Metaphyseal bone loss in revision knee arthroplasty

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Abstract The etiology of bone loss encountered during revision total knee arthroplasty (TKA) is often multifactorial and can include stress shielding, osteolysis, osteonecrosis, infection, mechanical loss due to a grossly loose implant, and iatrogenic loss at the time of implant resection. Selection of the reconstructive technique(s) to manage bone deficiency is determined by the location and magnitude of bone loss, ligament integrity, surgeon experience, and patient factors including the potential for additional revision, functional demand, and comorbidities. Smaller, contained defects are reliably managed with bone graft, cement augmented with screw fixation, or modular augments. Large metaphyseal defects require more extensive reconstruction such as impaction bone grafting with or without mesh augmentation, prosthetic augmentation, use of bulk structural allografts, or use of metaphyseal cones or sleeves. While each technique has advantages and disadvantages, the most optimal method for reconstruction of large metaphyseal bone defects during revision TKA is not clearly established.

Keywords Revision total knee arthroplasty · Bone loss · Augments · Metaphyseal cone · Metaphyseal sleeve · Bulk structural allograft

Introduction

Metaphyseal bone loss can compromise initial and long-term fixation of components during revision total knee arthroplasty (TKA). Malalignment of components is always a potential consequence of bone loss due to loss of normal anatomical landmarks. The etiology of bone loss is often multifactorial and can include stress shielding, osteolysis, osteonecrosis, infection, mechanical loss from abrasion due to a grossly loose implant, and iatrogenic loss at the time of implant resection [6, 15, 20]. The goals of revision surgery are to preserve viable host bone, reconstruct bone deficiencies for implant fixation, restore the joint line, achieve proper patellar tracking, establish neutral alignment, and optimize ligamentous stability and flexion-extension balance [6, 8]. The long-term goal is a well-fixed, stable knee joint that improves the patient's functional status and quality of life (Fig. 1).

Understanding the mode of TKA failure facilitates effective planning and execution of revision surgery. Mechanisms of failure include aseptic loosening, infection, polyethylene wear, osteolysis, instability, component malposition, periprosthetic fracture, extensor mechanism complications, and arthrofibrosis [7]. Physical examination should also assess for ligamentous incompetence that may affect decisions regarding prosthetic constraint. Preoperative radiographs need to be scrutinized to anticipate the quantity and quality of remaining bone stock [20]. All cases of TKA failure should be evaluated for possible deep infection with physical examination and appropriate laboratory studies. Selection of the reconstructive technique(s) to manage bone deficiency is

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Fig. 1 Management of bone loss during total knee arthroplasty revision for mechanical failure. **a** shows preoperative anteroposterior (*left*) and lateral (*right*) radiographs. **b** shows postoperative anteroposterior (*left*) and lateral (*right*) radiographs following reconstruction with a

constrained condylar knee (CCK) design, two 5-mm posterior femoral augments, a 5-mm medial distal femoral augment, a 10-mm lateral distal femoral augment, a trabecular metal tibial metaphyseal cone, and diaphyseal-engaging stems

determined by surgeon experience and training, the integrity of the posterior cruciate and collateral ligaments, the location and magnitude of bone loss, and patient factors including the potential for additional revision, functional demand, and comorbidities [6, 8, 16, 34].

Classification of bone deficiency during revision TKA

Multiple classification systems have been described to define the extent of bone loss and guide its management during revision TKA [4, 12, 13, 20, 31]. The size, symmetry, morphology, and location of bone loss are determined intraoperatively after resection of the failed implants [6]. Bone defects can be described as contained or uncontained. A contained defect has an intact peripheral cortical rim surrounding the area of bone loss that allows treatment with morselized bone graft or cement and screws, depending on the size of the lesion. In an uncontained defect, the peripheral cortical rim is absent and typically requires reconstruction with metal augments, bulk structural allograft, or metaphyseal sleeves or cones [6, 34]. The size and location of the uncontained defect dictate the options available for reconstruction.

