Exchange Nailing of Ununited Fractures

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Current Concepts Review

Exchange Nailing of Ununited Fractures

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- Exchange nailing is most appropriate for a nonunion without substantial bone loss.
- There is no clear consensus regarding the use of exchange nailing in the presence of active, purulent infection.
- The exchange nail should be at least 1 mm larger in diameter than the nail being removed, and it has been recommended that it be up to 4 mm larger when the nail being removed was greatly undersized. Canal reaming should progress until osseous tissue is observed in the reaming flutes.
- Exchange nailing is an excellent choice for aseptic nonunions of noncomminuted diaphyseal femoral fractures, with union rates reported to range from 72% to 100%. On the basis of the available literature, exchange nailing cannot be recommended for distal femoral nonunions at this time.
- Exchange nailing is an excellent choice for aseptic nonunions of noncomminuted diaphyseal tibial fractures, with union rates reported to range from 76% to 96%.
- On the basis of the available literature, exchange nailing is generally not indicated for humeral nonunions.

Historical Perspective

Early descriptions of intramedullary nailing for the treatment of delayed union and nonunion of fractures rarely distinguished between patients undergoing nail exchange and those undergoing nail stabilization following failure of another treatment method, such as plate fixation[1-9]. Most of these early studies demonstrated high rates of osseous union, but the studies were heterogeneous in nature and the precise details of the nailing procedure, such as the nail diameter and the reaming technique, were rarely discussed.

In 1972, Olerud and Karlström reported an exchange of an intramedullary nail for a larger-diameter nail in the treatment of a nonunion of the tibia[10]. The patient treated with this procedure was one in a series of fifteen patients undergoing "secondary intramedullary nailing" because of nonunion or hardware failure following plate fixation of a tibial fracture[10]. This one fracture that underwent exchange nailing failed to progress to osseous union by seven months following the secondary intramedullary nailing procedure. The following year, Christensen reported on nail exchange in nine patients who were part of a series of thirty-five patients treated with intramedullary nailing of a nonunion of the femur or tibia[1]. The reported union rate in the entire series was 100%. Oh et al. reported a series of fifteen femoral nonunions in which twelve were treated with closed nail exchange; two patients had active infection at the time of the nail exchange[4]. All patients had osseous union.

In contrast to these findings in the lower extremity, Christensen later reported five cases of nail exchange in a series of thirteen patients with humeral nonunion; only two of the patients had osseous union after the nail exchange[2].

Throughout the 1980s and early 1990s, several authors reported other examples of nail exchange for treatment of nonunion within larger series of patients undergoing intramedullary nailing following failure of other treatment methods[5-7,11,12]. The descriptions of the cases did not typically distinguish the patients treated with nail exchange from those who underwent intramedullary nailing after failure of other methods, although nail exchange appeared to be an effective treatment for lower-extremity nonunions in these reports. Clancey et al. reported a 96% rate of osseous union following intramedullary nailing of forty-eight tibial nonunions, including two that underwent nail

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exchange[11]. Harper reported that sixteen patients with femoral nonunion had osseous union following intramedullary nailing[12]. Eight patients in the series had undergone nail exchange (five with concomitant open autogenous bone-grafting); six of the eight had osseous union, and one additional patient had osseous union after a second exchange to a larger-diameter nail. Webb et al. described the results of intramedullary nailing of femoral nonunion in 105 patients, forty-nine of whom had been previously treated with intramedullary nailing of the fracture[7]. The overall rate of osseous union following intramedullary nailing for the entire series was 96%, but no specific details were given for the forty-nine patients treated with nail exchange. Klemm reported on a series of thirty-six patients in whom an infected femoral or tibial nonunion had been treated with nail exchange, continuous-irrigation suction drainage, and antibiotic therapy[6]. All sixteen infected femoral nonunions healed, and nineteen of twenty infected tibial nonunions healed. In a series of sixty-six lower-extremity nonunions, Kempf et al. found that four of six femoral nonunions and nineteen of twenty-one tibial nonunions united following nail exchange[5].

Contemporary Exchange Nailing

Exchange nailing for the treatment of an ununited long-bone fracture includes removal of the current intramedullary nail, reaming of the medullary canal, and placement of an intramedullary nail that is larger in diameter than the removed nail[13-15].

Effects of Exchange Nailing

Exchange nailing provides biological and mechanical effects that promote osseous healing. The biological effects result from reaming of the medullary canal, and the mechanical effects result from the use of a larger-diameter intramedullary nail.

Biological Effects

Reaming of the medullary canal increases periosteal blood flow and stimulates periosteal new-bone formation[16]. A large portion of the cortex loses perfusion immediately after reaming because the endosteal circulation is destroyed and bone marrow blocks the intercortical canals[16-18]. In response to these effects, periosteal blood flow increases in order to maintain circulation in the cortical bed[19,20]. Blood flow in the cortex re-

Fig. 1-A

Fig. 1-B

Anteroposterior (Fig. 1-A) and lateral (Fig. 1-B) radiographs made at the presentation of a twenty-five-year-old man with a hypertrophic nonunion, twelve months after an open diaphyseal-metaphyseal tibial fracture that was initially treated with a statically locked 10-mm closed-section nail.

turns to normal or supranormal levels within days after medullary reaming[16,20-22]. The periosteum reacts to the increased blood flow by forming new bone[16], which in turn aids in healing of the nonunion (Figs. 1-A through 1-D).

