Treatment of large segmental bone defects is a difficult challenge for orthopedic surgeons. These large defects can be caused by traumatic injury or surgical treatment of infection or tumors. Historically, amputation was the best option for many of these patients, but limb salvage has become more common. Review of available literature demonstrates that several treatment modalities have had some success in treating segmental bone defects:

- Ilizarov bone transport
- Autogenous cortical or cancellous bone graft
- Vascularized fibula graft
- Recombinant bone morphogenic protein
- Calcium phosphate fillers

Autogenous bone graft has been the gold standard for bone graft. It is osteogenic, osteoinductive, and osteoconductive. When the defect is large, however, the traditional supply of autogenous graft may not be sufficient. There can be significant morbidity with harvesting large quantities of bone. Many studies show high incidences of complications from iliac crest harvest, including donor site pain and injury to cutaneous nerves resulting in painful neuromas. With the recent availability of bone morphogenetic protein (BMPs), many surgeons have decreased their use of autogenous bone graft to avoid potential complications at the donor site. Although there are several studies that show BMP is effective for nonunions and healing cortical defects, its high cost...
may be prohibitive at some institutions, especially in very large defects, where a large quantity of graft would be needed.

Bone grafting of defects often is delayed after primary internal fixation to allow soft tissue healing, decrease infection risk, and prevent graft resorption during the early inflammatory healing phase. Cement spacers with antibiotics can be used to temporarily fill defects. This has many advantages. Cement can give structural support and decrease implant loading. It maintains a void that allows easy placement of graft and provides local antibiotics in areas of open fractures at high risk for infection. Cement spacers also induce formation of pseudosynovial membrane, which creates a contained defect for bone grafting.25 This membrane has been shown to produce growth factors and osteoinductive factors including BMP-2.26

The reamer-irrigator-aspirator (RIA) originally was designed as a single-pass intramedullary reamer that creates a negative pressure within the canal in an effort to decrease pulmonary insult from marrow contents during the course of reaming for femur fractures. RIA has several unique characteristics allowing it to achieve this result. The reamer head is extremely sharp. It is a single-use reamer that allows reaming to a pre-measured diameter with a single pass, as opposed to sequential passes with incrementally larger reamers. It also has both an irrigation and aspiration port. Irrigation of the canal with normal saline during the reaming process decreases the overall temperature within the canal and assists in the aspiration process, as it decreases the viscosity of the intramedullary contents. Aspiration allows for removal of reaming debris and creates constant negative pressure in the canal. RIA has been used to debride the intramedullary canal for treatment of bone infections. It also can be modified by placing a screen trap in line with the aspiration port to capture the bone debris aspirated from the medullary canal in a sterile fashion.

The ideal treatment for large segmental defects of long bones would be inexpensive, have minimal adverse effects, be effective at obtaining union, and provide enough graft volume to fill the defect. The intramedullary canal of femurs and tibias is relatively easy to access and contains large amounts of cancellous bone graft. Intramedullary reamings have been shown to have viable cells capable of new osteosynthesis.27-29 Recent quantitative analysis found higher levels of fibroblast growth factor (FGFa), platelet-derived growth factor (PDGF), insulinlike growth factor (IGF)-1, BMP-2, and transforming growth factor (TGF)-β1 in RIA bone graft compared with iliac crest bone graft.30 This study is designed to evaluate the efficacy of healing and associated complications in patients with large segmental defects treated with bone graft obtained by RIA.

MATERIALS AND METHODS

This prospective study was conducted between February 2003 and March 2007. Investigators obtained institutional review board approval and written informed consent from all patients. Twenty one patients, 13 male and 8 female, with an average age of 30.6 years, with segmental bone defects agreed to participate. The defect size ranged from 2 to 14.5 cm (average 6.6 cm). Three patients had at least one surgical procedure at an outside hospital. All subsequent surgeries were performed by fellowship-trained orthopedic trauma surgeons at a level 1 trauma center. Eight patients smoked, and 13 did not. Mechanism of injury included nine motorcycle collisions, five motor vehicle collisions, four gun shot wounds, one car versus pedestrian, one car versus bicyclist, and one crush injury. There were 5 femurs, 15 tibias and 1 ulna treated. The average time from initial injury to RIA procedure was 141 days (range 31 to 582 days).