The Anderson Orthopaedic Research Institute (AORI) classification is a widely adopted system for categorizing the severity of bone deficiency encountered during revision TKA and predicting the most appropriate method of reconstruction [12] (Table 1). Type 1 bone defects are minor contained deficiencies of trabecular bone involving the bone-implant interface. The adjacent metaphyseal bone is intact, and thus, the joint line is typically maintained. Such defects may be resected with a thicker bone cut or filled with bone graft or cement [6]. Type 2 bone defects are subdivided into involvement of one (type 2A) or both (type 2B) femoral condyles or

tibial plateaus. These defects have an intact or partially intact peripheral rim of bone but deficient metaphyseal bone. Metaphyseal bone loss can alter the joint line and provide a challenge for implant fixation. The operative techniques utilized for type 1 defects can be appropriate for smaller type 2 defects. However, more substantial metaphyseal type 2 and 3 bone loss requires the use of bulk structural allograft, prosthetic augments, or metaphyseal sleeves and cones. Type 3 bone defects involve cortical and metaphyseal bone loss. Cortical deficiency may result in partial or complete disruption of collateral ligament attachments. In massive segmental type 3 defects with loss of collateral ligamentous support, a condyle-replacing hinged prosthesis or a so-called “megaprosthesis” should be available [6].

Management of metaphyseal bone loss

Some degree of bone loss is present in all revision TKA procedures. Meticulous implant removal and minimal bone resection are critical principles to preserve viable host bone. The principles of revision TKA are otherwise the same as those of primary TKA, to establish the following: (a) neutral limb alignment, (b) proper component position, (c) soft tissue balance to provide stability throughout the range of motion, and (d) adequate motion for activities of daily living. However, metaphyseal bone loss and the poor quality of remaining bone make it challenging to achieve these goals in revision surgery.

There are several options for reconstruction of metaphyseal bone deficiencies. Regardless of the technique utilized, in all cases, attention must be given to restoration of an anatomic joint line. This optimizes ligamentous stability and joint kinematics. Compromised stability in the setting of bone loss may affect decisions regarding implant constraint. In most patients, a posterior-stabilized implant is used in the revision setting.

Table 1 Anderson Orthopaedic Research Institute (AORI) classification of bony deficiency during revision TKA and corresponding options for reconstruction of bone loss

Anderson Orthopaedic Research Institute classification of bony deficiency during revision TKA		
Type	Characteristics	Reconstruction options
1	Minor contained deficiency of trabecular bone at the bone-implant interface. Intact metaphyseal bone. Normal joint line.	Increase thickness of bone resection, fill defect with cancellous bone graft or cement
2A	Deficiency of metaphyseal bone involving one femoral condyle or tibial plateau. Intact or partially intact peripheral rim of cortical bone. Abnormal joint line.	Impaction bone graft, cement, prosthetic augmentation
2B	Deficiency of metaphyseal bone involving both femoral condyles or tibial plateaus. Intact or partially intact peripheral rim of cortical bone. Abnormal joint line.	Impaction bone graft, bulk structural allograft, prosthetic augmentation, metaphyseal sleeves or cones
3	Deficiency of metaphyseal and cortical bone. Partial or complete disruption of collateral ligament attachments. Abnormal joint line.	Bulk structural allograft, prosthetic augmentation, metaphyseal sleeves or cones, megaprosthesis

For cases with ligamentous insufficiency and moderate bone loss, a constrained condylar knee (CCK) design that supplements the collateral ligaments is appropriate [35]. In cases of massive bone deficiency with loss of collateral ligamentous support or gross flexion-extension mismatch, a hinged prosthesis is indicated [6]. Shen et al. evaluated the relationship between patients with specific patterns of bone loss and varied levels of prosthetic constraint [33]. In the presence of type 2 or 3 bone loss, prostheses with a lower degree of constraint are associated with a superior functional outcome, except in patients undergoing revision for infection who may benefit from the use of linked constrained prostheses [33]. In principle, the fixation and long-term durability of the prosthetic components are inversely proportional to prosthetic constraint [9]. An implant with the least constraint required for satisfactory knee stability is selected to reduce stress on the implant-fixation interface with compromised bone.

Stems are indicated whenever existing condylar bone support is compromised [9]. Stems offload stress from the implant-fixation interface, provide increased surface area for fixation, and help restore optimal implant alignment [9]. Cemented stems work well in most situations. When using press-fit stems, diaphyseal-engaging stems are critical to the management of bone loss during revision TKA.

The most optimal method of bone loss reconstruction is a challenging clinical problem. Smaller, contained defects are reliably managed with morselized cancellous bone graft, cement augmented with screw fixation, or modular augments attached to revision components. Large metaphyseal defects require more extensive reconstruction such as impaction bone grafting with or without mesh augmentation, prosthetic augmentation, use of bulk structural allografts, or use of metaphyseal cones or sleeves [9, 34]. Each technique has advantages, disadvantages, and outcomes such that the best technique for reconstruction of large metaphyseal bone defects during revision TKA is not clearly established.