Several authors have suggested that the products of reaming, which contain osteoblasts and multipotent stem cells[23-25], serve as local bone graft that stimulates medullary healing at the nonunion site[15,26-28]. In a study of a cadaver sheep model, Frolke et al. reported that a substantial amount of reaming debris was extruded through a femoral osteotomy site during reaming of the medullary canal[29]. In contrast, in a report on twenty-five patients with aseptic femoral nonunion, Furlong et al. stated that, in their opinion, it is unlikely that the products of intramedullary reaming can penetrate the fibrous tissue at a nonunion site to serve as bone graft in the periosteal region; however, they did not directly measure extruded reaming products[30]. At the present time, there is no consensus in the literature regarding whether reaming products act as local bone graft in cases of nonunion.

Other possible mechanisms by which reaming stimulates healing at a nonunion site include activation of growth factors[31], induction of an inflammatory response[31-33], and attenuation of immune system reactivity[32].

Mechanical Effects

A nail that has a larger diameter than the intramedullary nail that was removed provides greater bending rigidity and strength than the original nail[27,34,35]. Reaming also widens and lengthens the isthmic portion of the medullary canal. This increases the cortical contact area of the nail, which enhances mechanical stability.

Mechanical stability can also be improved by increasing the length of the nail when the original nail was too short in one of the fragments. Furthermore, mechanical stability can be improved either by increasing the number of interlocking screws or by using a nail that allows placement of interlocking screws that are not purely parallel to one another.

Indications for Exchange Nailing

The principal indication for exchange nailing is a nonunion in a long bone of the lower extremity following prior intramedullary nailing[14,36]. Pain and disability are the most common

