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Management of bone loss in revision total knee arthroplasty: therapeutic options and results

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- The treatment of small to moderate size defects in revision total knee arthroplasty (rTKA) has yielded good results with various techniques (cement and screws, small metal augments, impaction bone grafting and modular stems). However, the treatment of severe defects remains problematic.
- Severe defects have typically been treated with large allograft and metaphyseal sleeves. The use of structural allograft has decreased in recent years due to increased long-term failure rates and the introduction of highly porous metal augments (cones and sleeves).
- A systematic review of level IV evidence studies on the outcomes of rTKA metaphyseal sleeves found a 4% rate of septic revision, and a rate of septic loosening of the sleeves of 0.35%. Aseptic re-revision was required in 3% of the cases. The rate of aseptic loosening of the sleeves was 0.7%, and the rate of intraoperative fracture was 3.1%. The mean follow-up was 3.7 years.
- Another systematic review of tantalum cones and sleeves found a reoperation rate of 9.7% and a 0.8% rate of aseptic loosening per sleeve. For cones, the reoperation rate was 18.7%, and the rate of aseptic loosening per cone was 1.7%.
- The reported survival of metal sleeves was 99.1% at three years, 98.7% at five years and 97.8% at 10 years. The reported survival free of cone revision for aseptic loosening was 100%, and survival free of any cone revision was 98%. Survival free of any revision or reoperation was 90% and 83%, respectively.

Keywords: bone defects; revision total knee arthroplasty; treatment

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Introduction

Total knee arthroplasty (TKA) is a reliable and effective technique for treating advanced painful knee osteoarthritis, and its use worldwide has been increasing over the past few years. The number of relatively young patients who undergo TKA is also increasing. It is therefore highly likely that the rate of revision total knee arthroplasty (rTKA) will continue to increase in the future.[1]

An rTKA is a highly complex surgical technique, with a high rate of complications and failures, frequent bone loss and poor bone quality.[2] Bone deficiency is a common situation during rTKA,[3] with a diverse aetiology that can be due to aseptic loosening, causing a direct mechanical loss of bone, osteolysis, stress shielding and septic loosening, and it can be iatrogenic as the result of implant removal.[3] The purpose of this article is to review the treatment of bone deficiencies during rTKA, the various therapeutic options currently available and their results.

Preoperative assessment of bone deficiency

One of the main problems in rTKA is bone loss, which can affect the placement of the prosthesis, the limb's alignment and the implant's longevity. The bone deficiency in an rTKA is variable, and its treatment will therefore depend on the bone loss intensity.[1]

Not all revisions can be performed in the same manner. Surgeons need to evaluate the degree of complexity of each case and employ a large armamentarium. To properly manage bone loss, surgeons need to consider the size and location of the bone defect and the patient's demographic characteristics (body mass index [BMI], activity level, age and life expectancy).[3]

To successfully perform an rTKA and predict and compare its results, it is essential to correctly assess/classify the existing bone defect. Prior to the surgery and to prevent intraoperative problems, surgeons need to predict which materials will be needed (bone allografts, long stems, new-generation fixation devices). The most appropriate method for defining bone deficiency is through orthogonal radiographs of the tibia and lateral projections of the distal femur.[4] Computed tomography (CT) scan can be of assistance but is not essential.[5]

Classifications of bone defects in revision total knee arthroplasty

Several classifications of bone defects have been proposed for rTKA, although none fully meet the clinical requirements.[6–13] The Anderson Orthopaedic Research Institute (AORI) classification of bone defects is the most practical and widely used (Fig. 1)[5,9,14] and defines three types of bone defects each in the femur (F1, F2, F3) and tibia (T1, T2, T3). Each type is subdivided into 'A' when a femoral condyle or tibial plateau is affected and 'B' when the femoral involvement is bicondylar or involves the entire tibial plateau.[9]

In type 1, there is an intact cortical bone with small metaphyseal bone defects (cavity or contained, measuring less than 5 mm). These bone defects do not jeopardize the stability of the prosthetic component of the revision. In type 2, there is a loss of cortical bone and damage to the metaphyseal bone that needs to be filled in to restore the joint line. In type 3, the metaphyseal bone is deficient, and there is severe bone loss affecting a significant portion of a femoral condyle or one of the tibial plateaus, producing knee instability due to injury of the corresponding collateral ligament.

In 2019, Rosso et al, in a level IV evidence-based study, proposed a modified classification of bone loss from the AORI classification that also took into account bone quality.[2] The authors also evaluated the association between radiolucent line (RLL) development and various risk factors. Bone loss was assessed according to the proposed classification, including bone quality. The Knee Scoring System (KSS), the Hospital for Special Surgery Knee Score, and the SF-12 were employed for the clinical evaluation. Radiological assessment was performed using the Knee Society Roentgenographic Evaluation System. Various possible risk factors (sex, age, amount of bone loss) associated with the development of RLLs were identified, and this association was evaluated by means of logistic regression. Fifty-one patients (53 knees) were analysed (60.8% women; mean age, 71.5 years), and the mean follow-up was 56.6 months (range, 24–182). The most frequent cause of failure was aseptic loosening (41.5%), and in 18.9% of the cases, the bone quality was poor. Bone loss was treated according to the authors' own algorithm. In all cases, there was a significant improvement in all scores, with a mean postoperative range of motion of 110.5 degrees. In the radiological evaluation, all implants were well aligned, with a 15.1% non-progressive RLL. There were two failures, with a cumulative survival of 92.1% by the end of the follow-up. In the logistic regression, none of the variables evaluated were associated with the development of RLL. Rosso et al concluded that rTKA is a complex technique in which, to achieve good results, it is essential to adequately manage bone loss. However, bone quality also needs to be considered when addressing this bone loss. In the future, this proposed classification should be properly validated.

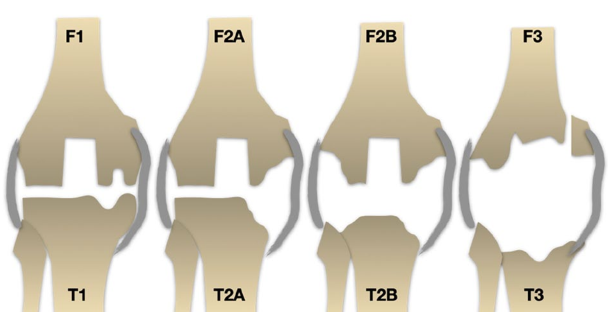

Fig. 1 Anderson Orthopaedic Research Institute (AORI) classification of femoral and tibial bone defects during revision total knee arthroplasty (rTKA).

