bone grafting and compression plating. *Ann Surg Innov Res* 3:5
23. Green SA, Dlabal TA (1983) The open bone graft for septic nonunion. *Clin Orthop* 180:117–124
24. Meyer S, Weiland AJ, Willenegger H (1975) The treatment of infected nonunion of fractures of long bones. *J Bone Joint Surg* 57-A:836–842
25. Pho RWH, Vajara R, Satku K (1983) Free vascularized bone transplants in problematic nonunions of fractures. *J Trauma* 23:341–349
26. Papineau LJ, Alfageme A, Dalcourt JP, Pilon L (1979) Ostéomyélite chronique: excision et greffe de spongieux à l'air libre après mises à plat extensives. *Int Orthop* 3:165–176
27. Papineau LJ, Blamoutier A (1993) Open sky bone graft in the treatment of non unions and extensive saucerizations. *Eur J Orthop Surg Trauma* 3:49–54
28. Han CS, Wood MB, Cooney WP (1992) Vascularized bone transfer. *J Bone Joint Surg* 74:1441–1449
29. Bullens PHJ, Schreuder BHW, de Waal Malefijt MC, Veth-Pieter Buma RPH, Verdonschot N (2009) The stability of impacted morsellized bone grafts in a metal cage under dynamic loaded conditions: an in vitro reconstruction of a segmental diaphyseal defect. *Arch Orthop Trauma Surg* 129:575–581