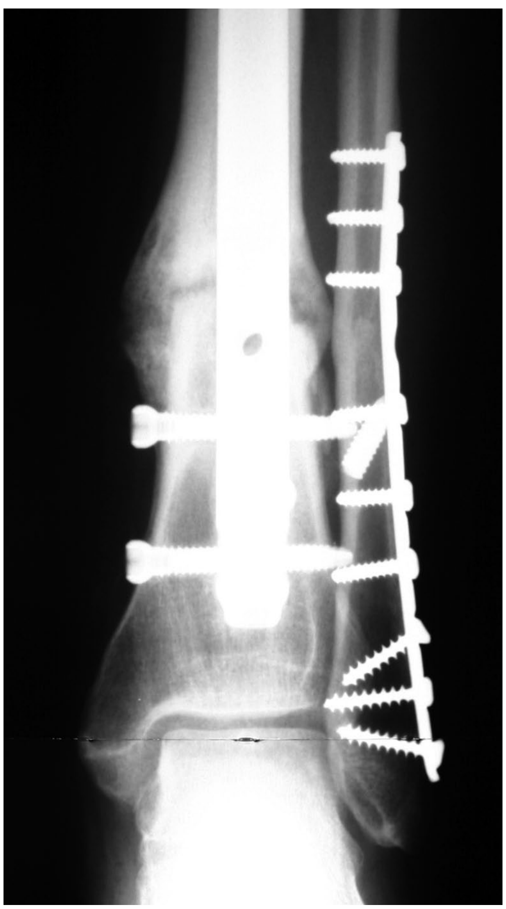

Fig. 1-C

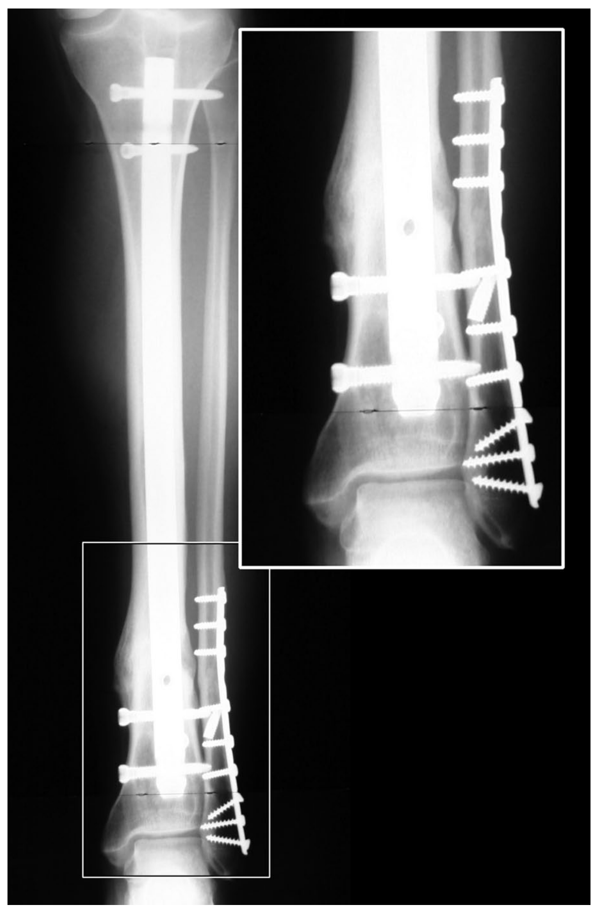

Fig. 1-D

Fig. 1-C Anteroposterior radiograph made four weeks after exchange nailing with a statically locked 13-mm closed-section nail (after reaming of the intramedullary canal to a diameter of 14 mm), showing early periosteal new-bone formation. **Fig. 1-D** Final anteroposterior radiograph, made twelve weeks after exchange nailing, showing solid osseous union.

presenting symptoms, although occasionally a patient with an obvious nonunion on radiographs will present without symptoms. In such cases, the decision of whether to perform exchange nailing should be made after careful consultation with the patient and his or her family. Whereas exchange nailing could potentially lead to pain in an otherwise asymptomatic patient, if exchange nailing is not done a broken nail may have to be extricated at some late date. Factors that should be considered include the patient's age, health status, and activity level; the type of nonunion (hypertrophic nonunions are typically more stable than atrophic nonunions); the presence or absence of neuropathy; and the diameter of the nail in situ.

Exchange nailing has been shown to be successful for the treatment of both atrophic and hypertrophic nonunions[37]. Exchange nailing of an atrophic nonunion may stimulate a healing response and augment mechanical stability. Exchange nailing of a hypertrophic nonunion augments mechanical stability, which is the main requirement to achieve osseous healing.

When a nonunion persists following exchange nailing, the treating surgeon is left with the difficult decision of whether to perform a repeat exchange nailing. In our opinion, repeat exchange nailing of the femur or tibia should be performed only in patients who have demonstrated clinical or radiographic improvement, or both, following the most recent exchange nailing procedure.

Several published reports have described patients who underwent repeat exchange nailing. Kempf et al. described performing a nail exchange procedure in six patients with a femoral nonunion and twenty-one patients with a tibial nonunion in a series of sixty-six patients treated with intramedullary nailing of a femoral or tibial nonunion[5]. Four of the six femora and nineteen of the twenty-one tibiae healed following the nail exchange. The two ununited femora healed following a second nail exchange. One of the ununited tibiae healed following a second nail exchange, and the other healed following débridement and external fixation for treatment of an infection that developed after the nail exchange[5].

Court-Brown et al. reported that, of thirty-three aseptic diaphyseal tibial nonunions, twenty-five healed after one exchange nailing procedure and four more healed after a second exchange nailing[15]. The four nonunions for which two rounds of exchange nailing had failed required bone-grafting to achieve osseous union.

In a study by Templeman et al. on twenty-seven diaphyseal tibial nonunions that underwent exchange nailing, twenty-three healed following one exchange nailing and two healed following a second exchange nailing[38]. The two remaining nonunions were associated with bone loss exceeding 30% of the cortical diameter. These nonunions underwent one exchange nailing and healed following a subsequent bone-grafting procedure.

Hak et al. reported on twenty-three patients with diaphyseal femoral nonunion who were treated with exchange nailing[39]. Of the five nonunions that failed to heal following the exchange nailing, two underwent repeat exchange nailing and one of them healed.

Weresh et al. described a series of nineteen diaphyseal femoral nonunions treated with exchange nailing, ten of which healed[40]. Of the nine nonunions that failed to heal, four were treated with a second exchange nailing and bone-grafting; three of those four healed.

Pihlajamaki et al. reported on eighteen patients who underwent exchange nailing in a larger series of thirty-five patients with diaphyseal femoral nonunion[37]. Of the eighteen patients, fourteen had healing following one exchange nailing. Of the remaining four, two had healing following a second exchange nailing and the other two had healing following dynamization of the exchange nail.

Banaszkiewicz et al. studied the results in eighteen patients with a total of nineteen femoral nonunions that were treated with exchange nailing[41]. Eleven nonunions healed following a single exchange nailing. Of the remaining eight nonunions, four underwent a second exchange nailing and all four united (one required dynamization of the second exchange nail).

Not all long-bone nonunions in the lower extremity for which intramedullary nailing has failed are appropriate for exchange nailing. Several other important considerations involved in the decision whether to perform exchange nailing include osseous contact, deformity, infection, and the anatomic site.

Exchange Nailing in the Presence of Bone Loss

Exchange nailing is most successful in the treatment of nonunions following closed or open fractures without substantial bone loss[14,15,38]. Templeman et al. noted that two tibial nonunions that had failed to unite following exchange nailing both had cortical bone loss exceeding 30% of the cortical diameter[38]. Court-Brown et al. reported that the only failures of exchange nailing among thirty-three cases of aseptic tibial nonunion occurred when >50% of the cortical diameter was missing for a length of >2 cm[15]. Partial cortical defects can be treated with exchange nailing in concert with the closed intramedullary bone-grafting technique, as described by Chapman[42].

