Current Concepts Review

Autogenous Bone Graft: Donor Sites and Techniques

Chad Myeroff, MD, and Michael Archdeacon, MD, MSE

Investigation performed at the University of Cincinnati College of Medicine, Cincinnati, Ohio

- Autogenous cancellous bone graft provides an osteoconductive, osteoinductive, and osteogenic substrate for filling bone voids and augmenting fracture-healing.
- The iliac crest remains the most frequently used site for bone-graft harvest, but the proximal part of the tibia, distal end of the radius, distal aspect of the tibia, and greater trochanter are alternative donor sites that are particularly useful for bone-grafting in the ipsilateral extremity.
- The most common complication associated with the harvest of autogenous bone graft is pain at the donor site, with less frequent complications including nerve injury, hematoma, infection, and fracture at the donor site.
- Induced membranes is a method that uses a temporary polymethylmethacrylate cement spacer to create a bone-graft-friendly environment to facilitate graft incorporation, even in large segmental defects.

Autogenous bone graft remains a reliable treatment option when structural stability is required, bone voids exist, or bone-healing augmentation is desired. Cortical autografts provide a structurally sound osteoconductive medium with minimal osteoinductive and osteogenic properties. Cancellous autografts provide a highly osteoconductive, osteoinductive, and osteogenic substrate while corticocancellous grafts provide some benefits of both. The iliac crest remains the most common donor site for autogenous bone graft, providing sufficient quantities of cortical and cancellous bone for most clinical settings, but with donor-site morbidity. Alternative donor sites include the proximal part of the tibia, distal end of the radius, distal aspect of the tibia, and greater trochanter. A novel technique uses a reamer-irrigator-aspirator (RIA; Synthes, West Chester, Pennsylvania) to harvest intramedullary bone graft. Bone graft harvested from any site can be combined with the so-called induced membrane in more complex bone void settings.

Use of Levels of Evidence in the Assessment of Scientific Information

The literature summarized in this article is evaluated with use of the Levels of Evidence ratings for studies addressing clinical care[1]. These levels are summarized with use of Grades of Recommendation (see Appendix) previously published in *The Journal of Bone and Joint Surgery* (American Volume)[2]. Grade-A recommendations are based on consistent Level-I studies. Grade-B recommendations are based on consistent Level-II or III evidence. Grade-C recommendations represent either conflicting evidence or are based on Level-IV or V evidence. A grade of I indicates that there is insufficient evidence to make a treatment recommendation.

Clinical Relevance

Each year 200,000 bone-graft procedures are performed in the United States[3]. Indications for bone-grafting include delayed union or nonunion, malunion, arthrodesis, limb salvage, and

Disclosure: None of the authors received payments or services, either directly or indirectly (i.e., via his institution), from a third party in support of any aspect of this work. One or more of the authors, or his institution, has had a financial relationship, in the thirty-six months prior to submission of this work, with an entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. No author has had any other relationships, or has engaged in any other activities, that could be perceived to influence or have the potential to influence what is written in this work. The complete **Disclosures of Potential Conflicts of Interest** submitted by authors are always provided with the online version of the article.

reconstruction of bone voids or defects[4-8]. With a strong history of clinical success, autogenous bone graft is biologically the graft material of choice because it provides osteoconductive, osteoinductive, and osteogenic properties and has complete histocompatibility[5,6,9,10] (Grade-C recommendation). However, autogenous bone graft has limitations, including donor-site morbidity, such as pain, infection, and nerve injury; volume-limited quantity; difficult accessibility; blood loss; and surgical time required[6]. In this article, we address autogenous bone-grafting in general, but focus primarily on autogenous cancellous bone-grafting indications, techniques, and complications.

Types of Autogenous Bone Graft

Various bone-graft options provide unique combinations of osteoconductive, osteoinductive, and osteogenic properties. *Osteoconduction* refers to the geometric scaffolding, which provides an environment for new bone apposition by supporting host capillary ingrowth, perivascular tissue, and osteoprogenitor cells[5,6]. *Osteoinduction* refers to the ability of the graft to recruit pluripotent mesenchymal stem cells that differentiate into bone-forming osteoblasts and chondroblasts[6]. *Osteogenic* material, best provided by fresh cancellous autograft, contains viable donor osteocytes, or their precursors, which promote primary bone formation[6].

Cortical Bone Graft

Autogenous cortical bone graft, which provides an osteoconductive medium with minimal osteoinductive and osteogenic properties, is best suited for structural defects for which immediate mechanical stability is required for healing[5,9,10] (Grade-C recommendation). The dense cortical matrix results in relatively slow revascularization and incorporation, as resorption must occur before deposition of new bone, and limited perfusion and donor osteocytes make this option poorly osteogenic[6,11]. Within the first six months after implantation, these nonvascularized cortical grafts become progressively weaker, secondary to resorption, but regain structural strength within twelve months[5,9,12] (Grade-C recommendation).

Cancellous Bone Graft

Cancellous bone graft is the most commonly used source of autogenous graft[6]. It provides an osteoinductive, osteoconductive, and osteogenic substrate, and the porous trabeculae are lined with functional osteoblasts, resulting in a graft that is highly osteogenic[6,10]. Additionally, the large surface area leads to rapid remodeling and incorporation, making cancellous graft an excellent option for arthrodesis and treatment of nonunions[13-16] (Grade-C recommendation). After implantation, a portion of the donor osteocytes survives, and these osteocytes, combined with graft porosity and local cytokines, promote angiogenesis and host mesenchymal stem-cell recruitment. These recruited mesenchymal stem cells have the potential to differentiate into osteoblasts[6,17]. Thus, the graft may be fully vascularized within two days[7,18]. New bone formation is observed within a few weeks and typically is remodeled by eight weeks, with complete graft turnover by one year[4,11]. This turnover occurs by the process of creeping substitution, defined as concomitant osteoblast deposition of new osteoid and osteoclast resorption of necrotic donor trabeculae[4,17]. This graft material offers rapid incorporation but no immediate structural stability.

Corticocancellous Bone Graft

Corticocancellous bone grafts intuitively offer the advantages of both cortical and cancellous bone: an osteoconductive medium and immediate structural stability from cortical bone and the osteoinductive and osteogenic capabilities of cancellous bone. The most frequent donor site is the iliac crest, which can provide unicortical, bicortical, and tricortical graft material.

Vascularized Bone Grafts

In order to improve graft incorporation and healing, cortical and corticocancellous grafts can be harvested with a vascular pedicle. Free vascularized grafts offer the most predictable incorporation and are indicated for bone defects of >12 cm[5,9,11,12,19] (Grade-B recommendation). Vascularized grafts are traditionally harvested from the iliac crest with its deep circumflex iliac artery, the fibula with branches of the peroneal artery, the distal end of the radius with the supraretinacular artery, or the ribs with the posterior intercostal artery[4,20,21]. More than 90% of the residual osteocytes can survive, making this graft osteogenic[5,12,19] (Grade-B recommendation).

Handling of Autogenous Bone Graft

Proper handling and storage of autogenous bone graft are critical to maintaining its inherent properties. Several authors have stated that graft should be stored in normal saline solution, 5% glucose solution, or a moistened swab, and this has resulted in greater metabolic activity and osteoblast cell count compared with dry storage. Most authors agree that open air storage is deleterious and that bone autograft should be harvested for immediate implantation whenever possible[18,22,23] (Grade-I recommendation).