According to Belt et al, the AORI classification does not quantify diaphyseal bone loss, and its reliability has not been well defined. In a level III diagnostic evidence study (preregistered observational study) published in 2020, Belt et al presented a new classification scheme for bone defects in rTKA patients, evaluated the intraobserver and interobserver reliability of the classification based on preoperative radiography and assessed whether additional CT scan images could improve the interobserver reliability,[15] which was analysed using preoperative radiographs of 61 rTKA-operated patients. The bone defects were classified by five experienced orthopaedic surgeons. For intraobserver reliability, the ratings were repeated at least two weeks after the first assessment (timepoints 1 and 2). Immediately following the radiographic assessments of timepoint 2, observers were provided with CT images of each patient and asked to rate the bone defects a third time (timepoint 3) to assess the additional value of the CT scan. The intraobserver and interobserver reliability were tested using Gwet's agreement coefficient 2, which is a measure of the interobserver agreement in the categorical data. Substantial agreement was defined as coefficients between 0.61 and 0.8 and near perfect agreement if the coefficient was greater than 0.8. The intraobserver reliability varied between 0.55 and 0.87 in the epiphysis, between 0.69 and 0.98 in the metaphysis, and between 0.95 and 0.99 in the diaphysis. The interobserver reliability ranged from 0.48 to 0.49 in the pineal and from 0.81 to 0.88 in the metaphysis and was 0.96 in the diaphysis at timepoint 1. The classification of bone defects was less reliable in the epiphyseal zone than in the metaphyseal and diaphyseal zones; a finding that can be explained by the prosthetic components that obscure this region or by the more severe bone defects in this region. The reliability of this classification still needs to be confirmed with observers from other centres, as well as to check its validity, comparing the classification with the intraoperative findings.

CT scans normally permit three-dimensional (3D) views of the bone stock and defects, as is currently utilized for preoperative planning prior to rTKA, especially for difficult revisions. In 2014, Meijer et al attempted to ascertain a dependable method of restoring the anatomical joint line and posterior condylar offset prior to rTKA based on 3D reconstruction of CT images of the distal femur.[16] They analysed the CT scans of 50 lower limbs. Key anatomical landmarks such as the medial epicondyle (ME), lateral epicondyle, and transepicondylar width (TEW) were determined on 3D models constructed from the CT images. Best-fit planes placed on the most distal and posterior loci of points on the femoral condyles were utilized to define the distal and posterior joint lines, respectively. There was a strong correlation between the distance from the ME to the distal joint line of the medial condyle (MEDC) and the distance from the ME to the posterior joint line of the medial condyle (MEPC). The mean ratio of MEPC to MEDC was 1.06 and that of MEPC to TEW was 0.33. The conclusions of Meijer et al were that the fixed ratios of MEPC to TEW (0.33) and that of MEPC to MEDC (1.06) provided a dependable tool for the orthopaedic surgeon to determine the anatomical joint line when utilized in combination.[16]

According to Lutz et al, one of the important factors for the successful rTKA is the reconstruction of the joint line, which can be obtained utilizing the epicondylar ratio (ER).[17] The measurement is established on X-ray and magnetic resonance imaging (MRI). Nonetheless, it is not known whether CT permits a more dependable determination. Their goal was to evaluate the dependability of the ER on CT and to determine the correlation between the ER on CT and antero-posterior X-ray of the knee. The ER was obtained on X-ray and CT images of a consecutive series of 107 patients who experienced rTKA. Measurements were made by two blinded observers, one measured twice. The inter- and intraobserver agreement, and the correlation between the two techniques, were quantified with the intraclass correlation coefficient. The average lateral ER was 0.32 on X-ray and 0.32 on CT. On the medial side, the average ER was 0.34 on X-ray and 0.35 on CT. The interobserver agreement for the same imaging modality was lateral 0.81 and medial 0.81 on X-ray as well as lateral 0.74 and medial 0.85 on CT. The correlation between the two techniques was lateral 0.81 and medial 0.79. Lutz et al concluded that the ER can be dependably obtained on X-ray and CT. Measurements of the two image techniques correlated. Therefore, before rTKA, the sole utilization of the X-ray is possible.[17]

Treatment options for managing bone loss in revision total knee arthroplasty

The treatment options for managing bone loss in rTKA include bone cement (polymethylmethacrylate) with or without reinforcing screws; modular TKA systems including optional stems, wedges, metal augments and cones made of porous metals; orthopaedic salvage systems such as megaprostheses and tumour prostheses; autografts; and morselized or structural allografts. Morselized allografts are better suited for reconstituting contained deficits and might be associated with a higher rate of incorporation. The disadvantages of allografts include late resorption, fracture and nonunion of the structural allograft as well as the risk of disease transmission.[1,3,5,14,18,19]

Bone cement with or without reinforcing screws

Bone cement is the best surgical option for filling bone losses in bone defects of less than 5 mm in width and depth, in peripheral deficiencies of up to 10% of the femoral condylar area, in small central defects, in cystic defects, and in contained bone defects.[7,11,20,21]

Cement with screws

In contained or uncontained defects measuring 5–10 mm, both in the proximal tibia and distal femur, a number of authors have suggested the use of cement in combination with screws.[22] Cement with screws can be used in AORI type 1 and 2A bone defects affecting less than 50% of the femoral condylar width and up to 10 mm in depth.[23,24]

Impaction bone grafting

Considering the need in young patients for future revisions and to preserve and possibly improve the residual bone reserve, it is advisable to use bone grafts,[7] which are usually employed to treat moderate-sized contained defects, in the form of impaction grafts with morselized cancellous bone.[25–28] To ensure the implant's stability, the bone fragments of the graft should be approximately 3 to 5 mm in diameter. The impaction force should also be sufficient to make the morselized bone grafts strong enough to support the weight load. Excessive impaction force will reduce the internal growth of the host bone.[29,30]

Modular stems

Stemmed components are crucial in rTKA to bypass metaphyseal bone defects and diminish the strain at the implant–host-bone interface, providing an additional surface for implant fixation. The length of the stemmed components is important, but the cornerstone is the bone/stem engagement level at which stable fixation is accomplished.[14] Cementless stems are employed with a hybrid fixation, engaging the cortical bone of the diaphysis but with cement at the implant–host-bone interface close to

