ABSTRACT

Bone deficiency hinders implant alignment and stabilisation of the bone-implant interface in revision total knee arthroplasty (TKA). Treatments for bone defects include bone cement, bone cement with screw reinforcement, metal augments, impaction bone grafts, structural allografts, and tantalum, depending on the location and size of the defects. Small defects are usually treated with cement, cement plus screws, or impaction allograft bone. Large defects are repaired with structural allografts or metal augments. Recent developments involve the use of highly porous osteoconductive tantalum. We reviewed the pros and cons of each method for bone defect management in revision TKA.

Key words: arthroplasty, replacement, knee; bone cements; bone transplantation; reoperation; tantalum

INTRODUCTION

The goal of revision total knee arthroplasty (TKA) is to produce a stable, painless knee with proper lower limb alignment and joint line levels. Bone deficiency hinders proper implant alignment and stabilisation of the bone-implant interface in revision TKA. The causes of bone loss in the revision setting include stress shielding, osteolysis, infection, mechanical bone loss generated from a loose implant,1–4 and iatrogenic loss during implant removal.5–7 Careful pre-operative planning is essential, but the true size of bone defects is usually underestimated, partially owing to removal of old bone cement and iatrogenic bone loss/fracture. Treatments for bone defects include bone cement, bone cement with screw reinforcement, metal augments, impaction bone grafts, structural allografts, and tantalum, depending on the location and size of the defects.8–15 Mechanical stability and long-term survivorship of each treatment method is not well reported. We thus reviewed the pros and cons of each bone defect treatment method in revision TKA.

BONE CEMENT

In a cadaveric study comparing 5 different techniques...
for reconstruction of medial tibial plateau bony defects,\textsuperscript{16} displacements of the tibial component under axial and varus-directed loads, respectively, were 100\% and 100\% for the cement-alone construct, 70\% and 72\% for cement with screw augmentation, 32\% and 44\% for the polymethylmethacrylate (PMMA) wedge, 17\% and 32\% for the metal wedge, and 9\% and 17\% for the custom implant. The cement-alone construct provides least stability. Nonetheless, cement achieves similar stability as impaction bone grafting and structural allografting when used for a 4-mm medial tibial bone defect.\textsuperscript{17} Cement is versatile and readily conformable to the size and shape of the defect. It is recommended for repairing small-contained defects, such as Anderson Orthopaedic Research Institute (AORI) type-1 or cystic defects.

59 knees with a defect of 10 to 20 mm (n=33) or >20 mm (n=23) in height were treated with cement and followed up for a mean of 7.1 years.\textsuperscript{18} The overall mean knee score was 78 and the radiographic score was 85. Non-progressive radiolucent lines were noted in 43 knees, but only one failed and needed revision. There was no correlation between radiolucent lines and symptoms. Long-term results of cement filling are good when the bone defects are <20 mm and affect <50\% of either plateau.\textsuperscript{18} In 54 patients with AORI type-1 defect followed up for 7 years, all had good outcomes, except for one who had loosening (and non-progressive radiolucent lines).\textsuperscript{19} In 8 TKA patients with rheumatoid arthritis, defects at the medial tibial plateau were repaired with bone cements, no progressive loosening was noted after a mean of 2.6 years.\textsuperscript{20} Cement filling can be used for tibial deficits of <5 mm.\textsuperscript{19} The cortical shell at the proximal tibial epiphysis is typically <1.5 mm,\textsuperscript{21} which is much thinner than the 5 mm when applying the cement technique. In clinical practice, the layer of bone cement to repair a cortical defect is much thinner than 5 mm. Other bone defect repairs (for tumours) also achieve similar satisfactory biomechanical and clinical outcomes.\textsuperscript{22,23}

Cement is not a biological scaffold and may cause thermal necrosis of the surrounding bone and blood supply to the bone,\textsuperscript{24,25} which is a cause for long-term loosening of the prostheses. The larger the defect, the greater the volume of cement used and the greater the amount of heat released when the cement sets, and the greater the risk of thermal necrosis. In the long run, the shrink volume of the cement may make the cement not amenable to pressing into the bony interstices.\textsuperscript{16} Radiolucent lines at the bone-defect interface are not a problem unless they are >2 mm. Better cement techniques, such as exposing a cancellous bed to bone, debridement with pulsatile lavage, or injecting the cement under pressure can all minimise radioluency.