There has been speculation that combining harvested bone graft with antibiotic powder may reduce perioperative infection. This practice does not appear to influence graft healing or incorporation[24-27] (Grade-C recommendation). However, a randomized controlled trial of ninety-six patients with an infected tibial nonunion, followed for an average of 4.5 years, showed a significantly greater ($p < 0.05$) reduction in infection rate when patients were treated with organism-specific antibiotic-impregnated autogenous cancellous bone graft[26]. In that study, infection was eliminated in forty-four (95.6%) of forty-six patients treated with antibiotic-impregnated bone graft compared with forty-one (82%) of fifty who were treated with graft alone (Grade-A recommendation). In that study, fresh autograft was mixed with 1 g of dry antibiotic powder specific to the infectious organisms. Such use can lead to local therapeutic levels of antibiotics for up to three weeks without systemic toxicity[26]. Furthermore, bone graft cultured in antibiotics such as clindamycin and cefuroxime has been shown to have time and dose-dependent stimulus effects on osteoblastic proliferation at therapeutic concentrations, but deleterious effects at higher concentrations[28,29] (Grade-B recommendation).

Autogenous Bone-Graft Donor Sites: Indications, Techniques, and Complications

Iliac Crest

Indications

The anterior or posterior iliac crest is the most commonly used donor site for cancellous and corticocancellous graft[4]. Corticocancellous, unicortical, bicortical, or tricortical segments can be harvested for structural segmental defects, and cancellous material can be obtained for its biologic activity. Harvest volumes may limit iliac crest bone-graft volume, which averages 13 cm^3 anteriorly and 30 cm^3 posteriorly[8,30] (Grade-B recommendation). Singh et al., in a retrospective review of the cases of forty-six patients who had an anterior iliac crest bone graft harvested, reported an average yield of 27 cm^3 of cancellous graft[31]. When larger volumes are needed, yields of 90 cm^3 have been reported with use of an acetabular reamer technique[8,32] (Grade-B recommendation). If inadequate graft volume is obtained with a single iliac crest approach, combined anterior and posterior crest harvest can be performed to increase the graft volume.

Techniques

Anterior iliac crest harvest: Traditionally, bone is harvested from the gluteal or iliac tubercle region about 4 to 5 cm posterior to the anterior superior iliac spine[7,32]. The incision is parallel to the iliac crest, beginning 3 cm posterior to the anterior superior iliac spine to avoid the lateral femoral cutaneous nerve. Electrocautery can be used to subperiosteally elevate the external oblique musculature, avoiding the ilioinguinal and iliohypogastric nerves[33-35]. The iliacus can be elevated from the inner table of the ilium when more exposure is needed (corticocancellous harvest or acetabular reamer harvest). Careful dissection with preservation of the tissue planes facilitates closure. Numerous techniques have been described for the harvest of graft from the ilium, including the curettage technique, which can allow inner or outer table harvest[7], the trapdoor technique[7,8], the iliac crest-splitting technique[7], the trephine technique[36], the segmental bicortical or tricortical technique[8,37], and the acetabular reamer technique[3]. Most of these techniques are similar in that the inner or outer table of the ilium is accessed for either corticocancellous graft or pure cancellous graft. We prefer to split the inner table of the crest with an oscillating saw and obtain cancellous graft by curet. Alternatively, the inner table can be harvested as corticocancellous graft. This procedure maintains the shape of the outer table and facilitates anatomic reconstruction of the external oblique musculature.

The acetabular reamer technique can produce large volumes of morselized corticocancellous graft as a paste-like substance to mold and pack into defects under implants or within dead spaces[3,38,39]. The procedure involves a low-speed, high-torque acetabular reamer for total hip arthroplasty that can be used to ream the inner or outer ilium, yielding as much as 90 cm^3 from the cortex and adjacent cancellous bone. The reamer procedure is faster than the traditional techniques with decreased operative time and lower costs[3,8] (Grade-C recommendation). Bone graft harvested with the reamer technique appears to be clinically effective. In a series of thirty-four patients with a fracture nonunion who were followed for an average of ten months, union occurred in thirty-three patients (97%) at an average of ten weeks with use of the acetabular reamer technique[8] (Grade-B recommendation).

Posterior iliac crest harvest: The posterior superior iliac spine is the most common source for autogenous bone graft, probably attributable to the frequent use of this site during posterior spine fusion procedures[40]. Compared with the anterior crest, this site offers up to 30 cm^3 of bone graft, so it is used when larger volumes of graft are required[41]. The incision is made parallel to the posterior iliac crest, with care taken to avoid the cluneal nerves[6,32]. The posterior superior iliac spine is exposed subperiosteally, with the periosteum and dorsolumbar fascia on the medial edge of the crest maintained intact. A so-called trapdoor technique is favored by many to access the inner tables of the posterior ilium and obtain cancellous graft. This harvest typically involves a horizontal cut through the outer cortex of the iliac crest followed by reflection of the crest medially without disturbing the attachment site of the abdominal musculature. After sufficient graft is harvested, the reflected iliac crest should be sutured back into place[7]. The surgeon should limit harvest to 4 cm distal to the posterior superior iliac spine and avoid penetrating the inner cortex of the ilium to prevent injury to the sacroiliac joint and the superior gluteal artery[7].

Complications

Although the iliac crest remains the most frequently harvested donor site, morbidity is a concern. We categorized complications associated with bone-graft harvest into minor and major complications. In general, minor complications were defined as those that required no or minimal treatment and resulted in no long-term disability, while major complications represented those that required repeat surgery, readmission, or a prolonged hospital stay or resulted in long-term disability. We classified persistent or long-term pain at the harvest site, superficial sensory nerve injury, superficial hematoma or seroma, and superficial infection as minor complications. Major complications included deep hematoma requiring operative drainage, incisional hernia, permanent neurologic injury, vascular injury, sacroiliac joint injury, ureteral injury, permanent Trendelenburg gait, donor-site fracture, and deep infection[7,33,42,43].

Arrington et al. reviewed 414 cases and found that forty-one (10%) had minor complications (superficial hematomas or seromas in thirty-six patients and superficial infections in five) and twenty-four (5.8%) had major complications (deep hematoma in four patients, incisional hernia in two, neurologic injury in six, vascular injury in three, iliac wing fracture in two, and deep infection in seven)[33] (Grade-B recommendation). Younger and Chapman retrospectively reviewed the records of 239 patients who had 243 iliac crest bone-graft harvest procedures with a mean follow-up of eleven months[42]. Minor complications were noted after fifty-seven (23.5%) of the 243 procedures. Major complications occurred after fifteen procedures (6.2%) and included deep hematoma after nine procedures and deep infection after six. Goulet et al., in a review of the cases of 170 patients who had iliac crest bone-graft harvest, found that thirty-five (20.6%) had minor complications (twenty-eight had donor-site pain; one, superficial nerve injury; and six, superficial infections) and four (2.4%) had major complications (deep infections)[43]. Banwart et al., in an analysis of the cases of 180 patients who had an iliac crest bone-graft procedure with a mean follow-up of sixty-six months, reported that seventy (39%) had minor complications, with the majority being persistent graft-site pain, and eighteen (10%) had major complications[44]. In the previously cited Level-III study of 243 iliac crest bone-graft procedures, major complications increased on the basis of medical comorbidities, with a rate of 5.8% in healthy patients and escalating to 14.3% in patients with preexisting medical illnesses[42]. Westrich et al. correlated body-mass index and smoking with the development of both minor and major complications[3]. In summary, minor complications have been reported to occur in 7.1% to 39% of patients and major complications, in 1.8% to 10% of patients[3,33,42-44] (Grade-B recommendation).