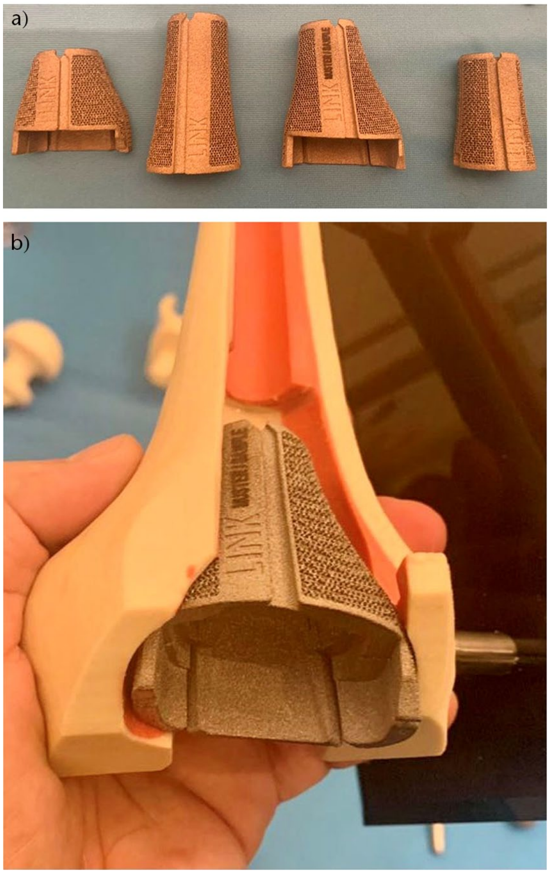

Fig. 2 Different sizes and shapes of femoral cones (a). Image showing how the definitive placement of a femoral cone should be accomplished (b).

Fig. 3 (a) Intraoperative image showing the placement of a tibial cone. (b) Postoperative radiographic check of a revision total knee arthroplasty (rTKA) in which tibial and femoral cones were employed.

the joint. These stems provide good primary stability and are easy to extract.[31] Longer stems cause tibial pain at the end of the stem in up to 10% of patients, and an offsetting might be required if diaphyseal engagement results in malalignment or a higher risk of fracture,[32–35] which is why cementless stems are preferred if there is a good diaphyseal bone and adequate geometry. In patients with large osteopaenic intramedullary canals or axial deformities, cementless stems are more useful and tend to be shorter than press-fit stems, although cementless stems have a higher risk of misalignment.[31,36] In short, the overall quality of the bone, bone defects and surgeon preference appear to be the most important factors influencing the choice of stem type.

Filling devices (cones and sleeves)

Several studies have reported favourable short-term results using tantalum cones to reconstruct massive bone defects during rTKA (Fig. 2, Fig. 3).[37–39]

In 2020, Bedard et al stated that metaphyseal cones with cemented stems are widely employed in rTKA. However, if the diaphysis has been previously breached, the resulting sclerotic canal can impair the fixation of the cemented stem, which is vital for bone ingrowth into the cone and its long-term fixation.[39] In their article, the authors described a method by which they attempted to solve the problem, analysing 32 patients (33 procedures) with severely compromised bone operated on by rTKA. A metaphyseal cone was combined with diaphyseal impaction grafting and cemented stems. The patients (mean age, 67 years; 20 [60%] men) had undergone a mean of four (range, 1–13) previous knee arthroplasty procedures. The indications for the revision were aseptic loosening (80%) and two-stage reimplantation for prosthetic joint infection (20%), and the mean follow-up was four years (range, 2–11 years). Survival free from revision of the cone/impaction grafting construct due to aseptic loosening was 100% at five years.

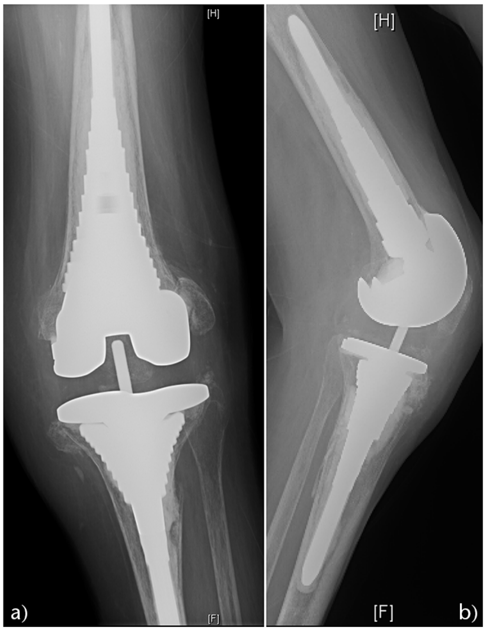

Fig. 4 Anteroposterior (a) and lateral (b) radiographs of a revision total knee arthroplasty (rTKA), in which the management of the bone defect was performed with a metaphyseal sleeve.

Survival free from any revision of the construct and free from any reoperation was 92% and 73% at five years, respectively. Six patients (six TKAs, 17%) required further revision: four for infection or wound issues and two for periprosthetic fracture. Radiologically, one unrevised TKA presented asymptomatic loosening. In all of the unrevised TKAs, the impacted diaphyseal bone graft appeared to be radiologically incorporated. Bedard et al considered that their technique provided successful implant fixation in cases of sclerotic diaphysis and significant metaphyseal bone loss. The X-rays showed bone graft incorporation and biological fixation of the cone. Although this technique offers an excellent option for managing complex rTKA, long-term follow-up is needed to confirm its results.[39]

Metaphyseal fixation with metaphyseal sleeves during rTKA has provided promising early results in terms of component stability and implant fixation (Fig. 4). In 2019, Bonanzinga et al published a systematic review of level IV evidence studies on the clinical and radiographic outcomes of rTKA metaphyseal sleeves,[40] which included 10 studies (904 patients with 928 implants). The patients' mean age was 69 years, and the mean follow-up was 3.7 years. In total, 1,413 metaphyseal sleeves were implanted, 888 in the tibia and 525 in the femur. There were 36 (4%) septic checks of the prosthetic components, with five loosened metaphyseal sleeves (septic loosening rate of 0.35%). Aseptic reexamination of the prosthetic components was performed on 27 (3%) occasions, during which 10 loosened sleeves were found (aseptic loosening rate of 0.7%). There were 44 (3.1%) intraoperative fractures. In short, the metaphyseal sleeves showed a high rate of radiographic signs of osseointegration, a low rate of septic loosening and intraoperative fractures and good to excellent clinical results. Metaphyseal sleeves are therefore a valid option for treating large metaphyseal bone defects during rTKA.[40]