CEMENT WITH SCREW

For small contained bone defects, cement with screw fixation results in 30\% less displacement of the prosthesis than cement alone did in tibial wedge defect reconstruction.\textsuperscript{16,26} A titanium screw was placed in the distal femoral condyle and the head was left proud to reinforce the cement and support the deficient condyle, when the femoral chamfer cuts did not provide stability and one of the distal femoral condyles was deficient.\textsuperscript{27} The screw should be inserted to such a depth that its head does not contact with the prosthesis.

Cement with screw is recommended for AORI type-1 defects (small uncontained bone defects) when used with standard non-stemmed implants.\textsuperscript{28} It is reliable, reproducible, easily performed, and inexpensive.\textsuperscript{29} There are no signs of failure after 15 years.\textsuperscript{16} In 57 patients with tibial defects (mean height, 9 mm) followed up for a minimum of 3 years, 25\% had non-progressive radiolucency at the bone-cement interface, but none of the components failed.\textsuperscript{29} There was no progression of radioluency lines in either the bone-cement or the cement-prosthesis interface after 7 years.\textsuperscript{30} The radioluency may have already existed at the time of surgery and was mainly due to poor penetration of the cement into sclerotic bones.\textsuperscript{31} This technique is recommended for tibial defects of 5 to 10 mm in height.\textsuperscript{31,32} In 23 TKAs with tibial bone defects fixed with cement and screws and followed up for a mean of 28 months, the mean knee rating score and functional score improved significantly and no radiolucent lines were detected between the prosthesis and cement, and around the threads of the screws within the bone.\textsuperscript{33} Only 8 patients had non-progressive radiolucent lines in the bone-cement interface.\textsuperscript{33}

Application of this technique in large uncontained bone defects is not recommended. It also carries the risk of thermal necrosis and radioluency in the bone-cement interface.

MODULAR METAL AUGMENTS

Metal augments in various shapes and sizes are readily available for both femoral and tibial defects.\textsuperscript{34} The augments are usually wedges (including hemi-wedges and full wedges), rectangular blocks, and sleeves. The size of the metal augments usually corresponds to the size of the prostheses, with different
thickneses and angles to replace bone defects of various severities.35–37 The best-fit augment should be used to fill up the bone defect, while removing as little host bone as possible. Augments can be assembled to fit the femoral and tibial components with screws and then cemented. For example, a medial tibial augment helped restore appropriate alignment for a varus deformity with a medial tibial defect. In a failed TKA with inadequate posterior bone stock, posterior femoral augments were used to reconstruct the appropriate condylar offset, restore proper femoral component rotation, and balance the flexion/extension gap.38 Augmented prostheses with a built-up metal wedge are mechanically superior to cement alone or cement with screws in terms of resisting deflections when loaded.16 The tibial tray can be customised at the time of surgery when modular metal wedges are used. Tensile strain within the cement-bone interface is less with block augments than with wedges; the maximal strain differential between blocks and wedges is slight. Thus, the augment that best fills the defect should be used.39

In 22 knees with modular metal wedges to augment tibial bone stock deficiency, there were no failures and no loosening of tibial components after a mean of 3 years.40 27% of the patients had non-progressive radiolucent lines; no patient underwent re-revision surgery.40 Five patients underwent revision TKA using modular tibial wedge augmentation with long-stemmed components for the tibial side for medial tibial bone deficiency.41 After a mean of 5.6 years, 2 of the patients had bone resorption beneath the metal wedge because of stress shielding, but none was progressive.41 Large (30 mm) metal distal femoral augments were used to compensate for type-3 bone deficiencies; there was no radiographic evidence of loosening, and no implants was revised after a mean of 37 months.42 In 102 revision TKA patients with AORI type-T2 defects treated with modular metal augments and stems, non-progressive radiolucent lines around the augment were observed after a mean of 7 years, but implant survival improved.43