Nonunions following comminuted fractures do not appear to respond to exchange nailing as favorably as nonunions following simple transverse or oblique fractures[41,43]. For example, in a prospective case series, Banaszkiewicz et al. reported that eleven of nineteen femoral nonunions resulting from a comminuted fracture required additional operative intervention to obtain osseous union following exchange nailing[41]. Similarly, in a retrospective case series, Mercado et al. found that tibial nonunions with comminution had an increased time to union following exchange nailing[43]. While comminution of the original fracture is not an absolute contraindication to exchange nailing, comminution may decrease the rate of osseous union and increase the time to osseous union.

Exchange Nailing in the Presence of Deformity

The most common reasons for nonunion of fractures treated with an intramedullary nail are the use of an undersized nail, inadequate interlocking, a metaphyseal or metadiaphyseal location of the fracture, or hardware failure. In the case of a lax[44,45] nonunion that can be manually reduced, the previously placed nail should be removed, the long bone should be realigned (and held reduced with a femoral distractor or a temporary external fixator), and an exchange nailing should then be performed. In the case of a stiff[44,45] hypertrophic nonunion that cannot be manually reduced, acute deformity correction can be accomplished with an osteotomy. The long bone should be realigned (and held reduced with a femoral distractor or a temporary external fixator), and an exchange nailing should be performed.

Exchange nailing alone has not been recommended for the treatment of nonunions with a segmental defect or in cases where the bone is foreshortened >1 cm.[26,36,46]. There have been several reports on patients in whom the exchange of an intramedullary nail was combined with open bone-grafting for the treatment of a femoral nonunion with a large segmental defect. Wu et al. reported successful osseous union and restoration of femoral length in thirty-nine of forty-one patients in whom a femoral shaft nonunion with shortening of between 1.5 and 4.5 cm had been treated with acute lengthening, open bone-grafting, and exchange of the intramedullary nail[47]. Wu and Lee subsequently reported that treatment with an open bone-grafting procedure and exchange of the nail achieved osseous union with restoration of femoral length in ten of eleven patients who had had a femoral nonunion with 1.5 to 3.5 cm of shortening[48].

Exchange Nailing in the Presence of Infection

No consensus can be found in the literature regarding the use of exchange nailing to treat an infected long-bone nonunion and, to the best of our knowledge, no randomized prospective studies of the topic have been performed.

Hak et al. found that a nondraining or quiescent infection discovered in five patients at the time of nail exchange, and treated with organism-specific antibiotics following the exchange nailing, had no effect on the rate of osseous union in their series of twenty-three patients with femoral nonunion[39]. Similarly, in a study by Richmond et al., of thirty-two patients, ten of whom underwent exchange nailing, a history of deep infection (which resolved before the exchange nailing procedure) in seven patients had no effect on the rate of healing following exchange nailing of the tibia[49].

In a recent report by Petrisor et al.[50], eighteen of thirty-five infected tibial nonunions treated with a protocol described by Court-Brown et al.[51] met the criteria for exchange nailing. Of these eighteen nonunions, only seven healed following the exchange nail procedure; the eleven that failed to heal required additional operative intervention[50].

When an orthopaedic surgeon decides to treat an infected nonunion with a planned series of surgical procedures, an antibiotic-impregnated polymethylmethacrylate nail can be implanted to provide temporary internal splinting and to bathe the medullary cavity with a local antimicrobial drug[52-54]. As the final treatment stage, the antibiotic-impregnated nail is removed and a permanent interlocking nail is implanted.

Technical Aspects of Exchange Nailing

Locked Compared with Unlocked Nails

Many authors have stated that locking screws are often unnecessary in exchange nailing[15,36,38-40,43,46]. These authors have proposed that locking of the exchange nail is necessary only when there is instability of the construct or a periarticular nonunion with a small distal or proximal fragment[15,38,43]. Some investigators have found no difference in the healing rates or time to union between patients treated with a statically locked nail and those treated with a dynamically locked nail[46,55]. One report showed the time to osseous union to be longer for fractures treated with a statically or dynamically locked exchange nail than for those treated with an unlocked exchange nail[43].

Unlocked or dynamically locked nails allow gradual compression at the nonunion site during weight-bearing and may promote osseous union[55]. Gradual axial compression at the nonunion site can be attained with a statically locked exchange nail if it has slotted interlocking holes[39].

Acute compression at the nonunion site can be obtained intraoperatively either with reverse impaction of the nail or through the use of a femoral distractor[39]. Following acute compression, the nail can be locked statically to provide added stability, particularly in the horizontal plane[39]. In addition, some of the more recently developed nails were designed to allow the surgeon to apply compression acutely across the site of injury.