The systematic literature review published in 2021 by Roach et al included 27 studies (12 sleeves and 15 cones) on rTKAs.[41] In the 12 sleeve studies, 1,617 sleeves were implanted in 1,133 rTKAs (1,025 patients). The overall reoperation rate was 9.7%, and the total rate of aseptic loosening per sleeve was 0.8%. In the 15 studies on tantalum cone implantation in rTKA, 701 cones were implanted in 620 rTKAs (612 patients). The overall reoperation rate was 18.7%, and the overall rate of aseptic loosening per cone was 1.7%. The aseptic loosening rates of the two implants were similar, whereas the reoperation rate was almost double in the rTKAs in which tantalum cones were employed. The variability of the selected studies and the probable multifactorial nature of the prosthetic failure did not allow for definitive conclusions to be drawn. Table 1 shows the main articles published in 2020 on the use of metaphyseal sleeves and cones in rTKA.[41–44]

It is important to mention that filling devices (cones, sleeves) are frequently recommended by sales representatives. Therefore, we believe that the issue of the cost of these devices is important. However, it is a tricky issue as every country in Europe, and even every European hospital, pays different prices. In our hospital the price for femoral and tibial cones and sleeves is 1,000 euros per unit.

Megaprostheses and tumour prostheses

In certain older adult patients with severe bone loss, joint deformity and severe ligament instability, tumour prostheses might be appropriate for saving the limb and achieving immediate stability.[45] The original designs for the prostheses, which consisted of a hinged implant with no degree of rotation, had a high rate of mechanical failure due to implant loosening. The introduction of the rotating hinge platform reduced the failure rate by allowing a more physiological load transmission.[46]

Modular endoprostheses have progressively replaced custom-made megaprostheses due to their cost, ductility and early availability in the operating room (Fig. 5).[47] In cases of mechanical implant failure, it is possible to replace only the component that has failed. The functional results,

Table 1. Main articles published in 2020 on the use of metaphyseal sleeves and cones in revision total knee arthroplasty

Author	Patients and results
Roach et al[41]	* Systematic review. A total of 27 studies (12 sleeves and 15 cones) of rTKAs were included. In the 12 studies on sleeve implantation in rTKAs, 1,617 sleeves were implanted in 1,133 rTKAs in 1,025 patients. * The overall reoperation rate was 9.7%, and the total rate of aseptic loosening per sleeve was 0.8%. * In the 15 studies on tantalum cone implantation in rTKAs, 701 cones were implanted into 620 rTKAs in 612 patients. * The overall reoperation rate was 18.7%, and the overall rate of aseptic loosening per cone was 1.7%. * The aseptic loosening rates of the two implants were similar, while the reoperation rate was nearly double in rTKAs using tantalum cones. * The variability of the selected studies and the likely multifactorial nature of failure do not allow for any definitive conclusions. This review elucidates the need for additional studies examining rTKA implants.
Tetreault et al[42]	* 142 rTKAs were performed in 139 patients using 202 cones (134 tibial, 68 femoral). Sixty involved tibial and femoral cones. * Most cones (149 of 202; 74%) were employed for type 2B or 3 bone loss. * The patients' mean age was 66 years, and 76 (55%) were women. The mean body mass index (BMI) was 34 kg/m^2. * The patients had undergone a mean of 2.4 (1 to 8) previous knee operations, and 68 (50%) had a history of prosthetic infection. * The mean follow-up was 2.4 years (2–3.6). * Survival free of cone revision for aseptic loosening was 100%, and survival free of any cone revision was 98%. Survival free of any revision and any reoperation was 90% and 83%, respectively. * Five cones were revised: three for infection, one for periprosthetic fracture and one for aseptic tibial loosening. * Radiologically, three unrevised femoral cones appeared loose in the presence of hinged implants, while the remaining cones appeared stable. * All cases of cone loosening occurred in patients with type 2B or 3 defects. * Three intraoperative fractures with cone impaction (two femoral, one tibial) healed uneventfully.
Gill et al[43]	* 36 patients (43 knees) with AORI type 2B (large metaphyseal bone defect) and AORI type 3 (metaphyseal defect with compromised collateral ligaments) underwent rTKA. *The patients' mean age was 59.4 years. * The mean follow-up was 5.42 years (maximum, nine years). * Metaphyseal sleeves were employed in 12 primary TKAs and 31 rTKAs. * During surgery, iatrogenic fracture of the tibial condyle was observed in three (6.9%) patients, all of whom were managed with no intervention, achieving union in all cases. * There was not a single case with aseptic loosening as per the radiological criteria. * Periprosthetic joint infection (PJI) was observed in one (2.3%) case.
Bloch et al[44]	* 319 rTKAs were performed with the use of a metaphyseal sleeve. * The mean follow-up was 91 months (minimum, two years): 73 patients were followed-up for more than 10 years. * Implant survival was 99.1% at three years, 98.7% at five years and 97.8% at 10 years. * No metaphyseal sleeve was revised for aseptic loosening. * Final radiographs showed that there were radiolucent lines present in 2.8% of the tibial sleeves and 2.7% of the femoral sleeves, none of which had progressed, and none of which were revised. Approximately 3.7% of the tibial sleeves subsided more than 1 mm compared with the immediate postoperative X-rays, but all stabilized and none were revised.

Note. rTKA, revision total knee arthroplasty; AORI, Anderson Orthopaedic Research Institute.