Impaction grafting

Contained bone defects are traditionally and effectively managed with impaction grafting using morselized cancellous autograft or allograft bone. Uncontained defects require the use of wire mesh for containment of the graft. Impaction grafting is unique in its ability to facilitate a more rapid and partial revascularization of the bone graft as compared with bulk structural allograft techniques. Restoration of host bone stock is particularly advantageous in younger patients in whom there is potential for future reconstructive surgeries. Radiographs typically show progressive incorporation and remodeling of the bone graft. Impaction grafting is cost-effective and obviates the need for excessive bone resection and the use of large metal augments, bulk structural allografts, or custom prostheses. Disadvantages include the time-consuming and technically demanding nature of these reconstructions, particularly when wire mesh is required [26]. The use of bone graft also carries the risks of nonunion, malunion, graft resorption, graft collapse, and a minimal risk of disease transmission [6].

Midterm results are available for the technique of impaction allograft reconstruction of bone loss in revision TKA. Lotke et al. prospectively reported on 48 revision TKA cases with substantial bone loss treated with impaction allograft. All radiographs demonstrated incorporation and remodeling of the bone graft with no mechanical failures at an average of 3.8 years [26]. In the setting of impaction grafting for moderate to severe bone loss, Hanna et al. demonstrated a cumulative prosthesis survival of 98 % at 10 years. Five patients (9 %) had reoperations for complications unrelated to the bone graft [16]. Three patients (5 %) had progressive radiolucency. In two patients, the radiolucency was adjacent to the tibial component and clinically asymptomatic. In the third patient, the radiolucency was adjacent to the femoral and tibial components with poor graft incorporation. Lonner et al. reported on 17 revision TKA cases in 14 patients with large

uncontained defects treated with impaction allograft and molded wire mesh for containment [25]. No patients required further revision surgery, although nonprogressive tibial radiolucency was observed in three patients. One patient required fixation of a periprosthetic supracondylar femur fracture. One patient with an acute postoperative infection was treated successfully with irrigation and debridement and retention of the implant.

While several studies support the versatility and durability of impaction grafting, Hilgen et al. highlighted a potential limitation of impaction grafting. Their study evaluated the 10-year outcomes following impaction grafting in revision of rotational and hinged knee arthroplasty. They reported a survival rate of 50 %. Twelve knees required re-revision surgery at a mean 5 years after the first revision due to mechanical failure and aseptic loosening of the components. In all failed cases, the surgeon observed a lack of incorporation with bone graft resorption in the femur or tibia during the re-revision procedure [17•].

Prosthetic augmentation

Modular or customized prosthetic augments are indicated for reconstruction of uncontained segmental defects of moderate size, between 5 and 20 mm in depth [26]. Most revision knee systems offer a variety of shapes and sizes of both tibial and femoral augments, which facilitates restoration of the joint line and proper balancing of the knee in a relatively efficient manner. Tibial augments are block- or wedge-shaped to reconstruct areas of deficient bone that span the entire plateau or are localized to the medial or lateral plateau [6]. Femoral augments are typically block-shaped and of variable thicknesses, ranging from approximately 5 to 15 mm, for the medial and lateral condyles, both distally and posteriorly or in combination. Posterior femoral augments are particularly useful in restoring proper anteroposterior dimension of the femoral component, achieving the correct femoral component rotation, optimizing mediolateral bone coverage, and addressing the extension-flexion mismatch by altering the flexion gap [34].

Prosthetic augmentation offers the advantages of extensive modularity, straightforward technique, and availability and are not associated with disease transmission, nonunion, malunion, or collapse. Modular prosthetic augmentation allows the surgeon to produce a custom implant that recreates a flat platform, restores an anatomic joint line, corrects limb alignment, and balances soft tissues and extension and flexion spaces [34]. Moreover, prosthetic augmentation offers favorable biomechanical properties, usually allowing immediate mobilization and loading. Disadvantages are that prosthetic augments are expensive, limited in size and shape options, do not restore bone stock, and usually require additional bone removal to match the pattern of bone loss encountered to the

configuration of the augment [20]. There is also potential for debris generated from their modular attachment to the tibial or femoral component or loosening if the bone supporting the augment is poor [6].

Patel et al. prospectively reported an 11-year component survivorship of 92 % among a series of 79 revision TKA cases with type 2 bone defects treated with augments [29]. Panni et al. also supported modular prosthetic augmentation as a technique to achieve stable and durable revision TKA in 38 knees with type 2 and 3 defects over a median of 7 years with no failures of the augment [28].