Metal augments confer the risk of fretting and corrosion.43,42,44,45 In the long run, the difference in elasticity between metal and bone may cause stress shielding and increase potential bone loss.43 This technique is mainly used for AORI type-2 or -3 defects (peripheral tibial deficiencies) in elderly, low-demand patients.40

**IMPACTION BONE GRAFTING**

Impacted, morselised bone grafts enable restoration of living bone stock,46 especially in younger patients in whom further revision surgeries are anticipated. Impaction bone grafting is usually used for contained defects. For uncontained defects, morselised bone is used with a wire mesh,47 which prevents the outflow of bone particles during impaction. Bone particles should be as large as practical (3–5 mm in diameter) to ensure early stability.48,49 Adequate impaction force makes morselised bone grafts strong enough to carry the load; excessive impaction reduces host bone ingrowths.50 Solid support of the implant-graft interface, graft-host bone interface, and the use of a supportive stem is imperative.51 Using stronger and stiffer instruments, larger particles, and removing fat are important strategies to reduce the effort of impaction and the risk of intra-operative fracture.52–57 In a study using goat femurs, the use of a cemented femoral stem in conjunction with impaction bone grafting was superior to an uncemented stem,58 because cement penetrated into the graft and formed a more stable construct.

Three methods of graft containment (mesh, cement, and a novel bag technique) for segmental medial tibial defects were compared in order to determine whether a repaired cortex provides sufficient support for the tibial tray.17 The novel bag technique uses a closed bioabsorbable polyester mesh bag filled with bone grafts to provides graft containment and direct tray support. It is tensioned and fixed in place across the defect using unicortical screws. The initial stability of an impaction-grafted tray on a repaired cortex was compared with that of a tray with a modular metal augment.17 The defects were cut to be 46% or 65% of the medial tibia to mimic different defect severities; these 3 methods were compared with a control group, which used a modular metal augment; cyclical and permanent tray displacements were recorded during cyclical mechanical loading.17 Stability was satisfactory with mesh and cement techniques with impaction bone grafting, except for the novel bag technique.17 Long stems were superior to short stems when used together with impaction bone grafting.59

The biological interaction between the graft and the host bone plays an important role in medium to long-term results.60 Cancellous bone allografts enable remodelling through re-vascularisation.61 The allografts used in impaction bone grafting are non-vascularised. The incorporation of allograft involves 2 overlapping processes: the union of the graft-host bone interface and the remodelling of the graft (i.e. the creep substitution), which is relatively slow.62,63 Bone grafts, even when covered with methylmethacrylate bone cement, still retain their viability and osteogenic
Impaction bone grafting is usually for contained defects. It is difficult to strike a balance between achieving initial stability and long-term graft incorporation. When initial stability is inadequate, the revision TKA may fail before the eventual incorporation of the grafts. Impaction bone grafting is not recommended for repairing cortical or uncontained defects, as the cortical rim is important to ensure stability of the tibial tray. Lack of support of the cortical rim increased permanent movement by a factor of 2.6 and cyclical movement by a factor of 1.7, compared to intact cortical rim support; this suggests poor support strongly decreased stability. An uncontained defect was repair by impaction bone grafting with a short-stemmed tibial tray; most of the grafts had not incorporated and the central portion was necrotic after 4 years, likely owing to lack of stability of the tibial cortical rim.