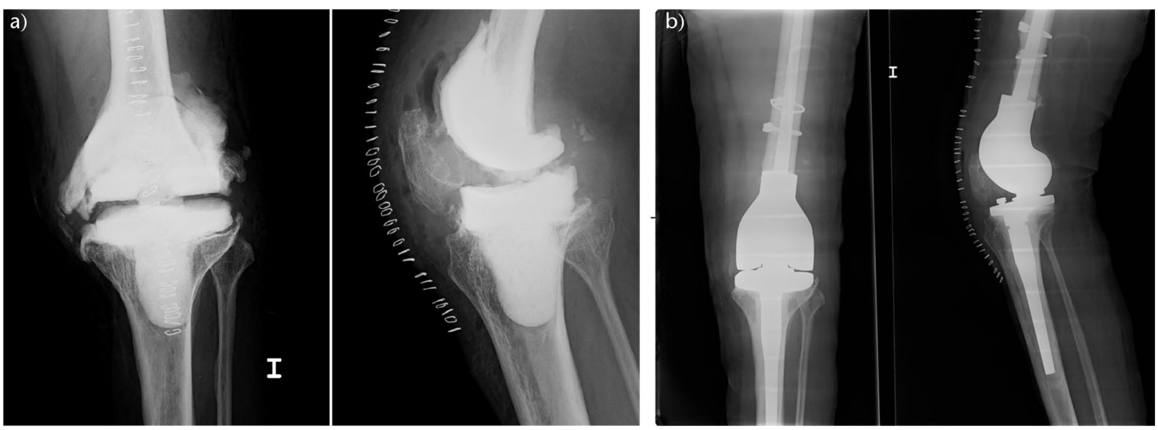

Fig. 5 Periprosthetic joint infection (PJI) resolved in two surgical stages. In the first stage, an articulated antibiotic-loaded cement spacer was implanted. In the second stage, the AORI type 3 femoral defect was managed with a distal femoral megaprosthesis. Anteroposterior and lateral radiographs (a) showing the articulated spacer. (b) Postoperative images showing the implantation of the megaprosthesis.

especially in older adult patients with low demand, have been satisfactory in terms of quality of life.[48]

Infection is frequent in these patients, due to the deficient soft tissue envelope that is usually present in these cases, as well as the extended approach and long duration of the surgery, and it is a disastrous complication that typically results in knee fusion (Fig. 6) or amputation above the knee.[49]

Recommendations for bony reconstruction in revision total knee arthroplasty

The recommendations for bone defect reconstruction during rTKA can be made according to the size and type of defect (contained or uncontained) or according to the type of bone deficiency as classified by the AORI.

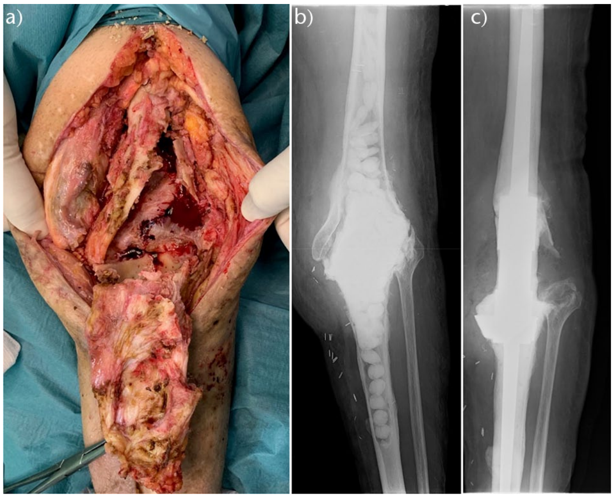

Fig. 6 Intraoperative image of a patient with periprosthetic joint infection (PJI) with an AORI (Anderson Orthopedic Research Institute) type 3 femoral defect (a), which was treated in two surgical stages: in the first stage, an articulated antibiotic-loaded cement spacer and antibiotic-loaded beads were implanted (b); in the second stage, knee fusion was performed using an intramedullary device (c).

According to the size and type of the bone defect

According to Lombardi et al, the indications for bone reconstruction during rTKA are as follows: If the bone deficit is less than 5 mm, use polymethylmethacrylate (PMMA) filling; if the deficit is 5–10 mm and affects less than 50% of the femoral condyle or tibial plateau, use PMMA with reinforcement screws; in contained deficits larger than 5 mm, use morselized allografts; in uncontained deficits measuring 5–15 mm and affecting more than 50% of the femoral condyle and tibial plateau, use modular systems with stems and augments; and in uncontained deficits larger than 15 mm, use structural allografts, megaprostheses and ultraporous metal augments.[3] Fig. 7 summarizes recommendations for bony reconstruction in rTKA according to the size and type of bone defect.

According to the type of bone defect in the AORI classification

A literature review published in 2017 by Mancuso et al found that there are several options for addressing metaphyseal bone loss during an rTKA. For small and contained defects (AORI type 1), the recommendation is screwed or unscrewed cement and autograft or allograft morselized bone. For light uncontained defects (AORI type 2A), metal augments should be employed, whereas for large and uncontained defects (AORI type 2B and 3), structural allografts or metal filling devices (cones and sleeves) should be the recommendation. Stemmed components (cemented or not) are recommended for reducing the stress on the implant–host interface. For the definitive management of bone defects during rTKAs, there are currently several options available that offer good results in the short and medium term. However, the long-term clinical outcomes and implant survival after rTKA remain suboptimal and depend on numerous factors, such as the cause of the revision, the surgical approach, the type of implant employed and various patient-related factors. Further scientific evidence is needed to help choose the optimal method for each patient.[14]

Small/contained defects (AORI type 1)

For managing AORI type 1 metaphyseal bone loss in rTKA, the therapeutic options are cement, cement with screws, autografts and bone allografts.[25,50,51]

+ *Cement*. Bone cement is the best surgical option for filling bone losses in bone defects measuring less than 5