Minor Complications

Persistent Donor-Site Pain

Early pain (occurring within three months after graft harvest) at the donor site has been reported to occur in 2.8% to 37.9% of patients[7,43,45-47] (Grade-B recommendation). However, persistent or long-term pain at the graft-harvest site is the most common minor complication reported in the bone-graft literature. In the series by Younger and Chapman, six (2.5%) of 243 iliac crest bone-graft procedures were in patients who reported long-term graft-site pain as their most common complaint[42]. Goulet et al. obtained follow-up data on pain for eighty-seven of 192 patients who were surveyed by mail[43]. They reported that thirty-three (37.9%) of the eighty-seven patients had donor-site pain at six months postoperatively and sixteen (18.4%) had donor-site pain at two years[43]. Singh et al. retrospectively reviewed forty-six patients who had anterior iliac crest bone-graft harvest with a mean follow-up of forty-one months[31]. Persistent pain at the iliac crest donor site averaged 1.7 of 10 on a visual analogue scale (VAS), while three (9.4%) of thirty-two patients who had long-term follow-up stated that donor-site pain caused functional disability.

Numerous surgeons have attempted to reduce both acute and persistent donor-site pain. In a case series in which the iliac crest bone-graft donor site was reconstructed by packing the void with a bone-graft substitute prior to closure, there was no reduction in immediate postoperative pain and persistent pain was reported by five of twelve patients[48]. However, the pain was mild, with an average VAS score of 0.6 of 10 (Grade-I recommendation). In a double-blind, randomized, controlled trial of fifty-four patients who underwent posterior iliac crest bone-graft harvest, intraoperative local administration of morphine at the harvest site had no effect on patient-controlled analgesia usage and no improvement in pain at twenty-four hours and at three, six, and twelve months postoperatively[49] (Grade-A recommendation). Another double-blind, randomized, controlled study of sixty patients who underwent iliac crest bone-graft harvest (the anterior iliac crest was used in fifty-four patients) evaluated postoperative pain in those who received a continuous infusion of 0.5% bupivacaine into the harvest site compared with placebo[50]. There was no improvement in the postoperative use of patient-controlled analgesia or in donor-site pain from the time of surgery through six weeks postoperatively. However, a similar Level-I study of thirty-seven patients who received a continuous infusion of 0.5% Marcaine (bupivacaine) into the graft site showed a significant decrease ($p < 0.05$) in narcotic dosage, demand frequency, and mean VAS score at twelve, twenty-four, and forty-eight hours compared with placebo[51]. Interestingly, a follow-up study of the same cohort at an average of 4.7 years postoperatively found the treatment group to have a significant decrease ($p < 0.05$) in the VAS score for pain at the graft site (1.4 versus 4.8 of 10) and increased satisfaction with the procedure compared with the control group, whereas none of the nine patients in the treatment group had chronic iliac crest dysesthesias compared with seven of ten in the control group[52]. At present, there are conflicting Level-I reports regarding the effects of postoperative local anesthetic infusion on donor-site pain[49-52] (Grade-I recommendation).

Superficial Nerve Injury, Hematoma Formation, Seroma Formation, and Infection

Superficial nerve injury following iliac crest bone-graft harvest does not appear commonly in the literature. Smith et al. reported two cases of ilioinguinal neuralgia from retraction of the abdominal wall where the nerve was pinched between the retractor and the iliac crest[34]. Arrington et al. noted meralgia paresthetica after anterior iliac crest bone-graft harvesting in three (0.73%) of 414 patients[33]. With posterior iliac crest bone-graft harvest, care must be exercised to prevent injury to the superior cluneal nerves, which cross just lateral to the posterior superior iliac spine and supply sensation to the superior two-thirds of the buttocks[14].

Superficial hematoma formation, seroma formation, and infection are considered collectively for this article as they are typically treated conservatively with or without antibiotics. In their respective studies, Banwart et al. noted that a superficial infection developed in one (0.5%) of 180 patients; Westrich et al., in one (0.6%) of 170 patients; and Arrington et al., in five (1.2%) of 414 patients[3,33,44]. Westrich et al. reported that superficial hematomas developed in two (1.2%) of 170 patients, and Arrington et al. reported that superficial hematomas developed in sixteen (3.9%) of 414 patients and superficial seromas, in twenty patients (4.8%)[3,33] (Grade-B recommendation).

Major Complications

Deep Hematoma Formation and Deep Infection

In the larger series, deep infection occurred in seven (1.7%) of 414 patients, six (2.5%) of 239 patients, and in four (2.1%) of 192 patients[33,42,43] (Grade-B recommendation). Other authors have reported rates of deep infection of approximately 1%, comparable with other clean surgical procedures[7,53]. Deep wound hematoma has been implicated in the development of deep infection; therefore, it has been hypothesized that a drain may reduce infectious morbidity. A prospective randomized study of 112 procedures showed no difference in the occurrence of wound complications between those done with use of a suction drain (10% [six] of sixty procedures) and those done without suction drainage (10% [five] of fifty-two procedures), concluding that suction drainage does not reduce wound infection rates in iliac crest bone-graft harvest[54] (Grade-A recommendation).

Incisional Hernia

Incisional hernia occurs when bowel protrudes through the osseous defect in the ilium after an inadequate abdominal musculature closure[7]. Arrington et al. reported that herniation developed after two (0.5%) of 414 harvest procedures, and both occurred through a tricortical graft site secondary to detachment of the abdominal musculature[33]. In all cases, the hernia must be reduced and the defect obliterated with repair of the abdominal musculature.

Sacroiliac Joint Injury, Ureteral Injury, and Gait Derangement

In the posterior superior iliac spine, if graft is harvested too far posteriorly, the sacroiliac joint can be inadvertently breached or the posterior sacroiliac ligaments may be compromised, leading to sacroiliac joint instability, pain, and arthrosis[7] (Grade-I recommendation). Ureteral injury is rare and has been recorded, to our knowledge, in only one case report[55]. It is thought to be relatively rare because of the mobility of this structure and its protective fat layer. Another complication of iliac crest harvest is gait disturbance, including a Trendelenburg gait that is often associated with hip abductor muscle weakness, which can be avoided by careful reapproximation of the abductor fascia and minimal retraction of the abductor muscles[7,42] (Grade-I recommendation).

Donor Site Fracture

Avulsion fractures of the anterior superior iliac spine can occur after graft harvest with forceful contraction of the sartorius muscle and/or tensor fasciae latae. In order to reduce the risk of this complication, many authors have recommended that the anterior iliac crest harvest site should not be <3 cm posterior to the anterior superior iliac spine[7,32,42] (Grade-C recommendation). Avulsion has been shown to be more frequent with bicortical and tricortical anterior superior iliac spine grafts than with unicortical grafts[7] (Grade-C recommendation).

Complications Associated with the Acetabular Reamer Technique

In a retrospective study of 390 bone graft procedures, the reamer technique was compared with anterior iliac crest bone-graft harvest[3]. Minor complications occurred in twenty-one (9.5%) of 220 patients managed with the reamer technique compared with twelve (7.1%) of 170 patients managed with traditional techniques of iliac crest bone-graft harvest. Major complications were noted in two patients (0.9%) in the reamer group compared with three patients (1.8%) in the group that had a traditional technique[3]. Bimmel and Govaers retrospectively reviewed the cases of eighty-eight patients who had reamer harvests and reported that twenty-six patients (29.5%) had persistent pain at the donor site and twenty-three (26.1%) had superficial nerve injury[35]. Gait disturbance occurred in eighteen patients (20.5%). In a separate series of thirty-four patients managed with an acetabular reamer, the reamer breached the inner table of the ilium with no obvious clinical sequelae[8].

Proximal Part of the Tibia

Indications

The proximal part of the tibia provides an easily accessible source of abundant cancellous, unicortical, or corticocancellous graft, especially if the ipsilateral limb is the recipient site[25,56-59] (Grade-C recommendation). The average volume of cancellous bone graft obtained from the proximal part of the tibia is approximately 25 cm^3, which compares favorably with iliac crest bone graft; however, we and others have succeeded in harvesting as much as 70 cm^3 of cancellous bone from the proximal part of the tibia in young patients with good bone stock[25,36,56,60-62] (Grade-C recommendation). In most patients, immediate postoperative weight-bearing is allowed, but when the harvest extends across the midline of the proximal aspect of the tibia, we recommend protected weight-bearing for six to twelve weeks[25,59,63] (Grade-I recommendation).