Slotted Compared with Closed-Section Nails

The optimal bending rigidity and torsional rigidity for an intramedullary nail are unknown[56]. Increasing the rigidity of the nail increases the stability of the nail-bone construct, but a nail that is too rigid may increase the risk of comminution at the time of insertion even if the medullary canal is reamed to a diameter 2 mm larger than that of the nail[56].

Closed-section and open-section (slotted) intramedullary nails have comparable bending rigidities and strengths[34,56]. The bending rigidity of both types of nails increases proportionately with the fourth powers of the inner and outer radii of the nail, while the strength increases proportionately with the third power of the radius[57-59]. Thus, a larger-diameter nail provides higher bending rigidity and strength[58,60,61]. Clinically, the decrease in bending rigidity attributable to the slot in the nail is small and does not result in a meaningful difference compared with the bending rigidity of a same-sized closed-section intramedullary nail[58,60].

In contrast, the torsional rigidity of a closed-section nail is many times higher than that of a slotted nail[34,56,60]. The torsional rigidity of a closed-section nail increases proportionately with the fourth powers of the inner and outer radii of the nail[58]. Thus, a larger-diameter closed-section nail has higher torsional rigidity. The torsional rigidity of a slotted intramedullary nail, however, increases not with the nail radius but with its circumference and the third power of the wall thickness of the nail[58]. For example, a 10-mm open-section nail with a 2-mm slot would have to have a wall thickness of nearly 4 mm to have the same approximate torsional rigidity as a 10-mm closed-section nail of the same material with a wall thickness of 1.2 mm. It is difficult to draw any conclusions from the literature or make any recommendations regarding the relative benefits of slotted compared with closed-section nails in exchange nailing of long-bone nonunions.

Nail Diameter

Appropriate exchange-nailing technique includes the insertion of a nail of a larger diameter than the nail being removed. The exchange nail should be at least 1 mm larger in diameter, but use of a nail that is 2 to 4 mm larger in diameter greatly increases the stiffness and strength of the construct[62]. The literature contains little definitive information regarding the optimal increase in nail diameter to be used in exchange nailing. The surgeon should be guided by clinical judgment based on the diameter of the medullary canal, the degree of undersizing of the previous nail, the thickness of the cortex, and other osseous and patient characteristics.

Reaming

The literature also provides little definitive information regarding the optimal amount of reaming to be performed during exchange nailing. Court-Brown et al. stated: "Successively larger bits, by 0.5 mm each time, are used to remove endosteal fibrous tissue until bone is seen on the end of the drill-bit, usually at about a diameter of 1 mm above the original reaming. More reaming is required if the original nail had been of an inappropriately small diameter."[15] We have recommended overreaming by an amount 1 to 2 mm greater than the diameter of the new nail being inserted[62], and we further recommend the use of sharp reamers, with slow gradual reaming.

Bone-Grafting

The indications for open bone-grafting during exchange nailing remain obscure, and no consensus of opinion can be found in the literature. Several specific options are available when bone-grafting is used in concert with exchange nailing. These include (1) open bone-grafting, whereby the graft material is delivered directly to the nonunion site through an incision overlying it; (2) posterolateral bone-grafting of the tibia; (3) intramedullary grafting, whereby the surgeon reinserts the reaming products collected from the reaming flutes back into the medullary canal to the level of the nonunion us-

Fig. 2-A Fig. 2-B Fig. 2-C Fig. 2-D

Figs. 2-A and 2-B Anteroposterior (Fig. 2-A) and lateral (Fig. 2-B) radiographs at the presentation of a thirty-year-old man with an oligotrophic nonunion (viable and vascular but with little or no callus formation) thirty-three months after a closed diaphyseal femoral fracture that was initially treated with a dynamically locked 11-mm nail. **Figs. 2-C and 2-D** Anteroposterior (Fig. 2-C) and lateral (Fig. 2-D) radiographs made twelve months following exchange nailing with a statically locked 15-mm closed-section nail (after reaming of the intramedullary canal to a diameter of 16.5 mm).

ing a chest tube; and (4) delivery of autogenous iliac crest bone graft to the site of injury through the medullary canal by means of a chest tube, as described by Chapman[42].

Harper used an open autogenous iliac crest bone-grafting technique in five of eight exchange nailing procedures on the femur[12], and Furlong et al. used a similar technique to treat twelve of twenty-five aseptic femoral nonunions[30], but these authors did not provide detailed indications for the use of the bone graft. Wu and Lee used an open autogenous bone-grafting technique when they performed acute lengthening and exchange nailing in a series of femoral nonunions[63]. Pihlajamaki et al. reported the use of open autogenous iliac crest bone-grafting in three of eleven patients who underwent exchange nailing for femoral nonunion[37]. They stated that the decision to use bone-grafting was based on "the fracture and on the disturbed union pattern as well as the personal preferences of the surgeon." Weresh et al. reported that four of nineteen patients underwent bone-grafting at the time of exchange nailing of the femur, but they did not describe the indications for the use of the bone graft or the type of bone-grafting performed[40]. In their report on thirty-three uninfected tibial nonunions treated with exchange nailing, Court-Brown et al. stated that "bone loss of more than 2 cm and 50% of the circumference almost always requires open bone grafting."[15] McKee et al. used autogenous iliac crest bone graft in three of ten patients who underwent exchange nailing for the treatment of a humeral nonunion and commented that the addition of bone graft was "at the discretion of the consultant surgeon."[64] Lin et al. reported the use of exchange nailing with cancellous bone-grafting in twenty-three patients with humeral nonunion[65]. These authors stated that they added cancellous bone graft to the humeral exchange nailing technique "because of the low healing potential of nonunions and the low morbidity of the bone grafting procedure."[65]