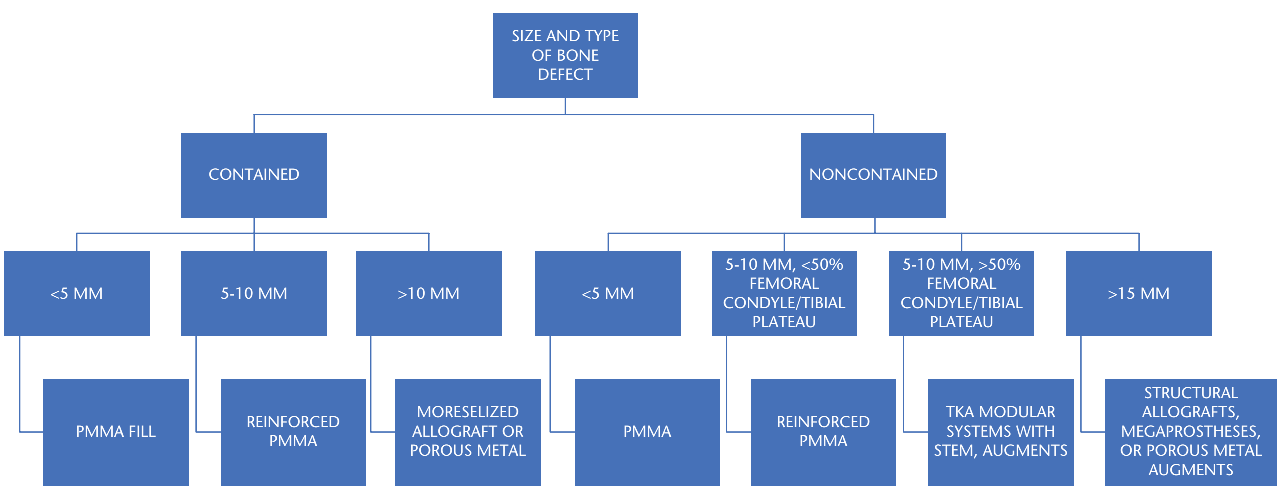

Fig. 7 Recommendations for bony reconstruction in revision total knee arthroplasty (rTKA) according to the size and type of bone defect.
Note. PMMA, polymethylmethacrylate; TKA, total knee arthroplasty.

mm in width and depth, in peripheral deficiencies of up to 10% of the condylar femoral area, in small central defects, in cystic defects and in contained bone defects.[11,20,21,52]

+ *Cement with screws*. Several authors have reported good medium-term clinical results with cement with screws. Ritter et al analysed 57 patients with tibial defects with a three-year follow-up, with 25% presenting non-progressive radiolucencies at the cement–bone interface; however, none of the components failed, and after seven years of follow-up, there was no progression of the radiolucency lines.[23]

+ *Bone autografts and allografts*. Grafts are generally employed to treat contained defects of moderate size, in the form of impaction grafting with morselized cancellous bone.[25–27] Several studies have been published on the medium-term outcomes of impaction allograft reconstruction in cases of bone loss in rTKA. Hanna et al reported a cumulative prosthesis survival of 98% at 10 years, with five (9%) patients requiring reoperations for complications unrelated to the bone grafting and three (5%) patients developing progressive radiolucencies.[25]

While the previously mentioned studies support the versatility and durability of impaction grafting, Hilgen et al highlighted the possible limitations of impaction grafting for more severe bone defects. In fact, the authors reported a 50% survival rate at 10 years of follow-up for rTKAs with rotary hinge implants in AORI type 2 and 3 defects.[53]

Small/uncontained defects (AORI type 2)

There are differing surgical solutions, depending on the dimensions and location of the AORI type 2A–2B defects. Uncontained defects (5–20 mm deep) with a broken cortical edge can ideally be treated with modular metal augmentations that selectively fill in the bone deficiencies; for example, in the distal and posterior femoral condyles or in the proximal tibia.[54]

Metal augments are available in wedge or block form, from 5 mm to 25 mm in size, to accommodate a wide range of defects of one or both condyles.[55] The augments are usually attached to the implant outside the surgical field and then cemented to the prepared bone. Unlike cement, which fits the space, the augments require remodelling of the defects with certain bone sacrifice, especially if blocks are employed. Wedge augments, which can be useful in revising unicompartmental to total knee prostheses in cases of tibial plateau collapse, enable greater bone preservation while still being subject to shear stress due to their oblique shape.[56,57] Symmetrical blocks help restore the joint line, while asymmetrical augments contribute to filling the defect and to rotational stability, as is usually the case with the posterolateral femoral condyle.[58]

Failure will occur if the bone loss is severe, with deterioration of the spongy bone structures. In this situation, the interface between the device and the host bone is compromised. To achieve a stable construction, surgeons therefore need to employ structural allografts or porous metaphyseal implants.[14]

Large/uncontained defects (AORI type 3)

AORI type 2B and 3 defects have typically been treated with large allografts[37,38,59–80] and metaphyseal sleeves.[32,50,81–88]

+ *Allografts*. Structural allografting is an attractive biological option for treating bone defects, especially in young patients. The objective of structural allografting is to restore bone in anticipation of possible subsequent revisions. Options include the head of the femur, the distal femur and the proximal tibia. The possibility of shaping the allograft, especially when using femoral heads, is one of the main advantages of this technique. In the area of the defect, all soft tissues, osteolytic membranes and residual cement need to be removed. During the operation, the graft is prepared by removing the sclerotic peripheral bone with a burr or a female reamer at the interface with the host to fit into the defect.[63]

If a femoral head allograft is employed, the diameter of the male reamer to prepare the host bone should be 2 mm narrower to obtain primary pressure fixation. The temporary fixation of the graft is improved with 2–3 K-wires, normally parallel to the expected junction line, which do not interfere with the implant stem. A drill is employed to remove the excess bone graft; the canal is then ready, and the usual cuts are made to receive the test implant.

Stemmed components (either cemented or press-fit) should be employed to avoid the defect and reduce the stresses on the allograft, host bone and fixation interface.[9,62] Additional plates and screws can help achieve primary stability, especially in major uncontained defects.[14] The main disadvantages of allografts are their limited availability, increased susceptibility to infection,[60] lack of union, fracture and periprosthetic resorption, which will result in implant loosening.[62] According to Stevenson et al, the risk of disease transmission, although present, is very low if strict donor selection criteria and screening are performed.[89]

In a series of 65 knees, Baumann et al observed a greater than 20% rate of complications and failures directly or indirectly related to allografts. The size of the allografts appeared to play an important role in the failure mechanism. The authors' explanation was that smaller allografts, such as femoral heads, tend to fail due to resorption, resulting in secondary loosening of the implant. In contrast, larger allografts have a higher rate of infection or nonunion, which leads to failure. Other factors that affect bone union are the host's immune response and the type of graft.[60]

Stevenson et al reported on the unpredictability of the graft incorporation process;[89] after a mean period of 41 months, only the peripheral portions of the grafts were infiltrated by new bone, with no evidence of remodelling or revascularization, which explains an 11% rate of nonunion for large frozen allografts, although it does not always mean that the graft is not retained.[90,91] The use of impaction grafting is not recommended for uncontained defects, except in combination with metal augments or meshes.[92]