**STRUCTURAL ALLOGRAFT**

Structural allografts provide a stable and durable reconstruction of large or segmental bone deficiency. They can be blocks of material and can conform with defects of different shapes. Femoral heads, distal femoral segments, and proximal tibial segments are most commonly used. Structural allografts may incorporate into the host bone and provide some stress protection to the implant. They work in a way analogous to the biological attachments of ligaments and tendons. The early results are comparable to traditional metal augment reconstruction. Of 24 knees with structural bone grafts for tibial defects in primary or revision TKA, 22 achieved bone union and revascularisation of bone grafts with no clinical collapse after 3 to 6 years, whereas the remaining 2 were nonunions with collapse in one. Incorporation was present by 6 months, but the time to complete remodelling was not determined. Structural bone grafts are recommended for tibial defects involving ≥50% of the bony support of either tibial plateau. Of 35 knees with AORI type-3 tibial bone defects treated with structural allografts, the mean Knee Society Function Score improved significantly, and no graft collapse or aseptic loosening was found after a mean of 95 months. 13 distal femoral allografts (6 whole distal femurs and 7 distal and posterior condyles) were used for reconstruction of large uncontained defects; all allografts had achieved incorporation or union to host bone, and no collapse or infection had occurred after one year. In 15 patients using structural allografts (7 distal femurs and 12 proximal tibias) for revision TKA with large segmental,
cavitary, or combination defects of the femur and/or tibia,
82 femoral head allografts were used for cavitary
defects, whereas size-matched allografts were used for
segmental or combination defects. All patients
except one had improvement of pain and stability;
there were no fractures, subsidence, or osteolysis
after a mean of 47 months; no patient underwent
revision surgery secondary to any femoral component
complication.82 In patients with a life expectancy
of >10 years, structural bone grafts to restore bone
stock is preferred.83 Nonetheless, in cases of infection,
the use of prosthetic augments and antibiotic bone
cement is a safer option. The supply of allografts
usually cannot satisfy the demand. In some cases,
more bone is sacrificed to make the interface smooth,
which may enlarge the defect. Allografts also carries
the risk of bacterial and viral disease transmission
and biological issues such as immune response,
graft disincorporation, resorption, load transfer, and
fatigue fracture.15 The safety of allografts depends
on the sterilisation process, which may compromise
tissue biology and biomechanics.84

TANTALUM

Porous tantalum is a relatively new solution for
repairing bone defects in revision TKA; it has an
interconnected porous structure with a mean porosity
diameter of approximately 400 microns.85 The current
designs for orthopaedic implants maintain a high
volumetric porosity (70–80%) for bone ingrowth,
with low modulus of elasticity (3 MPa), and high
frictional characteristics, making this metal conducive
to biologic fixation.86 The low modulus of elasticity
of such components enables more load transfer and
preservation of bone stock.86 Tantalum does not react
with or irritate bodily fluids; in vivo biocompatibility
was excellent (e.g. with pacemaker electrodes,
cranioplasty plates, and as radiopaque markers).87
Trabecular metal cones help reconstruct large cavitary
defects; these implants, along with offset stems when
necessary, may eliminate the need for extensive bone
grafting or allografting.34 Its re-creates the cortical rim
in the proximal tibia and provides a stable platform
for the final tibial component; the various shapes can
address both cancellous bone loss and cortical defects.
The distal femoral cones re-establish the metaphyseal-
diaphyseal junction and create a stable base for
the femoral component; these modular constructs
absorb compressive loads, and provide structural
and mechanical support. Initial clinical data support
its use as an alternative to traditional orthopaedic
implant materials. Of 15 revision TKAs (8 knees had
a AORI type-3 defect and 7 knees had a type-2B bone
defect) using porous tantalum metaphyseal cones,88
the mean Knee Society clinical scores improved
significantly after a mean of 34 months. All knees
showed evidence of osseo-integration with reactive
osseous trabeculation at points of contact with the
tibia; there was no evidence of loosening or migration
of any tibial reconstruction.88 In 16 revision TKAs
using porous tantalum tibial cones for AORI type-T2
and -T3 bone defects,89 radiographs demonstrated
reestablishment of the joint line, a neutral mechanical
axis, and signs of stable osteointegration into the
cones after a mean of 31 months. All the trabecular
metal components stabilised eventually.90

Tantalum has superior osteoconductive
properties, but its high cost is a concern.89,90 Long-
term follow-up and comparison with alternative
reconstructive techniques are required to evaluate its
true effectiveness.

DISCUSSION

Bone defects are commonly encountered during
revision TKA, for which there is no standard
treatment. Treatment options include cement
filling, cement with screw augmentation, metal
augmentation, morselised or structural bone grafts,
and tantalum, depending on the location and size of
bone loss, the bone quality, the surgeon’s experience
and preference, and the availability of grafts and
implants (Table 1).16,18,19,31,32,40,43,51,71–73,80–82,88–93 In severe
cases, meta-prostheses, modular implants, and long
stems can also be used.