Techniques

Numerous techniques, including access from both the medial and lateral aspect of the proximal part of the tibia, have been described, with no differences reported in graft quantity[18,20,25,36,56,57,61] (Grade-C recommendation). On the lateral side, the entry point is at or just below Gerdy's tubercle, but care must be exercised to avoid knee joint violation during harvest[18,25,36]. The entry portal into the proximal part of the tibia should be circular or have rounded edges to prevent stress-risers with possible fracture propagation[36,56,57] (Grade-C recommendation). During closure, the periosteum should be repaired to provide osteoblasts for the reconstitution of bone at the harvest site[64] (Grade-I recommendation).

We prefer to access the proximal part of the tibia by means of the lateral approach with a 3-cm incision directly over Gerdy's tubercle. We split the confluence of the iliotibial band and the anterior compartment fascia in line with the incision and reflect periosteum both anteriorly and posteriorly, exposing Gerdy's tubercle. Osteotomy of the tubercle provides an oval access portal into the proximal tibial cancellous bone. Harvest is performed with either curets or a trephine, and the metaphyseal void is filled with cadaveric allograft chips. The osteotomized tubercle is discarded or used as bone graft to facilitate closure of the iliotibial band insertion.

Complications

The rate of complications at the donor site of the proximal tibial bone graft has been reported to be as low as 1% to 2%[25,59].

A study of 230 procedures for harvesting proximal tibial bone graft for the treatment of nonunion of lower-extremity fractures noted a rate of donor-site complications of 1.3% at a mean follow-up period of 20.4 months[59]. In a retrospective review, Alt et al. followed fifty-four patients for a mean of 26.4 weeks to determine appropriate weight-bearing status after proximal tibial bone-graft harvesting[25]. They reported an overall complication rate of 1.9%, with one complication (a local hematoma) that developed with immediate postoperative weight-bearing. In a study of forty proximal tibial bone-graft procedures, superficial hematoma was noted in six patients (15%)[65]. Frohberg and Mazock reported minor complications in nine (14.3%) of sixty-three patients who had a proximal tibial bone-graft harvest[66]. In a review of 148 procedures, Whitehouse et al. noted that 20% of patients reported mild pain immediately postoperatively, but only 4% reported persistent long-term pain[58] (Grade-B recommendation).

Major complications associated with the harvest of proximal tibial bone graft, including deep hematoma formation, deep infection, joint perforation, donor-site fracture, gait disturbance, and permanent nerve injury, have been reported. Geideman et al., in a study of 155 patients who had foot and ankle surgery with use of bone graft harvested from the proximal part of the ipsilateral tibia, reported that one patient (0.65%) had deep hematomas and there were no other major complications[67]. Deep hematoma formation has been reported to occur in 0.5% to 2.0% of patients and deep infection, in <1% of patients[25,59]. Frohberg and Mazock, in a study of sixty-three proximal tibial bone-grafting procedures, reported that one patient (1.6%) had a complication, a joint perforation[66]. Two donor-site fractures have been reported, one as a single case report and one in a series of 230 harvest procedures[59,68]. In one series, gait disturbance was reported to have developed in one (2.5%) of forty patients who had proximal tibial bone-graft harvesting[65]. While use of the proximal part of the tibia for bone-graft harvest does not typically place neurovascular structures at risk, if the incision is too extensive, the peroneal nerve may be injured. Moreover, the saphenous vein requires protection on the medial side of the leg[25]. Proximal tibial bone graft harvest is contraindicated in patients with open physes.

Distal End of the Radius

Indications and Techniques

The distal end of the radius can supply approximately 3 cm^3 of cancellous or corticocancellous graft for hand and upper-extremity surgery applications[20,21,69-73]. Distal radial bone harvest can be performed by a dorsal or volar approach[71] (Grade-C recommendation). The dorsal approach accesses the distal end of the radius between the first and second extensor compartments, with care taken to prevent injury to the dorsal veins and superficial radial nerve. A small osteotome can be used to create a cortical window at Lister's tubercle, where cancellous bone graft can be harvested[20]. An alternative approach between the second and third compartments moves the surgical field away from the superficial radial nerve[69]. The volar approach involves a longitudinal incision proximal to the wrist crease, and the plane between the radial artery and the brachioradialis tendon is developed. The pronator quadratus is elevated, and a cortical window is opened. Corticocancellous or cancellous graft can be harvested from the volar distal aspect of the radius. The volar approach provides some advantages in that the extensor compartments are not violated, painful adhesions of the scar to the superficial distal end of the radius itself are avoided, and the volar wrist scar is less cosmetically apparent than a dorsal incision[72].

Complications

Immediate postoperative pain was reported to occur in approximately 5% of twenty patients after bone graft was harvested from the distal end of the radius, with 15% reporting some immediate functional disability in the postoperative period[69]. Persistent pain at the graft harvest site is rare[70]. Patel et al. retrospectively reviewed the cases of 1670 patients who had distal radial autogenous bone-graft harvesting, with an average follow-up period of 4.5 years[20]. Complications occurred in sixty-six patients (4%). The authors considered failure of union to be a graft complication as this accounted for the reported complications in thirty-eight patients (2.3%). If the patients with failure of union are excluded, the resultant complication rate was 1.7% (twenty-eight of 1670 patients). Actual donor-site complications included de Quervain tenosynovitis in twenty-one patients (1.3%), donor-site infection in three (0.2%), donor-site fracture in two (0.1%), and superficial radial nerve injury in two (0.1%)[20]. Injury to the superficial radial nerve can result in pain, sensory loss, or neuroma pain, so meticulous care with incisions and retraction is necessary[20] (Grade-C recommendation).

Distal End of the Tibia

Indications, Techniques ,and Complications

The distal tibial metaphysis can be a source of corticocancellous struts, and is an easily accessed source of small volumes of cancellous bone[18,74,75] (Grade-C recommendation). This site is particularly convenient in foot and ankle surgery because of the proximity within the operative field and the minimal increase in blood loss or operative time[73] (Grade-C recommendation). Several techniques for harvest have been reported, with similar technical aspects[18,74,75]. The graft can be obtained from the distal medial aspect of the tibia, just proximal to the medial malleolus, or directly anterior, with care taken to avoid injuring the dorsalis pedis artery and vein. Cancellous graft is most easily obtained by means of a small cortical window with use of curets or trephines to harvest graft. This technique has been reported to provide approximately 2 to 3 cm^3 of cancellous graft without adverse influence on weight-bearing status. The limited supply from this location makes it a poor choice for most applications other than surgery in the foot and ankle, but there are few complications[18,74]. Persistent donor-site pain and hematoma are rare, and infection and fracture have not been reported[18,74,75] (Grade-C recommendation).

Greater Trochanter

Indications, Techniques, and Complications

The greater trochanter is a useful source of bone graft for surgery of the ipsilateral lower extremity[32,67,76,77] (Grade-C recommendation). We reserve this harvest site for acute femoral neck fractures with comminution. Our preferred technique is to create a circular entry portal into the lateral aspect of the greater trochanter during femoral neck surgery with use of a trephine. A 5 to 10-cm^3 volume of cancellous bone graft can be obtained[76]. For other limited applications, a 3 to 5-cm longitudinal incision directly over the trochanter can be used. The iliotibial band is incised in line with the skin incision, followed by entry into the trochanter. Graft is harvested through a lateral bone window in the direction of the femoral neck[32,67,77]. In a series of eighty-five patients who had foot and ankle surgery, with a mean follow-up of forty-nine months, twenty-six (30.6%) noted some element of persistent hip pain and nineteen (22.4%) underwent treatment, including therapy and ice, for persistent pain at the trochanteric harvest site[77].