+ *Highly porous tantalum cones*. Highly porous cones have been employed for many years in various reconstructive procedures, especially in hip prostheses to treat severe acetabular bone loss.[37,93–97] The cones are usually constructed of tantalum, although titanium porous devices have recently been introduced. Tantalum has a mean porosity of 80% and a modulus of elasticity (3 GPa) close to that of cancellous bone, which provides a greater physiological load transfer, thereby reducing stress shielding and improving the osteoconductive properties with better potential osseointegration.[37,98,99] The low modulus of elasticity and high coefficient of friction contribute to a stable scaffold for joint reconstruction.[90] Histological studies have shown a low potential for bacterial adhesion with increased activation of leukocytes, which reduces the risk of infection.[100,101] Currently, cones are available in several shapes and sizes for both knees, with symmetrical and asymmetrical options that adapt to most defects.[102]

The surgical technique for cone insertion includes host bone sculpting with a broach or free-hand high-speed burr to optimize cone contact and enhance bone ingrowth. The cone is press-fitted into position, and cement is employed only to fix the implant to the porous device, allowing for a greater range of rotation and alignment of the implant, regardless of the cone's location. The spaces that might remain between the porous surface and the host bone should be filled with morselized bone allograft, autograft or bone substitutes.[37]

Axial stability is provided by the stems (cemented or not), while rotational stability is improved with keel and box together with the cone for tibial and femoral components, respectively. As reported by Bédard et al, cones do not affect the use of cementless stems, allowing a channel filling ratio of more than 85% to be achieved in most patients.[31] In selected cases of severe bone loss with massive femoral defects, two overlapping cones can be employed.[38]

The immediate metaphyseal stability allows for early weight bearing. The need for reintervention is usually due to a recurrence of the infection; however, aseptic loosening of the device at the bone–cone interface is rare (< 1%).[37] In fact, safe fixation has been confirmed at five years using radiostereometric analysis.[31,67,102]

As with sleeves, the main disadvantage of cones is the difficulty of extraction in case of new revisions, because they present solid osseointegration even in cases of reinfection[67,68,103] and are therefore not the first-line option for bone loss in young patients. A careful surgical technique is recommended to reduce the risk of patellar tendon avulsion and intraoperative fractures during broaching or cone impaction, taking into account that the residual bone reserve is usually of low quality.[77,102] The surgical efficacy and good clinical and radiological results achieved with highly porous tantalum cones indicate that the cones are a viable option, at least as effective as other strategies.

Treteault et al evaluated the survival, radiological results and clinical outcomes of new porous 3D-printed titanium metaphyseal cones featuring a reamer-based system.[42] The authors evaluated 142 rTKAs in 139 patients (mean age, 66 years; 76 [55%] women; mean BMI, 34 kg/m^2) using 202 cones (134 tibial, 68 femoral). Most of the cones (149 of the 202; 74%) were employed for type 2B and 3 bone loss. The patients had undergone a mean of 2.4 previous knee operations, and 68 (50%) had a history of prosthetic joint infection. The mean follow-up was 2.4 years (range, 2–3.6 years), and survival without cone revision due to aseptic loosening was 100%, while survival without cone revision was 98%. Survival without revision and without reoperation were 90% and 83%, respectively. Five cones were checked: three for infection, one for periprosthetic fracture and one for aseptic loosening of the tibia. Radiologically, three unchecked femoral cones appeared to be loose in the presence of hinged implants, while the remaining cones appeared stable. All cases of cone loosening occurred in patients with type 2B or 3 defects. The mean Knee Society score improved significantly from 50 prior to surgery to 87 post surgery. Three intraoperative cone impaction fractures (two femoral, one tibial) healed without problems. Novel 3D-printed titanium cones with a reamer-based system showed excellent early survival and few complications in patients with severe bone loss operated on for difficult rTKA. The various cone options, relative ease of preparation and results that rival those of previous designs support the continued use of these cones.[42]

+ *Titanium sleeves*. Metal sleeves are available for both the tibial and femoral components. Unlike cones, the sleeves are attached to the implant with a Morse taper junction instead of cement, eliminating a possible source of failure at the cement–implant interface.[50] Primary stability, either axial or rotational, is achieved through a press-fit using an instrumented broach, which helps in preparing the host bone.[32,50,82,83] Moreover, the porous surface helps achieve long-term internal bone growth to improve secondary stability. Sleeves of various sizes and lengths are available to fill in defects.

In general, the Morse junction allows a certain degree of rotation of the tibial component to adapt to each case. The first step in preparing the tibia is the sequential drilling of the medullary canal until a stable endosteal fit is achieved, which allows for satisfactory rotational stability.[50,82] During broaching of the metaphyseal area, it is important to check the proper orientation according to the usual reference points, because the final pattern of the endosteal metaphyseal bone will force the rotation of the component. The final step is proximal resection using the final broach as a tibial cutting guide. The tibia is now ready to hold the test implant.

If there is significant bone loss on the femoral side, a sleeve can be employed, eventually with augments. It is important to establish the distal cut that will determine the joint line. The spinal canal is drilled in the same manner as the tibia, taking into account femoral bowing, which can force the component into an incorrect position if an excessively long stem is employed.[32] Once the surgeon is satisfied with the tests, the final components are attached to the sleeves through the Morse junction and, lastly, implanted onto the broached area.[81] The most frequent intraoperative complication related to the sleeves is fracture during broaching or upon impact of the final components.[82,83]

End-of-stem tibia pain is one of the most frequent long-term complications[50] and is usually due to the stem's length, which should be sufficient to assist in the intraoperative alignment and early stability. The main fixation is based mainly on the metaphyseal press-fit of the sleeves.[32]

In the case of a new revision, the removal of a well-fitted sleeve can be a major problem and will lead to increased bone loss. Although there are specialized instruments, an osteotomy of the tibial tuberosity is often necessary to remove the sleeve. Considering that final stability is achieved when secondary osseointegration of the sleeves is completed, it is advisable to protect weight bearing at the beginning, especially when the sleeve has been placed on the femoral side, an area in which rotational stability might be more compromised.[5,14]