Bulk structural allografts

Bulk structural allografts are a reconstructive option for type 3 and uncontained type 2 defects too large to be managed with prosthetic augments or impaction grafting. Dorr et al. suggested that tibial defects involving more than 50 % of the osseous support of either tibial plateau would benefit from allograft reconstruction [11]. Sources of allograft include distal femur, proximal tibia, or femoral head. This reconstructive approach requires careful preoperative preparation, meticulous operative technique to maximize surface contact between the allograft and the host bone, availability of large structural allografts, and considerable experience in complex knee arthroplasty [26, 34]. Advantages of this technique include relative cost effectiveness, the ability to create any shape or size of construct according to the bone defect, excellent support of the revision implant, the potential for long-term biologic integration of the graft restoring host bone stock, and the potential for ligamentous reattachment [2]. Disadvantages include technical difficulty and prolonged operative times required to fashion the grafts, limited availability of adequate graft, nonunion, delayed union, collapse, graft resorption, graft infection, and the possibility of disease transmission [2, 34]. Failure of bulk structural allografts in revision TKA has been associated with a reoperation rate of 8 to 23 % [1, 3, 5, 14, 23].

The early-to-midterm results of bulk structural allograft reconstructions of bone loss in revision TKA are variable. Engb and Ammeen reported an 87 % good-to-excellent outcome at a mean follow-up of 4.2 years and no collapse or aseptic loosening at a mean of 7.9 years in their study involving 46 knees with type 3 defects managed with bulk structural allograft [14]. The authors reported two failures due to infection. Clatworthy et al. prospectively reported a less favorable allograft survival rate of 72 % at 10 years in a series of 52 revision procedures with 12 repeat revisions at a mean 70.7 months [5]. Five knees demonstrated graft resorption, resulting in implant loosening. Four knees failed because of infection, and two knees demonstrated nonunion between the host bone and the allograft. Two knees (one patient) did not

achieve a 20-point improvement in the Hospital for Special Surgery knee score, defining them as failures. Backstein et al. presented a midterm review of 68 revision knees reconstructed with bulk structural allograft followed a mean of 5.4 years [1]. Thirteen knees (21 %) failed due to graft related complications including one graft nonunion, three cases of aseptic loosening, three periprosthetic fractures, four infections, and two cases of instability. There were three cases of graft resorption, two graded as severe and one as moderate. Bauman et al. presented 70 revision TKA cases with bulk structural allograft reconstruction followed for a minimum of 5 years [3]. Sixteen patients required additional revision surgery, eight of which were due to allograft failure, three were due to failure of a component not supported by the allograft, and five were due to infection. They reported a revision-free survival rate of 75.9 % at 10 years. While most authors support the use of bulk structural allograft for reconstruction of severe tibial or femoral bone defects in revision TKA, the rate of complications and reoperations suggest a need for more durable alternative methods for these challenging reconstructions.

Metaphyseal cones and sleeves

Metal metaphyseal cones and sleeves are designed to fill large contained cavitory and combined cavitory-segmental metaphyseal defects in the femur and tibia. Both cones and sleeves are placed in direct contact with host bone to achieve peripheral osseous ingrowth and offer the potential for long-term structural support. The high porosity of tantalum and its scaffolding abilities for osteoblast activity enables bone ingrowth and makes it a suitable material for these augments [18, 23, 34]. Upon osseointegration, the augment shares the intramedullary axial loading forces, effectively protecting the epiphyseal fixation and improving the rotational stability of the construct. However, cones and sleeves differ at the interface of the augment with the revision prosthesis. Metaphyseal sleeves are implant-specific and mated to the revision implant by a Morse taper and therefore avoid the necessity of cement in the final construct [2, 6]. Conversely, a variety of prosthetic devices can be cemented into the inner, central surface of many metaphyseal cone designs [34].

Cones and sleeves offer potential advantages over traditional techniques for the treatment of large defects at the time of revision TKA. Advantages include the ability to provide mechanical support for the prosthetic component, provide the potential for long-term biologic fixation, decrease the complexity of the reconstruction, enable immediate weight-bearing, and avoid the issues of disease transmission, graft resorption, and collapse associated with bone graft material. Disadvantages include the expense, the short-term clinical experience, the requirement to remove host bone for positioning of

the implant in certain cases, and the possibility of difficult extraction if removal is required [26].