All patients with open fractures were treated with appropriate surgical debridements and antibiotics. Box 1 outlines the treatment algorithm. An average of 4.8 procedures were performed at the defect site before placement of bone graft. The 20 open fractures were classified as 8 grade 3A, 9 grade 3B, and 2 grade 3C. Eight patients needed soft tissue flap coverage, including three free flaps and five local flaps. Eighteen patients had antibiotic spacers placed into the defect site before bone grafting. The RIA graft was obtained from 21 femurs and 2 tibias. One patient had bone graft harvested from both the contralateral tibia and femur, and another had bone harvested from the ipsilateral femur and contralateral tibia. Filtered bone graft volume was measured in 19 patients. The amount of bone graft harvested was not maximized in patients with smaller defects.

Surgical Technique

After induction of general anesthesia, the patients were positioned supine on a radiolucent table. The defect site was prepared first to ensure that there was no sign of infection and to limit the time span that the graft was exposed out of the body. An appropriate skin incision was made depending on location of the defect and previous incisions. In cases with PMMA spacers, the pseudomembrane enveloping the spacer was incised longitudinally to allow for closure after grafting. The
spacer was removed and the bone edges cleaned of interposed fibrous tissue.

When graft was harvested from the femur, a bump was placed under the ipsilateral pelvis similar to position for free leg femoral nail. The narrowest section of the femur or tibia was templated on anterior–posterior (AP) and lateral fluoroscopy to determine the intramedullary canal size (Fig. 1). Reamer size then was chosen to be approximately 1 to 1.5 mm larger than the determined canal size. A percutaneous technique was used to locate the piriformis fossa or lateral starting point at the tip of the greater trochanter. This was verified with biplanar fluoroscopy. The standard entry point for tibial intramedullary nailing was used for tibial graft harvest. A 13 mm cannulated drill bit was used to open the entry site, after which a ball tip guide rod was advanced down the canal. The Reamer Irrigator Aspirator (RIA) system (Synthes, West Chester, Pennsylvania) then was prepared to harvest bone graft (Fig. 2). This included attaching an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow. The canal then was reamed with an appropriately sized reamer head, a 3 or 5 L saline bag to the irrigation port, suction to the aspiration port and a screen trap in line with the suction tubing. The Screen Trap (Biomet, Warsaw, Indiana) has a pore size of approximately 500 μm. Gravity flow and vacuum suction were used to maintain irrigation flow.

Incisions and soft tissues allowed to heal (4 to 6 weeks)

Psuedomembrane incised and cement spacer removed

Fibrous tissue debrided from defect if poly-methylmethacrylate (PMMA) spacer not used

Medullary canal opened

Defect grafted with RIA bone graft if no sign of infection

Weight bearing limited until radiographic consolidation

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Box 1

<table>
<thead>
<tr>
<th>Treatment algorithms</th>
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<tr>
<td><strong>Open Fractures</strong></td>
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<tr>
<td>Antibiotics in emergency room</td>
</tr>
<tr>
<td>Urgent irrigation and debridements (I&amp;d) in operating room with removal of devascularized soft tissue and bone</td>
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<tr>
<td>Internal or External Fixation</td>
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<tr>
<td>Plus or minus VAC dressing</td>
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<tr>
<td>Repeat I&amp;Ds until wound clean and all devitalized tissue removed</td>
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<tr>
<td>Definitive fixation with plate or nail if previously ex fixed</td>
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<tr>
<td>Wound closed or covered with flap</td>
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<tr>
<td>Antibiotic cement spacer placed into defect</td>
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<tr>
<td>Incisions and soft tissues allowed to heal (4 to 6 weeks)</td>
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<td>Weight bearing limited until radiographic consolidation</td>
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Fig. 1. Templating and reaming canal.
RESULTS

Follow-up

Twenty of the 21 patients (95%) have been followed to conclusion. Patients were followed clinically and radiographically until declared healed or failure of treatment. One patient (5%) was lost to follow-up before complete healing.

Graft Harvest

The bone graft volume was measured in 19 of the 21 patients and averaged 64 cc. Two patients had graft harvested from a femur and a tibia. As expected, tibia bone graft volume (37.5 cc) was less than femur volume (67 cc). These extracted volumes, however, were not the maximum volume of graft available. Patients with smaller defects needed less bone graft; therefore less graft was harvested.

Donor Site Complications

No patients had serious donor site morbidity. There were no donor site hematomas, infections, or fractures. No second surgeries were required at donor sites. The authors did not perform routine radiographic examinations of donor bone site. Eight patients who had antegrade femoral RIA procedures had pelvis or hip radiographs for follow-up of pelvic ring or contralateral hip injuries.