In 2020, Gill et al evaluated the reliability of metaphyseal sleeves in the treatment of massive bone defects to provide stability for early weight bearing and to check the sleeves' short- and medium-term survival.[43] The authors analysed 36 patients (43 knees; 21 men; mean age, 59.4 years) who underwent primary TKA or rTKA with AORI type 2B (large metaphyseal bone defect) and AORI type 3 (metaphyseal defect with damaged collateral ligaments). The mean follow-up was 5.42 years, with the longest follow-up being nine years. The authors employed metaphyseal sleeves in 12 primary TKAs and 31 rTKAs. There were three intraoperative iatrogenic fractures (6.9%) of the tibial condyle, which were resolved with no additional surgery, achieving union in all cases. There was no aseptic loosening according to the radiological criteria, but there was one case of periprosthetic joint infection (2.3%). The mean preoperative Knee Society score was 36.21, which improved to 92.00 six months after the surgery. The flexion range increased from 76.83 degrees to 122.91 degrees. In the study, the metaphyseal sleeves showed excellent short- to medium-term survival in AORI types 2B and 3 bone loss. The metaphyseal sleeves are a reliable tool in the armamentarium of arthroplasty surgeons and are easy-to-use implants that provide immediate stability for early full weight bearing.[43]

In 2020, Bloch et al published their results on a series of rTKAs using a metaphyseal sleeve.[44] The authors analysed 319 rTKAs over a mean follow-up of 7.5 years (minimum, two years), and 73 patients were followed-up for more than 10 years. Implant survival was 99.1% at three years, 98.7% at five years and 97.8% at 10 years. None of the metaphyseal sleeves were checked for aseptic loosening. The final radiographic evaluation showed that there were RLLs in 2.8% of the tibial sleeves and 2.7% of the femoral sleeves, although none of them had progressed and none was reviewed. Approximately 3.7% of the tibial sleeves yielded more than 1 mm when compared with the immediate postoperative radiographs, although all of them stabilized and none was reviewed. In this study, the use of metaphyseal sleeves in rTKA was associated with excellent survival and excellent medium- to long-term radiographic outcomes.[44]

In short, the published short- to medium-term results indicate that, in terms of subjective, functional and radiological outcomes, uncemented metaphyseal sleeves are an appropriate option for treating AORI type 2B and 3 deficits during rTKA.

+ Megaprosthesis and modular endoprosthesis. In certain older adult patients, tumour prostheses might be appropriate to save the limb and achieve immediate stability.[45] However, postoperative infection is frequent, and the patient often requires an above-the-knee amputation.[49] Table 2 shows the recommended therapeutic options

Table 2. Therapeutic options for managing bone defects in revision total knee arthroplasty according to their AORI type

AORI type 1	AORI types 2 and 3
Bone cement +/- screws	Modular metal augmentation, porous titanium metaphyseal sleeves, porous tantalum metaphyseal cones
Bone graft: autograft, allograft, impaction grafting	Structural bone allograft
	Megaprosthesis / customized prosthesis

Note. AORI, Anderson Orthopaedic Research Institute.

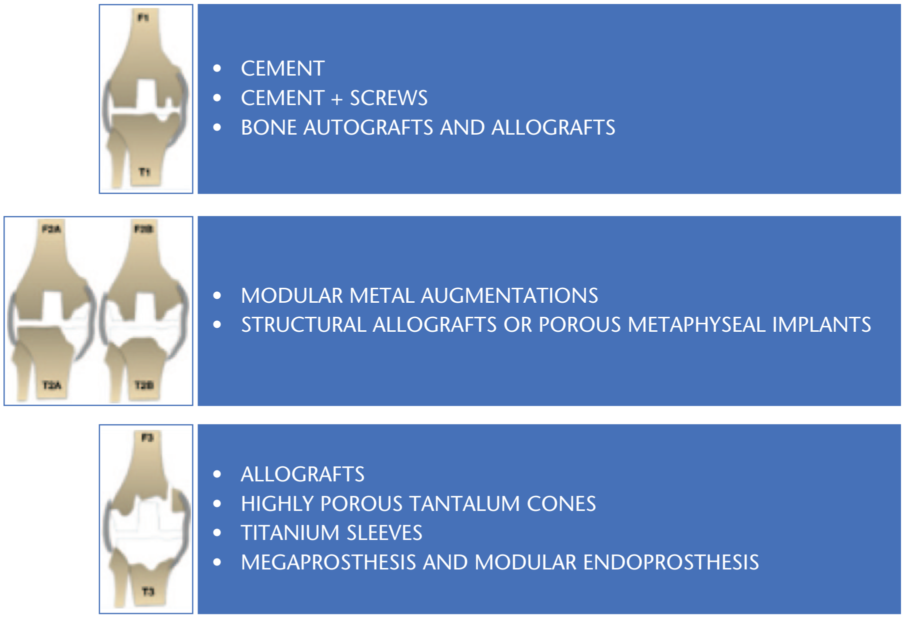

Fig. 8 Recommendations for bony reconstruction in revision total knee arthroplasty (rTKA) according to the type of bone defect in the AORI (Anderson Orthopaedic Research Institute) classification.

for managing bone defects in revision rTKA according to their AORI type. Fig. 8 summarizes recommendations for bony reconstruction in rTKA according to the type of bone defect in the AORI classification.

Conclusions

There are several therapeutic options for addressing bone loss in rTKA, and the choice will depend on the type, size and location of the defect and the quality of the host bone. Unfortunately, the literature does not provide any evidence-based approaches for this situation. The classifications, especially AORI, are useful for quantifying the defects and planning the operation, although the final evaluation should always be performed during surgery (after removing the components). Filling in and fixing are the fundamental concepts to consider. To achieve satisfactory fixation, the filling of bone defects should be performed with impaction grafting, cement or metaphyseal porous devices.

The treatment of small- to moderate-sized defects has yielded good results with various techniques (cement and screws, small metal augments, impaction bone grafting and modular stems). However, the treatment of severe defects remains problematic. The use of a structural allograft has decreased in recent years due to the increased rate of long-term failures and the introduction of highly porous metal augments that emphasize biological metaphyseal fixation. Recently published medium-term results on the use of tantalum cones in patients with severe bone loss have supported the use of this therapeutic strategy. The existing systematic reviews and meta-analyses to date are of low quality, given that the analysed studies are case series with no control groups. The immense variety of intraoperative situations and surgeon preferences for a certain technique make it difficult to conduct controlled trials that allow for different options to be compared. More higher-quality long-term studies need to be conducted to be able to draw scientifically firm conclusions about the true value of highly porous metal augments (cones and sleeves).

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