Reamer-Irrigator-Aspirator

Indications

The reamer-irrigator-aspirator (RIA; Synthes) is a single-use intramedullary reaming device that combines reaming with simultaneous intramedullary irrigation and aspiration. Standard reaming has been associated with pulmonary complications, including fat embolism and acute respiratory distress syndrome secondary to high intramedullary pressures[78,79]. The RIA was proposed to decrease pulmonary complications associated with reamed femoral nailing in patients who have sustained multiple injuries by decreasing intramedullary pressure and its systemic effects[80,81].

An unanticipated benefit of the RIA device is harvest of autogenous intramedullary bone graft. Harvest volumes have been reported to range from 30 to 90 cm^3 with comparable union rates and lower scores for immediate and chronic pain compared with iliac crest bone graft[30,80,82-84] (Grade-C recommendation). On average, the technique provides approximately 40 cm^3 of bone graft from the femur and 33 cm^3 from the tibia[30] (Grade-C recommendation).

Cell biology studies have demonstrated that this graft is rich in stem cells, osteogenic cells, and growth factors, which are at least equivalent to iliac crest[30,80,85,86] (Grade-B recommendation). Although there are few robust reports to support the use of the RIA graft, the results of case series and small studies are encouraging. In a prospective case series of twenty-one patients with segmental bone defects averaging 6.6 cm^3, McCall et al. showed defect consolidation in 85% at eleven months postoperatively[80] (Grade-C recommendation). In their study, they report one case of a 14-cm defect that united with internal stabilization and RIA graft[80] (Grade-I recommendation).

Techniques

Graft is obtained by introducing the RIA into the femoral or tibial canal and using the aspiration ability of the device to collect reamed bone graft in a filtered canister. The femur may be approached in an antegrade fashion, with use of either the piriformis fossa or greater trochanter as an entry portal, or in a retrograde fashion with use of the intercondylar notch as an entry portal. The tibia is best approached in an antegrade fashion with use of an entry portal into the proximal part of the tibia similar to that used for intramedullary nail fixation of a tibial fracture. The greater trochanteric entry point is preferred over the piriformis fossa by many authors in order to avoid damage to the femoral neck[30] (Grade-I recommendation). The RIA entry angle should be as narrow as possible to minimize eccentric reaming[82] (Grade-I recommendation). A cadaver study compared three RIA starting points (greater trochanter, piriformis fossa, and intercondylar notch). The femora were tested with cyclical loading, and no significant differences ($p = 0.606$) were noted in the mechanical behavior including load failure with any of the starting points[87] (Grade-B recommendation).

Lateral and anteroposterior radiographs or a computed tomography scan should be made to determine the width of the isthmus preoperatively, so that an appropriate reamer head can be chosen. Reamer heads range from 12 to 16.5 mm in 0.5-mm increments, and the initial size should be selected on the basis of the width of the isthmus, which represents the narrowest region. Overall, there is a negligible loss of strength when the intramedullary cortices are reamed by ≤2 mm; however, reaming of >2 mm can compromise torsional strength and potentially lead to iatrogenic fracture[30,84,88,89] (Grade-B recommendation). For the same reason, the reamer head should not exceed 50% of the outer diaphyseal diameter[84] (Grade-I recommendation). A 2.5-mm intramedullary guidewire is centered in the canal to guide harvest. For the femoral harvest, the wire can be pre-bent to allow intraoperative readjustment to harvest from the center of the distal aspect of the femur and both condyles[82]. Frequent intraoperative fluoroscopy in both the anteroposterior and lateral planes is required to prevent cortical breaching.

As the filtrate is suctioned off, the residual material in the filter contains the harvested bone graft, which is a combination of bone marrow and reamed cortical bone fragments. Several authors have suggested that reaming does not substantially decrease the strength of the femur, but fracture at the harvest site has been reported[30,87]. Weight-bearing recommendations and fracture risk associated with an RIA harvest are inconclusive (Grade-I recommendation). The RIA should be considered an option for autogenous graft in patients at risk for infection at other harvest sites, who may have an insufficient volume of iliac crest bone stock, who have previously had bone graft harvested from the iliac crest, or in patients in whom the volume of bone graft needed exceeds that which is available with traditional techniques[82] (Grade-C recommendation).

Complications

Several authors have reported equipment problems including eccentric reaming from guidewire displacement, lodging of the reamer in the canal, and product malfunctions[30,82,84]. Two of the most important complications include hemodynamic compromise and iatrogenic fracture[82,83]. Because of the nature of continuous suctioning and reaming, a high volume of blood can be aspirated from the intramedullary canal; however, the average operative blood loss for this harvest technique has been reported[82] to range from 200 to 500 mL. Scharfenberger and Weber harvested an average of 73 cm^3 of bone graft from eight patients who had a mean decrease in hemoglobin level of 4.4 g/dL and a mean decrease in hematocrit level of 12.3%, with one of the eight patients requiring a transfusion[83]. Quintero et al. reported a single case of a patient in whom the RIA head lodged in the femoral isthmus for three minutes, with resultant hemodynamic instability requiring acute volume resuscitation[82]. We experienced a similar event in which 1500 mL of blood was lost rapidly, requiring acute volume resuscitation. To minimize this risk, the RIA suction should be discontinued and the reamer removed whenever reaming is not in progress, or if the reamer becomes incarcerated in the canal[82] (Grade-I recommendation). The risk of incarceration can be reduced by reaming no more than 1.0 to 1.5 mm larger than the isthmus of the intramedullary canal[80] (Grade-I recommendation).

Iatrogenic fracture can result if the reamer follows an eccentric path in the intramedullary canal, and breaching of the anterior or medial cortex results[82] (Grade-C recommendation). Quintero et al. reported the cases of two patients in whom the anterior cortex was breached[82]. This complication can be avoided with frequent intraoperative fluoroscopy to evaluate the reamer path and cortical thinning[88]. Reaming of the distal cortices should be discontinued once adequate bone graft has been obtained as this is also associated with iatrogenic fracture in osteopenic patients[82] (Grade-I recommendation). Lowe et al., in a series of ninety-seven patients who had RIA graft harvests, reported that complications developed in six patients, for an overall rate of 6.2%[84]. Iatrogenic fracture occurred with minimal trauma in four patients (4.1%). The authors noted that a history of osteoporosis or radiographic osteopenia was a risk factor for iatrogenic fracture after RIA harvest[84].

Belthur et al. retrospectively reviewed the cases of forty-one patients who underwent RIA harvest from the tibia or femur and compared this group with a control group of forty patients who had bone graft harvested from the iliac crest[30]. In one (2.4%) of forty-one patients, eccentric reaming led to a perforation of the distal part of the anterior femoral cortex with localized pain for four months. A second complication occurred in one patient (2.4%) who had excessive reaming of the femoral neck through the piriformis entry portal that required prophylactic fixation. Lower pain scores were reported for the RIA group compared with the iliac crest bone-graft group[30]. No episodes of superficial or deep hematoma formation, deep infection, or fat embolism were noted in the RIA group. In the iliac crest bone-graft group, one patient (2.5%) had a hematoma and three (7.5%) had deep infections[30] (Grade-C recommendation). At the current time, the literature is inadequate to provide sound recommendations for or against the RIA.