Partial Fibulectomy in the Treatment of Tibial Nonunions

Some authors have recommended routine partial fibulectomy in conjunction with exchange nailing of the tibia on the basis of the belief that the intact fibula may hold an ununited tibia in distraction[43]. Others have found that partial fibulectomy is not usually necessary, unless it is required to permit manipulation of a poorly reduced nonunion[15,36,55]. Two reports demonstrated no difference in the rate of union between patients treated with and those treated without partial fibulectomy[43,55].

Clinical Results by Anatomic Location

Femur

Uninfected Diaphyseal Femoral Nonunions

Exchange nailing remains an excellent treatment choice for aseptic, noncomminuted nonunions of the femoral diaphysis following prior intramedullary nailing (Figs. 2-A through 2-D)[26,37,46]. Rates of osseous union following a single exchange nailing of an aseptic, noncomminuted femoral diaphyseal nonunion have been reported to range from 72% (thirteen of eighteen) to 100% (sixteen of sixteen) (Table I)[26,30,37,39,46]. In a prospective, randomized trial, Wu and Chen compared exchange nailing in sixteen patients with open autogenous bone-grafting in nineteen patients who had an aseptic nonunion of the femoral shaft with an in situ intramedullary nail[26]. Osseous union was achieved in all patients in both groups. The authors concluded that, although union can be achieved with either method, exchange nailing is a simpler procedure associated with a shorter time to union[26]. Wu and Chen later reported successful osseous union in thirty-three of thirty-six patients treated with exchange nailing of an aseptic noncomminuted femoral diaphyseal nonunion following a closed fracture[46]. Hak et al. reported successful osseous union in only thirteen of their eighteen patients in whom an aseptic noncomminuted femoral diaphyseal nonunion had been treated with a single exchange nailing[39]. All five patients in whom the exchange nailing failed were smokers and had an atrophic nonunion[39].

Two recent reports have questioned the effectiveness of exchange nailing in the treatment of nonunions following intramedullary nailing of comminuted fractures of the femoral diaphysis[40,41]. Weresh et al. reported that only ten of nineteen femoral diaphyseal nonunions following locked intramedullary nailing of comminuted femoral fractures went on to osseous union after treatment with exchange nailing[40]. Similarly, Banaszkiewicz et al. reported that only eleven of nineteen aseptic femoral nonunions following locked intramedullary nailing of high-energy, comminuted fractures went on to osseous union after treatment with exchange nailing alone[41]. The authors of both papers stated that since the introduction of interlocking screws and other technological advances, intramedullary nailing is being used to treat more complex femoral fractures. The authors concluded that these more complex fractures are more likely to go on to nonunion and that these nonunions may not be appropriate for exchange nailing.

The benefit of adding bone graft to exchange nailing in the treatment of femoral nonunions is unclear. In a series by Furlong et al., twenty-one of twenty-two patients with an aseptic femoral diaphyseal nonunion following intramedullary nailing had osseous union after exchange nailing alone; all twelve patients in whom autogenous bone graft had been placed at the nonunion site at the time of the nail exchange had osseous union after that procedure[30]. Pihlajamaki et al. reported that fourteen of eighteen patients with an aseptic midshaft femoral nonunion had osseous union after a single exchange nailing procedure; all three patients in whom an autogenous bone graft had been placed had osseous union after a single procedure[37]. In contrast, Weresh et al. found that osseous union failed to occur in three of four patients who had undergone open bone-grafting at the time of an exchange nailing[40].

Infected Diaphyseal Femoral Nonunions

Exchange nailing has also been used in the treatment of infected nonunions of the femoral diaphysis. In the study by Hak et al., a quiescent infection was detected by intraoperative culture in five of twenty-three femoral nonunions at the time of exchange nailing[39]. All five patients had osseous union fol-

TABLE I Review of the Literature on Contemporary Techniques of Exchange Nailing ➤