Multiple studies have demonstrated favorable short-term outcomes using metaphyseal cones, though in limited numbers of patients [10, 18, 23, 24, 27, 30, 32, 36]. Long and Scuderi described 16 patients who were treated with tibial metaphyseal cones and followed for 31 months [24]. There were no revisions for aseptic loosening, and all patients showed radiographic evidence of osseointegration. Two cones required removal for recurrent sepsis but were well-fixed at the time of surgery. Meneghini et al. reviewed a series of 15 patients who underwent revision TKA with tibial metaphyseal cones and were followed for a minimum of 2 years [27]. All of the cones demonstrated radiographic evidence of osseointegration, and there were no reported failures. Howard et al. reported on ten tibial metaphyseal cones with no mechanical failures at 1-year follow-up [18]. Lachiewicz et al. retrospectively reviewed 27 patients followed for a minimum of 2 years (mean 3.3 years) after implantation of 33 tantalum cones (nine femoral, 24 tibial) [23]. One knee with two cones was removed for infection. All but one cone showed osseointegration. One knee was revised for femoral cone and component loosening. There was one reoperation for femoral shaft fracture and one for superficial wound dehiscence.

Kamath et al., including senior authors who are surgeon-developers of the porous tantalum metaphyseal cone, are the first to report midterm clinical and radiographic results of tibial cone implantation [22•]. Sixty-six tibial cones for type 2 or 3 defects were assessed at a mean follow-up of 5.8 years (range, 60 to 106 months). One patient had progressive radiolucency about the tibial stem and cone. One patient had complete radiolucency about the tibial cone, concerning for fibrous ingrowth. Three cones were revised: one for infection, one for aseptic loosening, and one for periprosthetic fracture. Revision-free survival of the tibial metaphyseal cone was >95 % at the time of the latest follow-up.

Similarly, use of metaphyseal sleeves is largely supported by short-term results. Alexander et al. reported on the use of 30 tibial metaphyseal sleeves for type 2B and type 3 defects with minimum 2-year follow-up. Six patients required a repeat surgery though none were sleeve related. All radiographs at final follow-up showed well-fixed components with evidence of osseous ingrowth. Huang et al. prospectively reported the short-term results of revision TKA in 83 knees with both femoral and tibial metaphyseal sleeves using both nonhinged and hinged designs over a minimum 2-year follow-up [19•]. None of the cases demonstrated progressive radiolucent lines around the metaphyseal sleeves. At final follow-up, two (2.7 %) tibial components required revision for aseptic loosening. Barnett et al. retrospectively reviewed data on 40 patients who underwent revision TKA utilizing a metaphyseal sleeve for type 2 and 3 tibial defects [2]. At a mean of 38 months, four revision procedures were necessary, but none

for aseptic loosening. Radiographic review at final follow-up revealed stable, osseointegrated components in all cases. Mid-term follow-up on the use of metaphyseal sleeves was presented by Jones et al. in 30 hinged revision TKAs at a mean of 4 years with no mechanical failures, and all sleeves showed radiographic apposition and positive remodeling of bone [21].

Conclusion

The number of revision TKA procedures performed annually in the USA alone is expected to rise from 38,300 in 2005 to 268,300 by the year 2030 [13, 19•]. Metaphyseal bone loss compromises the support, alignment, and fixation of components during revision TKA. While numerous reconstructive options are available to manage bone loss, the most optimal method is not clearly established. Selection of the method of reconstruction is based on many factors including ligamentous stability, the location and magnitude of bone loss, and patient factors including the potential for additional revision, functional demand, and comorbidities [6, 8, 16, 34]. If the defect is large and segmental, more robust structural augments such as prosthetic augments, bulk structural allograft, or metaphyseal cones or sleeves will typically create a more biomechanically stable construct.

Porous metal metaphyseal cones and sleeves represent the most recent advances in the treatment of metaphyseal bone loss during revision TKA. These technologies seem to offer biologic ingrowth fixation and a mechanically sound scaffold for revision components while avoiding the significant concerns associated with bone grafting. Long-term analysis and comparison with other reconstruction options are needed to determine whether these novel reconstruction methods will provide superior long-term clinical success.

Compliance with Ethics Guidelines

Conflict of Interest The authors report the following conflicts of interest with regards to this publication: Zimmer (Royalties), AAOS (CME Courses Committee), AAHKS (Evidence-based Medicine Committee-Vice-Chair), Journal of Arthroplasty (Editorial Board).

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