Induced Membranes

The options for managing bone defects of ≥6 cm have traditionally been limited to major operative reconstructions including major cancellous grafting, vascularized and nonvascularized fibular autograft and bone transport (the Ilizarov method) along with an endoprosthesis, and other nonbiological options[80,90-92]. Cancellous autograft has been recommended for voids of ≤5 cm with a well-vascularized, healthy recipient site[43]. Recently, Masquelet and Begue introduced the so-called induced membranes treatment technique[90]. This method has shown favorable union rates, even in tissue beds with recent irradiation or infection, and may be a viable option for patients who are poor medical hosts, are not ideal candidates for other more complex reconstructive options, or have large bone voids (Grade-C recommendation).

Masquelet and Begue retrospectively reviewed a series of thirty-five reconstructions of bone defects ranging from 5 to 24 cm and observed radiographic healing at four months in all of the patients[90] (Grade-C recommendation). Union was independent of defect length, and all deep bone infections had resolved by 8.5 months[90,93] (Grade-C recommendation). In a rabbit model, Pelissier et al. found that the induced membrane produced multiple cytokines potentially responsible for promoting union and bone graft consolidation including vascular endothelial growth factor (VEGF), bone morphogenetic protein-2 (BMP-2), and transforming growth factor-beta 1 (TGF-β1)[93] (Grade-B recommendation). The membrane itself is highly vascularized, with a synovium-like inner surface and an outer layer of fibroblasts and collagen[90].

The induced membranes technique is a two-stage procedure. The first stage requires complete excisional debridement of necrotic or compromised tissue at the nonunion site similar to the Papineau procedure for chronic osteomyelitis[94]. This stage is completed with the application of a polymethylmethacrylate cement spacer (with or without antibiotics) placed into the bone void, which provides provisional stability as well as a surface for pseudomembrane formation. After a period of four to six weeks, the second stage, or reconstructive stage, begins with spacer removal. The pseudosynovial membrane, or induced membrane, void is filled with autogenous cancellous bone graft[90,91,93]. The membrane should be sutured closed in order to contain the graft and thus prevent the collapse of soft tissue into the defect and the invasion of inflammatory cells. This membrane appears to protect the autograft from rapid resorption and to promote graft consolidation[90,91,93] (Grade-C recommendation). Another adjuvant method combines the induced membranes technique with RIA graft to fill large bone voids[80,95] (Grade-C recommendation).

Overview

Cancellous autogenous bone graft can be harvested from the iliac crest, proximal part of the tibia, distal end of the radius, distal end of the tibia, and greater trochanter. The novel technique of intramedullary bone-graft harvest with use of the RIA provides a possible alternative, although outcomes and complications with this technique are not yet fully defined. The induced membranes method can be combined with any of the graft options for management of more complex bone defects or voids. The most common complication noted with bone-graft harvest is persistent pain at the donor site, but the most concerning complications are deep infection and fracture at the donor site. Fortunately, these major complications are relatively rare. The orthopaedic surgeon must be familiar with the indications, techniques, and potential complications of each of these options for autogenous bone-graft harvest.

Appendix

eA A table showing the Level-of-Evidence grades for the autogenous bone graft recommendations is available with the online version of this article as a data supplement at jbjs.org. ■

Chad Myeroff, MD
Department of Orthopaedic Surgery,
University of Minnesota, 2450 Riverside Avenue South,
R200, Minneapolis, MN 55454.
E-mail address: myero315@umn.edu

Michael Archdeacon, MD, MSE
Health Department of Orthopaedic Surgery,
University of Cincinnati College of Medicine,
231 Albert Sabin Way, ML 0212, Cincinnati, OH 45267.
E-mail address: michael.archdeacon@uc.edu

References

1. Wright JG, Swiontkowski MF, Heckman JD. Introducing levels of evidence to the journal. J Bone Joint Surg Am. 2003;85:1-3.

2. Wright JG, Einhorn TA, Heckman JD. Grades of recommendation. J Bone Joint Surg Am. 2005;87:1909-10.

3. Westrich GH, Geller DS, O'Malley MJ, Deland JT, Helfet DL. Anterior iliac crest bone graft harvesting using the corticocancellous reamer system. J Orthop Trauma. 2001;15:500-6.

4. Kakar S, Tsiridis E, Einhorn T. Bone grafting and enhancement of fracture repair. In: Bucholz RW, Heckman JD, Court-Brown C, Tornetta P, Koval KJ, Wirth MA, editors. Rockwood and Green's fractures in adults. 6th ed. Vol 1. Philadelphia: Lippincott Williams and Wilkins; 2006. p 313-31.

5. Finkemeier CG. Bone-grafting and bone-graft substitutes. J Bone Joint Surg Am. 2002;84:454-64.

6. Khan SN, Cammisa FP Jr, Sandhu HS, Diwan AD, Girardi FP, Lane JM. The biology of bone grafting. J Am Acad Orthop Surg. 2005;13:77-86.

7. Ebraheim NA, Elgafy H, Xu R. Bone-graft harvesting from iliac and fibular donor sites: techniques and complications. J Am Acad Orthop Surg. 2001;9:210-8.

8. Brawley SC, Simpson RB. Results of an alternative autogenous iliac crest bone graft harvest method. Orthopedics. 2006;29:342-6.

9. Gazdag AR, Lane JM, Glaser D, Forster RA. Alternatives to autogenous bone graft: efficacy and indications. J Am Acad Orthop Surg. 1995;3:1-8.

10. Sen MK, Miclau T. Autologous iliac crest bone graft: should it still be the gold standard for treating nonunions? Injury. 2007;38:S75-80.

11. Bauer TW, Muschler GF. Bone graft materials. An overview of the basic science. Clin Orthop Relat Res. 2000;371:10-27.

12. Dell PC, Burchardt H, Glowczewskie FP Jr. A roentgenographic, biomechanical, and histological evaluation of vascularized and non-vascularized segmental fibular canine autografts. J Bone Joint Surg Am. 1985;67:105-12.

13. Olsen BS, Vaesel MT, Søjbjerg JO. Treatment of midshaft clavicular nonunion with plate fixation and autologous bone grafting. J Shoulder Elbow Surg. 1995;4:337-44.

14. Bradbury N, Hutchinson J, Hahn D, Colton CL. Clavicular nonunion. 31/32 healed after plate fixation and bone grafting. Acta Orthop Scand. 1996;67:367-70.

15. Sanders R. Displaced intra-articular fractures of the calcaneus. J Bone Joint Surg Am. 2000;82:225-50.

16. Easley ME, Trnka HJ, Schon LC, Myerson MS. Isolated subtalar arthrodesis. J Bone Joint Surg Am. 2000;82:613-24.

17. Cypher TJ, Grossman JP. Biological principles of bone graft healing. J Foot Ankle Surg. 1996;35:413-7.

18. Mendicino RW, Leonheart E, Shromoff P. Techniques for harvesting autogenous bone graft of the lower extremity. J Foot Ankle Surg. 1996;35:428-35.

19. Nusbickel FR, Dell PC, McAndrew MP, Moore MM. Vascularized autografts for reconstruction of skeletal defects following lower extremity trauma. A review. Clin Orthop Relat Res. 1989;243:65-70.

20. Patel JC, Watson K, Joseph E, Garcia J, Wollstein R. Long-term complications of distal radius bone grafts. J Hand Surg Am. 2003;28:784-8.

21. Bruno RJ, Cohen MS, Berzins A, Sumner DR. Bone graft harvesting from the distal radius, olecranon, and iliac crest: a quantitative analysis. J Hand Surg Am. 2001;26:135-41.

22. Laursen M, Christensen FB, Bünger C, Lind M. Optimal handling of fresh cancellous bone graft: different peroperative storing techniques evaluated by in vitro osteoblast-like cell metabolism. Acta Orthop Scand. 2003;74:490-6.