Anatomic Region/Study	Total	Infection at Time of Exchange Nailing*	Bone-Grafting at Time of Exchange Nailing*
Femoral diaphysis			
Wu and Chen[26], 1997	16	0 (0%)	0 (0%)
Furlong et al.[30], 1999	22	0 (0%)	12 (48%)
Hak et al.[39], 2000	23	5 (22%)	0 (0%)
Weresh et al.[40], 2000	19	Not reported	4 (21%)
Wu and Chen[46], 2002	36	0 (0%)	0 (0%)
Pihlajamaki et al.[37], 2002	18	0 (0%)	4 (22%)
Banaszkiewicz et al.[41], 2003	19	0 (0%)	0 (0%)
Distal part of femur/Koval et al.[66], 1995	4	0 (0%)	Not reported
Proximal part of tibia/Lang et al.[67], 1995	9	0 (0%)	2 (22%)
Tibial diaphysis			
Court-Brown et al.[15], 1995	33	0 (0%)	5 (15%)
Templeman et al.[38], 1995	27	0 (0%)	0 (0%)
Wu et al.[36], 1999	25	0 (0%)	0 (0%)
Mercado et al.[43], 2001	32	0 (0%)	0 (0%)
Zelle et al.[55], 2004	40	0 (0%)	0 (0%)
Petrisor et al.[50], 2005	18	18 (100%)	0 (0%)
Distal part of tibia/Richmond et al.[49], 2004	10	0 (0%)	Not reported
Ankle fusion/Pinzur[68], 2001	3	0 (0%)	0 (0%)
Humeral diaphysis			
Robinson et al.[69], 1992	5	0 (0%)	0 (0%)
McKee et al.[64], 1996	10	0 (0%)	3 (30%)
Flinkkilä et al.[70], 2001	13	0 (0%)	0 (0%)
Lin et al.[65], 2003	23	0 (0%)	100% (83% also had intefrag. wiring)

*The values are given as the number of cases with the percentage in parentheses. †The percentages of cases are given in parentheses.

lowing exchange nailing and the administration of culture-specific antibiotics postoperatively.

Distal Femoral Nonunions

Koval et al. reported on a series of sixteen distal femoral nonunions treated with retrograde nail fixation[66]. Because none of the fractures had initially been treated with a nail, none of these fixation procedures used for the nonunions was an exchange nailing. Of the sixteen nonunions treated with nailing, only four healed[66]. Of the remaining twelve nonunions, four were subsequently treated with exchange nailing only; none of the four healed after that procedure (Table I).

Tibia

Proximal Tibial Nonunions

Lang et al. performed exchange intramedullary nailing in nine patients in whom a nonunion had developed following a proximal tibial fracture (Table I)[67]. Seven of the nine patients eventually had osseous union, although one patient did so only after a subsequent bone-grafting procedure and two of the nonunions healed with 4.5 cm of foreshortening. The authors recommended that other fixation methods be used in the treatment of proximal tibial fractures, although exchange nailing appeared to have a good success rate in the treatment of nonunions with minimal bone loss.

Diaphyseal Tibial Nonunions

Exchange nailing of uninfected diaphyseal nonunions of the tibia has reported success rates ranging from 76% to 96% (Table I)[15,36,38,43,55]. Court-Brown et al. reported on thirty-three aseptic diaphyseal tibial nonunions[15]. Twelve of fifteen nonunions that had followed a closed fracture and thirteen of eighteen nonunions that had followed an open fracture healed after a single exchange nailing procedure.

In a study by Templeman et al., osseous union was achieved in twenty-three of twenty-seven patients with an aseptic nonunion of the tibial shaft treated with a single exchange nailing procedure[38]. Two patients required a second exchange nailing, two patients with a segmental defect involving >30% of the bone circumference required open bone-grafting, and an infection developed in three patients after exchange nailing. A varus deformity developed in two of the patients who

TABLE I ***(continued)***

Interlocking of Exchange Nail†	Osseous Union After One Exchange Nailing*	Average Time to Osseous Union Following Exchange Nailing for the Nonunions that Healed *(mo)*
Dynamic (56%), unlocked (44%)	100%	4
Static (16%), dynamic (84%)	95%	7
Static (70%), dynamic (26%), unlocked (4%)	78%	10
Static (79%), dynamic (21%)	53%	8
Static (14%), dynamic (86%)	92%	4
Not reported	78%	<6
Static (47%), dynamic (32%), unlocked (21%)	58%	9
Static (100%)	0%	Not applicable
Not reported	78%	Not reported
Static (18%), unlocked (82%)	76%	4
Static (33%), dynamic (11%), unlocked (46%)	85%	Not reported
Not reported	96%	4
Static (19%), dynamic (28%), unlocked (53%)	84%	5
Static (78%), dynamic (22%)	95%	7
Not reported	39%	Not reported
Not reported	Not specified	Not reported
Static (100%)	100%	3
Not reported	40%	Not reported
Static (100%)	40%	Not reported
Not reported	23%	Not reported
Static (100%)	96%	4

had osseous union, and a valgus deformity developed following exchange nailing in one patient.