Defect Site Complications

Of the 20 patients followed to conclusion, 10 had no defect site complications after bone grafting. Ten patients (50%) had defect site complications. There were six deep infections and four nonunions (two with hardware failure). Four of the patients with infection and three with nonunion eventually healed the defect.

Defect healing

Twenty patients with segmental bone defects were followed to conclusion. There were 5 femurs, 14 tibias, and 1 ulna. Eighteen of these 20 patients had PMMA spacers in the defect before bone grafting. Sixteen patients were treated with plates, and 4 were treated with intramedullary (IM) nails. Seventeen of 20 patients (85%) completely healed at an average 11 months (range 2.5 to 39 months). Ten of these 17 (58%) healed with no additional surgery after RIA bone graft. Seven patients needed additional surgeries after original RIA. Two patients healed after exchange intramedullary nail; one patient developed a deep infection but healed after I&D and repeat RIA. One proximal tibia healed after revision compression plating with cancellous bone graft harvested from the distal femur, and one healed after I&D and Enders rod (West Chester, Pennsylvania) placement. One healed after repeat I&Ds, and one developed deep infection after the defect healed, requiring I&D and plate removal (Table 1).

Illustrative Case (1st RIA Case Performed)

A 35-year-old woman presented 6 months after a motorcycle accident with a large, open, draining wound of her tibia. After debridement of the wound...
and bone, she had a 14 cm defect that was managed with a block of methylmethacrylate and covered with a free flap (Fig. 4). Eight weeks later with a stable wound, the RIA was used to harvest bone graft from the ipsilateral femur using a piriformis entry site. The bone graft was used to fill the 14 cm defect with no adjunctive materials added. Ultimately, the patient went on to union of the defect at about 10 months after bone grafting. Hardware removal was performed because of prominent hardware that was causing pain. Unfortunately, the patient fractured through the graft while snow skiing and required a replating. An attempt was made at union with casting. At the time of replating the patient did not have any formal bone grafting other than some local bone graft taken from prominent bone where the bone had grown up around the previously removed plate. Her final radiographs after replating show solid union (Figs. 5–8) of the tibia and recovery of the donor femur site.

Failures

Three patients were considered to be treatment failures: two deep infections requiring removal of RIA bone graft, and one recurrent nonunion with multiple hardware failures. The first failure was a male smoker with grade 3B open tibia and a 10 cm tibial defect from a motorcycle accident. The wound was contaminated with dirt and organic debris. He underwent external fixation and multiple irrigation and debridements with antibiotic spacers and required a gastrocnemius muscle flap for coverage. The defect was fixed with a locking plate, and RIA bone graft was performed at 3 months after injury. He developed wound drainage 2 weeks after operating and was treated with antibiotics. At 22 days after operating, the patient had surgical irrigation and debridement. Much of the graft was removed, but there was a shell of cortical–cancellous bone around the periphery, which was left intact. The patient had subsequent repeat bone graft with BMP-2. He was noncompliant with intravenous antibiotic treatment and did not show up for the most recent clinic appointments. At last follow-up, he had incomplete radiographic consolidation, but clinically had minimal pain at fracture.

The second failure was another grade 3B tibia with a 10 cm defect from a motorcycle accident. The patient had external fixation of his tibia and

<table>
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<th>Table 1</th>
<th>Results</th>
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<tr>
<td><strong>Outcome</strong></td>
<td><strong>N</strong></td>
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<tr>
<td>Healed without further surgery</td>
<td>10</td>
</tr>
<tr>
<td>Healed with further surgery</td>
<td>7</td>
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<tr>
<td>Failed</td>
<td>3</td>
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Fig. 4. Anterior–posterior radiograph showing 14 cm defect with methylmethacrylate spacer.
Fig. 5. Anterior–posterior (A) and lateral (B) radiographs 10 months after reamer-irrigator-aspirator bone grafting to the tibia showing union of the defect.

Fig. 6. Radiographs of a ununited tibial fracture from a skiing accident. Previous union attempt using a cast had failed. (A) Lateral view, (B) Anterior-posterior view, (C) Stress view.
four I&Ds before open reduction and internal fixation with a locked plate. He then required free flap coverage. RIA bone graft procedure was performed 3 months after injury. Four months after RIA, he developed wound dehiscence and drainage requiring surgical debridement with removal of the bone graft.

The third failure was a female smoker with a grade 3A distal femur fracture and a 3.5 cm defect. She was treated with irrigation and debridement and open reduction and internal fixation with a distal femur locking plate, followed by RIA bone grafting 1 month after injury. She progressed to full weight bearing as the defect consolidated radiographically. She developed nonunion with plate failure 5 months after injury. At the time of revision surgery, most of the defect had healed, but the proximal junction was not united. She had iliac crest bone graft and revision plate fixation. Sixteen months later, she had continued nonunion with hardware failure. She had revision of hardware with revision bone graft and BMP. Presently, she has good alignment, and the fracture appears to be healing.