23. Maus U, Andereya S, Gravius S, Siebert CH, Schippmann T, Ohnsorge JA, Niedhart C. How to store autologous bone graft perioperatively: an in vitro study. Arch Orthop Trauma Surg. 2008;128:1007-11.

24. Lindsey RW, Probe R, Miclau T, Alexander JW, Perren SM. The effects of antibiotic-impregnated autogeneic cancellous bone graft on bone healing. Clin Orthop Relat Res. 1993;291:303-12.

25. Alt V, Nawab A, Seligson D. Bone grafting from the proximal tibia. J Trauma. 1999;47:555-7.

26. Chan YS, Ueng SW, Wang CJ, Lee SS, Chen CY, Shin CH. Antibiotic-impregnated autogenic cancellous bone grafting is an effective and safe method for the management of small infected tibial defects: a comparison study. J Trauma. 2000;48:246-55.

27. Chen CE, Ko JY, Pan CC. Results of vancomycin-impregnated cancellous bone grafting for infected tibial nonunion. Arch Orthop Trauma Surg. 2005;25:369-75.

28. Naal FD, Salzmann GM, von Knoch F, Tuebel J, Diehl P, Gradinger R, Schauwecker J. The effects of clindamycin on human osteoblasts in vitro. Arch Orthop Trauma Surg. 2008;128:317-23.

29. Salzmann GM, Naal FD, von Knoch F, Tuebel J, Gradinger R, Imhoff AB, Schauwecker J. Effects of cefuroxime on human osteoblasts in vitro. J Biomed Mater Res A. 2007;82:462-8.

30. Belthur MV, Conway JD, Jindal G, Ranade A, Herzenberg JE. Bone graft harvest using a new intramedullary system. Clin Orthop Relat Res. 2008;466:2973-80.

31. Singh JR, Nwosu U, Egol KA. Long-term functional outcome and donor-site morbidity associated with autogenous iliac crest bone grafts utilizing a modified anterior approach. Bull NYU Hosp Jt Dis. 2009;67:347-51.

32. Meeder PJ, Eggers C. Techniques for obtaining autogenous bone graft. Injury. 1994;25:A5-16.

33. Arrington ED, Smith WJ, Chambers HG, Bucknell AL, Davino NA. Complications of iliac crest bone graft harvesting. Clin Orthop Relat Res. 1996;329:300-9.

34. Smith SE, DeLee JC, Ramamurthy S. Ilioinguinal neuralgia following iliac bone-grafting. Report of two cases and review of the literature. J Bone Joint Surg Am. 1984;66:1306-8.

35. Bimmel R, Govaers K. Does harvesting of iliac bone grafts with an acetabular reamer reduce complication rate? Acta Orthop Belg. 2006;72:598-602.

36. Ilankovan V, Stronczek M, Telfer M, Peterson LJ, Stassen LF, Ward-Booth P. A prospective study of trephined bone grafts of the tibial shaft and iliac crest. Br J Oral Maxillofac Surg. 1998;36:434-9.

37. Behairy YM, Al-Sebai W. A modified technique for harvesting full-thickness iliac crest bone graft. Spine (Phila Pa 1976). 2001;26:695-7.

38. Gossman DG, Rosenblum W, Arosarena O, Valentino J. The acetabular reamer: a unique tool for anterior iliac crest bone graft harvesting. Laryngoscope. 2005;115:557-9.

39. Dick W. Use of the acetabular reamer to harvest autogeneic bone graft material: a simple method for producing bone paste. Arch Orthop Trauma Surg. 1986;105:235-8.

40. Sandhu HS, Grewal HS, Parvataneni H. Bone grafting for spinal fusion. Orthop Clin North Am. 1999;30:685-98.

41. Ahlmann E, Patzakis M, Roidis N, Shepherd L, Holtom P. Comparison of anterior and posterior iliac crest bone grafts in terms of harvest-site morbidity and functional outcomes. J Bone Joint Surg Am. 2002;84:716-20.

42. Younger EM, Chapman MW. Morbidity at bone graft donor sites. J Orthop Trauma. 1989;3:192-5.

43. Goulet JA, Senunas LE, DeSilva GL, Greenfield ML. Autogenous iliac crest bone graft. Complications and functional assessment. Clin Orthop Relat Res. 1997;339:76-81.

44. Banwart JC, Asher MA, Hassanein RS. Iliac crest bone graft harvest donor site morbidity. A statistical evaluation. Spine (Phila Pa 1976). 1995;20:1055-60.

45. Schnee CL, Freese A, Weil RJ, Marcotte PJ. Analysis of harvest morbidity and radiographic outcome using autograft for anterior cervical fusion. Spine (Phila Pa 1976). 1997;22:2222-7.

46. Sawin PD, Traynelis VC, Menezes AH. A comparative analysis of fusion rates and donor-site morbidity for autogeneic rib and iliac crest bone grafts in posterior cervical fusions. J Neurosurg. 1998;88:255-65.

47. Summers BN, Eisenstein SM. Donor site pain from the ilium. A complication of lumbar spine fusion. J Bone Joint Surg Br. 1989;71:677-80.

48. Dusseldorp JR, Mobbs RJ. Iliac crest reconstruction to reduce donor-site morbidity: technical note. Eur Spine J. 2009;18:1386-90.

49. Wai EK, Sathiaseelan S, O'Neil J, Simchison BL. Local administration of morphine for analgesia after autogenous anterior or posterior iliac crest bone graft harvest for spinal fusion: a prospective, randomized, double-blind, placebo-controlled study. Anesth Analg. 2010;110:928-33.

50. Morgan SJ, Jeray KJ, Saliman LH, Miller HJ, Williams AE, Tanner SL, Smith WR, Broderick JS. Continuous infusion of local anesthetic at iliac crest bone-graft sites for postoperative pain relief. A randomized, double-blind study. J Bone Joint Surg Am. 2006;88:2606-12.

51. Singh K, Samartzis D, Strom J, Manning D, Campbell-Hupp M, Wetzel FT, Gupta P, Phillips FM. A prospective, randomized, double-blind study evaluating the efficacy of postoperative continuous local anesthetic infusion at the iliac crest bone graft site after spinal arthrodesis. Spine (Phila Pa 1976). 2005;30:2477-83.

52. Singh K, Phillips FM, Kuo E, Campbell M. A prospective, randomized, double-blind study of the efficacy of postoperative continuous local anesthetic infusion at the iliac crest bone graft site after posterior spinal arthrodesis: a minimum of 4-year follow-up. Spine (Phila Pa 1976). 2007;32:2790-6.

53. Kurz LT, Garfin SR, Booth RE Jr. Harvesting autogenous iliac bone grafts. A review of complications and techniques. Spine (Phila Pa 1976). 1989;14:1324-31.

54. Sasso RC, Williams JI, Dimasi N, Meyer PR Jr. Postoperative drains at the donor sites of iliac-crest bone grafts. A prospective, randomized study of morbidity at the donor site in patients who had a traumatic injury of the spine. J Bone Joint Surg Am. 1998;80:631-5.

55. Escalas F, DeWald RL. Combined traumatic arteriovenous fistula and ureteral injury: a complication of iliac bone-grafting. J Bone Joint Surg Am. 1977;59:270-1.

56. Herford AS, King BJ, Audia F, Becktor J. Medial approach for tibial bone graft: anatomic study and clinical technique. J Oral Maxillofac Surg. 2003;61:358-63.

57. van Damme PA, Merkx MA. A modification of the tibial bone-graft-harvesting technique. Int J Oral Maxillofac Surg. 1996;25:346-8.

58. Whitehouse MR, Lankester BJ, Winson IG, Hepple S. Bone graft harvest from the proximal tibia in foot and ankle arthrodesis surgery. Foot Ankle Int. 2006;27:913-6.