Wu et al. reported that twenty-four of twenty-five aseptic nonunions of the tibial shaft healed after one exchange nailing[36]. Mercado et al. reported that twenty-seven of thirty-two aseptic nonunions of the tibial shaft healed after a single exchange nailing and that there was a "significant correlation of time to union with time between initial injury and exchange nailing, fracture configuration, and type of fixation (ie, static, dynamic, or unlocked) at p<.05."[43] Patients who had undergone exchange nailing within four months after the initial intramedullary nailing had an average time to osseous union of thirty-six weeks, as compared with an average of only nineteen weeks for nonunions treated more than four months after the initial intramedullary nailing. AO type-A (noncomminuted) fracture nonunions healed in an average of sixteen weeks following exchange nailing, whereas AO type-B or C (comminuted) fracture nonunions healed in an average of twenty-four and twenty-one weeks, respectively, following exchange nailing. Nonunions treated with a statically or dynamically locked nail healed in an average of twenty-two weeks, whereas those treated with an unlocked nail healed in an average of nineteen weeks.

Zelle et al. reported that thirty-eight of forty patients with an aseptic tibial nonunion had osseous union following exchange nailing[55]. Reaming and insertion of a larger nail was performed in all patients, and no patient underwent bone-grafting in that series.

Distal Tibial Nonunions

Richmond et al. reported that ten patients had undergone locked antegrade exchange nailing to treat a nonunion in the distal fourth of the tibia, but the results for those patients were reported in combination with those of thirty-two other patients who had undergone intramedullary nailing for nonunions following other internal fixation methods (Table I)[49]. Rotational and angular deformities were corrected acutely with the use of a femoral distractor at the time of the exchange nailing. The overall union rate following the intramedullary nailing in the entire series was 91%, with osseous union achieved in one patient after dynamization.

Ankle Fusion

Pinzur reported the results of ankle fusion with use of an intramedullary nail to treat five nonunions of stress fractures of the distal part of the tibia in patients with type-I diabetes mellitus who had lost sensation in the foot[68]. Three patients underwent subsequent exchange nailing following failure of the ankle fusion to unite. Two of those three patients had been initially treated with an antegrade tibial nail, and the third had been initially treated with a retrograde ankle fusion nail. All three of these patients had osseous union following the exchange nailing (Table I).

Humerus

Exchange nailing has not produced good results following failures of intramedullary nail fixation of humeral shaft fractures (Table I).

Robinson et al. reported that osseous union was achieved following exchange nailing in only two of five patients who were part of a larger series of thirty patients in whom a humeral shaft fracture was treated with a locked intramedullary nail[69].

McKee et al. reported that osseous union was achieved in only four of ten patients who had undergone locked exchange nailing after failure of a locked intramedullary nailing of a humeral shaft fracture[64]. Three of the ten patients had also undergone concomitant open bone-grafting of the nonunion site, and only two of these four nonunions united despite the use of the bone graft. This poor rate of healing was contrasted with a 100% rate of healing in nine patients in the same series who had undergone plate and screw fixation with bone-grafting following failure of locked intramedullary nailing. The authors concluded that the high rate of failure of exchange nailing in the humerus may have been a result of the relatively large amount of osteolysis and bone loss in the humerus that occurred after failure of the locking screws.

Flinkkilä et al. performed exchange nailing in thirteen patients with a nonunion of the humeral diaphysis[70]. Only three of the patients had osseous union after a single exchange nailing procedure. The authors concluded that "exchange nailing results in a poor union rate in nonunion after IM nailing of humeral shaft fractures."[70]

Lin et al. reported that twenty-two of twenty-three patients with a nonunion of the humeral diaphysis had osseous union after exchange of a locked intramedullary nail, although all had had augmentation with autogenous bone graft and 83% had had interfragmentary wiring at the nonunion site[65]. The authors concluded that compression of the nonunion fragments by the supplementary wiring and the use of bone-grafting led to their high success rate.

Nonunion following intramedullary nailing in the humerus presents some unique problems[65]. First, cortical thinning due to the so-called "windshield wiper" effect and bone loss at the nonunion site make reaming difficult and may lead to instability of a newly inserted exchange nail[64]. Initial fracture management by means other than intramedullary nailing may not cause as much cortical erosion and bone loss at the nonunion site as occurs with a failed locked intramedullary nail[64]. Second, humeral nonunions experience rotational and distraction (gravity) forces, as opposed to the compressive force of weight-bearing in lower-extremity nonunions[64].

Intramedullary nailing of humeral nonunions that occurred following other types of operative or nonoperative treatment of the initial fracture can be successful[71], although others have noted that open bone-grafting or augmentation with another type of internal fixation such as cerclage wiring is usually required[72,73]. These adjunctive procedures also appear to be necessary to increase the healing rate when exchange nailing is used to treat humeral nonunions for which intramedullary nailing has failed[65].

Overview

In conclusion, exchange nailing is an excellent treatment choice for aseptic, non-comminuted diaphyseal femoral and tibial nonunions. On the basis of the available literature, exchange nailing cannot be recommended for distal femoral nonunions at this time and exchange nailing is generally not indicated for humeral nonunions.

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