DISCUSSION

The treatment method used for patients with segmental defects of long bones depends largely on the training and experience of the surgeon. There are two major treatment methods that can be used: stabilizing the bone out to length and filling in the defect, or using the Ilizarov principles to transport bone to correct the defect. Each of
these methods has many variations that can be used.

Review of literature of bone transport for tibial bone defects shows high healing rates but prolonged time in external fixators. Paley and Maar\(^7\) reported 19 patients with tibial defects averaging 10 cm. They had a union rate of 100% and an external fixation index (EFI) (external fixation time [EFT] per centimeter of distraction gap) of 1.7 months per centimeter (average EFT, 17 months). A mean of 1.6 unplanned surgical procedures were performed for problems. Ten docking sites were bone grafted, and nine healed primarily. Polyzois and colleagues\(^31\) reported on 42 patients with diaphyseal bone defects (25 tibial and 17 femoral). Preoperatively, 19 had active infection with drainage. After debridement, the mean defect was 6 cm. The mean duration of external fixation was 10 months. All patients healed, 38 without bone grafting; 4 required autogenous bone grafting. Dendrinos and colleagues\(^32\) treated 28 tibias using the Ilizarov bone transport method. The average bone defect was 6 cm. The mean duration of treatment was 10 months. Three patients were treated with bone grafting of the docking site. Twenty-seven patients (96%) had eventual healing. There 71 minor and major complications (2.5 complications per patient), including 1 amputation. Dagher and Roukoz\(^33\) reported on nine patients with grade 3B open tibias. Tibial defects averaged 6.3 cm and were treated with Ilizarov transport. Four patients were infected preoperatively. All nine healed with no residual infection and with less than 1 cm of leg length discrepancy (LLD). No bone graft was performed, and the EFI was 1.8 months per centimeter.

Bosse and Robb\(^13\) reported on 16 patients with grade 3B tibia fractures. The average bone defect was 9.5 cm. External fixators were used to stabilize the fractures. Local muscle or free muscle grafts were performed to cover soft tissues. Antibiotic beads were placed in all defects. When the soft tissue was healed, the antibiotic beads were removed, and a large amount of autogenous bone graft was obtained from the posterior iliac crest and placed into the defect. All 16 fractures and defects healed at an average of 10 months. Only 6 of 16 patients healed after initial bone graft procedure. Patients required an average of six surgical procedures to achieve consolidation. The authors identified four factors associated with early failure of union: inadequate graft volume, suboptimal graft placement, infection at surgical site, and errors in surgical judgment.

Jones and colleagues\(^1\) recently compared rBMP-2 combined with allograft bone with autogenous bone graft for reconstructing tibial cortical defects in a randomized study. The mean length of defect was 4 cm. They found no significant difference in healing rate without reintervention between the groups.

Two other authors have compared bone transport with bone grafting. Cierny and Zorn\(^4\) reported on 44 consecutive patients with segmental tibial defects. Twenty-one patients (mean defect size 6.4 cm) were treated with bone transport using the Ilizarov apparatus, and 23 patients (mean defect 8.5 cm) were treated with massive cancellous bone grafts and soft tissue transfer. After one treatment, 71% of the Ilizarov patients and 74% of the bone graft patients achieved union and had resolution of infection. Complication rates were lower for the Ilizarov group (33%) than the bone graft group (60%). Retreatment led to union without infection in 95% of both groups. Ilizarov patients averaged fewer hours in the operating room, hospital days, months of disability, units of blood, and adjunctive surgical procedures, resulting in a cost savings. The authors concluded that Ilizarov bone transport reconstruction was faster, safer, less expensive, and easier to perform, but the final result was the same.

Green\(^3\) retrospectively reviewed two treatment groups with bone defects: 17 patients treated by Ilizarov bone transport (mean defect 5 cm) and 15 patients treated by the Papineau bone grafting technique (mean defect 4 cm). Six of the 17 transport patients required bone grafting at the docking site to achieve union. Only two patients in the bone graft group required a second bone graft procedure. The treatment time was identical for the two groups; the EFI was 1.9 months per centimeter of defect reconstructed for both.