59. O'Keeffe RM Jr, Riemer BL, Butterfield SL. Harvesting of autogenous cancellous bone graft from the proximal tibial metaphysis. A review of 230 cases. J Orthop Trauma. 1991;5:469-74.

60. Judet H, Gilbert A, Mathoulin C, Judet J, Judet T, Siguier M, Brumpt B. [Reconstruction of loss of bony substance in limbs by free vascularized fibula transplant]. Chirurgie. 1991;117:469-77. French.

61. Catone GA, Reimer BL, McNeir D, Ray R. Tibial autogenous cancellous bone as an alternative donor site in maxillofacial surgery: a preliminary report. J Oral Maxillofac Surg. 1992;50:1258-63.

62. Wang K, Almeida LE, Olsson AB. Volume analysis of the proximal tibial metaphysis. J Oral Maxillofac Surg. 2007;65:2425-9.

63. Gause NL, Ivy A, Myeroff C. Complications associated with proximal tibia bone graft compared to iliac crest bone graft. Presented at the Annual Meeting of the American Academy of Orthopaedic Surgeons. 2010 Mar 9-12; New Orleans, LA.

64. Crenshaw AH. Surgical techniques and approaches. In: Canale ST, Beaty JH. Campbell's operative orthopedics. 11th ed. Philadelphia: Mosby; 2007. p 14-23.

65. Chen YC, Chen CH, Chen PL, Huang IY, Shen YS, Chen CM. Donor site morbidity after harvesting of proximal tibia bone. Head Neck. 2006;28:496-500.

66. Frohberg U, Mazock JB. A review of morbidity associated with bone harvest from the proximal tibial metaphysis. Mund Kiefer Gesichtschir. 2005;9:63-5.

67. Geideman W, Early JS, Brodsky J. Clinical results of harvesting autogenous cancellous graft from the ipsilateral proximal tibia for use in foot and ankle surgery. Foot Ankle Int. 2004;25:451-5.

68. Galano GJ, Greisberg JK. Tibial plateau fracture with proximal tibia autograft harvest for foot surgery. Am J Orthop (Belle Mead NJ). 2009;38:621-3.

69. Schuringa MC, Fechner MR. Cancellous bone grafting from the distal radius. Eur J Plast Surg. 2002;25:319-22.

70. Horne LT, Murray PM, Saha S, Sidhar K. Effects of distal radius bone graft harvest on the axial compressive strength of the radius. J Hand Surg. 2010;35:262-6.

71. Jarrett P, Kinzel V, Stoffel K. A biomechanical comparison of scaphoid fixation with bone grafting using iliac bone or distal radius bone. J Hand Surg Am. 2007;32:1367-73.

72. Mirly HL, Manske PR, Szerzinski JM. Distal anterior radius bone graft in surgery of the hand and wrist. J Hand Surg Am. 1995;20:623-7.

73. Biddulph SL. Bone donor site. Iliac crest or distal radius? J Hand Surg Br. 1999;24:645-6.

74. Saltrick KR, Caron M, Grossman J. Utilization of autogenous corticocancellous bone graft from the distal tibia for reconstructive surgery of the foot and ankle. J Foot Ankle Surg. 1996;35:406-12.

75. Weiss GA, Saxby TS. Distal tibial bone graft for foot and ankle surgery. Foot Ankle Surg. 1998;4:93-7.

76. Lindberg EJ, Katchis SD, Smith RW. Quantitative analysis of cancellous bone graft available from the greater trochanter. Foot Ankle Int. 1996;17:473-6.

77. Hayes WR Jr, Smith RW. Trochanteric bone grafts in foot and ankle surgery. Foot Ankle Int. 1996;17:402-5.

78. Pape HC, Auf'm'Kolk M, Paffrath T, Regel G, Sturm JA, Tscherne H. Primary intramedullary femur fixation in multiple trauma patients with associated lung contusion–a cause of posttraumatic ARDS? J Trauma. 1993:34:540-8.

79. Roberts CS, Pape HC, Jones AL, Malkani AL, Rodriguez JL, Giannoudis PV. Damage control orthopaedics: evolving concepts in the treatment of patients who have sustained orthopaedic trauma. J Bone Joint Surg Am. 2005;87:434-49.

80. McCall TA, Brokaw DS, Jelen BA, Scheid DK, Scharfenberger AV, Maar DC, Green JM, Shipps MR, Stone MB, Musapatika D, Weber TG. Treatment of large segmental bone defects with reamer-irrigator-aspirator bone graft: technique and case series. Orthop Clin North Am. 2010;41:63-73.

81. Husebye EE, Lyberg T, Madsen JE, Eriksen M, Røise O. The influence of a one-step reamer-irrigator-aspirator technique on the intramedullary pressure in the pig femur. Injury. 2006;37:935-40.

82. Quintero AJ, Tarkin IS, Pape HC. Technical tricks when using the reamer irrigator aspirator technique for autologous bone graft harvesting. J Orthop Trauma. 2010;24:42-5.

83. Scharfenberger AV, Weber TG. Reamer irrigator aspirator (RIA) for bone graft harvest: applications for grafting large segmental defects in the tibia and femur. J Bone Joint Surg Br. Proceedings. 2008;90:95.

84. Lowe JA, Della Rocca GJ, Murtha Y, Liporace FA, Stover MD, Nork SE, Crist BD. Complications associated with negative pressure reaming for harvesting autologous bone graft: a case series. J Orthop Trauma. 2010;24:46-52.

85. Sagi CH, Young M, Gerstenfeld L, Shah AR, Tornetta P. Quantitative differences between bone graft obtained with a reamer/irrigator/aspirator and from the iliac crest. Presented at the Orthopaedic Trauma Association Annual Meeting; 2009 Oct 7-10; San Diego, CA.

86. Porter RM, Liu F, Pilapil C, Betz OB, Vrahas MS, Harris MB, Evans CH. Osteogenic potential of reamer irrigator aspirator (RIA) aspirate collected from patients undergoing hip arthroplasty. J Orthop Res. 2009;27:42-9.

87. Finnan RP, Prayson MJ, Goswami T, Miller D. Use of the Reamer-Irrigator-Aspirator for bone graft harvest: a mechanical comparison of three starting points in cadaveric femurs. J Orthop Trauma. 2010;24:36-41.

88. Pratt DJ, Papagiannopoulos G, Rees PH, Quinnell R. The effects of medullary reaming on the torsional strength of the femur. Injury. 1987;18:177-9.

89. Conway JD. Autograft and nonunions: morbidity with intramedullary bone graft versus iliac crest bone graft. Orthop Clin North Am. 2010;41:75-84.

90. Masquelet AC, Begue T. The concept of induced membrane for reconstruction of long bone defects. Orthop Clin North Am. 2010;41:23-37.

91. Biau DJ, Pannier S, Masquelet AC, Glorion C. Case report: reconstruction of a 16-cm diaphyseal defect after Ewing's resection in a child. Clin Orthop Relat Res. 2009;467:572-7.

92. DeCoster TA, Gehlert RJ, Mikola EA, Pirela-Cruz MA. Management of posttraumatic segmental bone defects. J Am Acad Orthop Surg. 2004;12:28-38.

93. Pelissier P, Masquelet AC, Bareille R, Pelissier SM, Amedee J. Induced membranes secrete growth factors including vascular and osteoinductive factors and could stimulate bone regeneration. J Orthop Res. 2004;22:73-9.

94. Papineau LJ. [Excision-graft with deliberately delayed closing in chronic osteomyelitis]. Nouv Presse Med. 1973;2:2753-5. French.

95. Huffman LK, Harris JG, Suk M. Using the bi-masquelet technique and reamer-irrigator-aspirator for post-traumatic foot reconstruction. Foot Ankle Int. 2009;30:895-9.