In this study, 18 of 20 patients had a PMMA spacer placed into the defect before the RIA bone graft procedure. This technique first was described by Masquelet, who reported on 35 cases. He described a pseudosynovial membrane that formed around the cement spacer. He stated that this membrane prevents graft resorption and improves vascularity and corticalization.\(^25\) Pelissier and colleagues\(^26\) studied the properties of this induced membrane in a sheep model. They found that this membrane secreted several growth factors including BMP-2, vascular endothelial growth factor (VEGF), and TGFβ1. The BMP-2 level was highest at 4 weeks, which may indicate an ideal time to bone graft defect site. Viateau and colleagues studied this technique in a sheep model and found that the membrane alone was insufficient to heal critical size defects. When autologous bone graft was placed within membrane, all of the defects healed.\(^35\)
The RIA system may have many uses, including obtaining large amounts of bone graft, debriding intramedullary infections, and reaming for intramedullary nailing. Although using RIA to obtain bone graft is a new technique, several authors previously reported on the use of intramedullary reaming material as viable bone graft.\textsuperscript{27,29,36–39} Wenisch and colleagues\textsuperscript{28} studied human reaming debris using cell cultures and found multipotent stem cells capable of differentiating along the osteogenic pathway. Schmidmaier and colleagues recently compared quantitative levels of growth factors from RIA aspirate, iliac crest, and platelet preparations. They found higher concentrations of five of seven growth factors (TGF-\(\beta\)1, IGF-I, FGFa, PDGFbb, and BMP-2) in samples obtained from intramedullary reaming debris compared with those from the iliac crest.\textsuperscript{30}

Several recent studies have demonstrated benefits of RIA compared with traditional reaming. Husebye and colleagues\textsuperscript{40} found that the intramedullary pressure during reaming of pig femurs was significantly lower with RIA compared with traditional reamers. Higgins and colleagues\textsuperscript{41} showed significantly lower maximum reaming temperatures (42°C versus 58°C) with RIA compared with a traditional reamer using fresh-frozen human cadaver tibias. Pape and colleagues\textsuperscript{42} compared traditional reamed, unreamed, and RIA-reamed femoral nailing in sheep with unilateral lung contusion. They found that the traditional reamed nailing group had a higher systemic response than the RIA reamed group (higher D-dimer levels, lower systemic response, and a higher rate of healing of the defect consolidation).

There are very few published human data regarding the safety and efficacy of using RIA as a bone-grafting tool. Belthur and colleagues\textsuperscript{43} recently reported the first series of prospectively monitored RIA graft patients compared with historic iliac crest bone graft (ICBG) patients. In that series, pain scores at each of the three time points—acute (less than 48 hours), intermediate (greater than 48 hours to less than 3 months), and chronic (greater than 3 months)—were significantly lower in the RIA cohort. There were no instances of numbness in the RIA group, but eight ICBG patients reported numbness. They noted two complications specifically related to RIA bone harvesting: distal perforation of the femur caused by an eccentric guide wire and an excessively anterior piriformis entry portal. Both technical errors were noted and compensated for with no final adverse effect. In this study, there were no clinically significant complications at the RIA donor site. There were no infections, no secondary surgeries, and no fractures from the use of RIA at harvest site. Two of eight patients had Brooker class 1 heterotopic ossification (HO) at the proximal femur.\textsuperscript{44} None of these small islands of ossification in the soft tissues caused clinical or subjective symptoms. Having a small amount of HO is not unexpected given that previous studies on HO after femoral nails found incidences of 36% after reamed nails and 9% after unreamed nails.\textsuperscript{45}

This is a report on the initial case series at the authors’ institution. The authors feel that their results have improved as they learned more and improved on their operative techniques. Specifically, the authors have noted that during their early cases, they packed the graft in very tightly to maximize the amount of graft placed into the defect. During revision grafting of some of the early failures, it was found that this tightly packed graft had not consolidated. There was some peripheral revascularization and ossification, but a central core remained with a consistency similar to when it initially was placed. Although the mechanism is unclear, it appears that in later cases where the graft was not packed tightly, much faster graft incorporation and higher rate of healing of the defect were obtained.

Although the authors did not have any donor site complications, there is potential for significant complications if correct technique is not used. The RIA reamers are much sharper than traditional reamers and have the potential to ream through cortical bone. The donor bone should be templated on both AP and lateral fluoroscopy, and the smaller diameter measurement should be used. Care also should be used to center the guide wire in the canal to avoid reaming eccentrically. If good technique is used, RIA is a safe technique to obtain large quantities of autogenous bone graft with minimal donor site morbidity and a high rate of defect consolidation.

**REFERENCES**