Cement is commonly used for AORI type 1
defects of <5 mm. If defects are 5 to 10 mm and <50%
of the femoral condyle or tibial plateau is available,
cement with reinforcing screws provides better
biomechanical stability. Whether this technique
can be used in defects of >10 mm is unknown. For
contained defects of >10 mm, metal augments,
structural allografts or impaction bone grafts are
preferred, especially the latter 2 can replenish host
bone stock for the next possible revision (Table 2).

For type-2 defects, structural bone grafts and/or
metal augment are preferred, depending on the
location, size, and bone quality (Table 2). Structural
bone grafts can be used to repair cortical defects
and to replenish host bone stock. However, not
all joint replacement centres have a bone bank to
satisfy clinical demand. Initial stability of allografts
may be insufficient owing to absorption and fatigue
fractures, until incorporation with host bone. Impaction bone grafting is usually not considered in
uncontained defects where adequate biomechanical support cannot be provided owing to the lack of an intact cortical rim. Metal augments are widely used to repair uncontained and various shapes of defects. They are available in various shapes and sizes and provide better initial stability. Nonetheless, in the long run, fretting and stress shielding are concerns. Compared to bone grafting, if metal augments fail, re-revision is even more difficult owing to creation of larger bone defects.

In severe osteoporotic cases or re-revision of large segmental defects, tantalum is warranted. The bio-conductive feature of tantalum provides a trabecular-like porous structure. Short-term results are promising; long-term results remain unknown. Further research is warranted.

Table 1
Review for each treatment option

<table>
<thead>
<tr>
<th>Study</th>
<th>Advantage</th>
<th>Disadvantage</th>
</tr>
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<tbody>
<tr>
<td>Cement</td>
<td>Repair small contained defect</td>
<td>Risk of necrosis</td>
</tr>
<tr>
<td>Lotke et al.18</td>
<td>Convenient</td>
<td>Radiolucent, only used in small defect</td>
</tr>
<tr>
<td>Brooks et al.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cement+screw</td>
<td>Better biomechanical properties than cement</td>
<td>Risk of necrosis</td>
</tr>
<tr>
<td>Dorr et al.19</td>
<td>Used to fill 5–10 mm defect</td>
<td>Radiolucent</td>
</tr>
<tr>
<td>Ritter et al.31,32,91</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Metal augments</td>
<td>Various shapes and sizes</td>
<td>Stress-shielding</td>
</tr>
<tr>
<td>Brand et al.40</td>
<td></td>
<td>Fretting and corrosion</td>
</tr>
<tr>
<td>Pagnano et al.92</td>
<td></td>
<td>Potential bone loss in the long-run</td>
</tr>
<tr>
<td>Patel et al.43</td>
<td></td>
<td></td>
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<tr>
<td>Impaction bone graft</td>
<td>Osteoinduction</td>
<td>Could not repair cortex</td>
</tr>
<tr>
<td>Benjamin et al.71</td>
<td></td>
<td>Biomechanical properties</td>
</tr>
<tr>
<td>Lotke et al.72</td>
<td>Osteoconduction</td>
<td>Resorption</td>
</tr>
<tr>
<td>Ullmark and Hovellius59</td>
<td>Bone graft incorporation and remodelling</td>
<td></td>
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<tr>
<td>Structural allograft</td>
<td>Physiologic material</td>
<td>Disease transmission</td>
</tr>
<tr>
<td>Engh and Ammeen80</td>
<td>Repairing large bone defect</td>
<td>Immunology</td>
</tr>
<tr>
<td>Stockley et al.91</td>
<td></td>
<td>Resorption</td>
</tr>
<tr>
<td>Tsahakis et al.81</td>
<td>Osseointegration</td>
<td>Fatigue fracture</td>
</tr>
<tr>
<td>Mow and Wiedel82</td>
<td>Potentially add bone stock</td>
<td></td>
</tr>
<tr>
<td>Tantalum</td>
<td>Biocompatibility, bioactivity</td>
<td>Not a popular choice</td>
</tr>
<tr>
<td>Long and Scuderi99</td>
<td>Low modulus of elasticity</td>
<td>Lack long-term follow-up</td>
</tr>
<tr>
<td>Henrikson et al.90</td>
<td>High frictional characteristics, a high volumetric porosity</td>
<td>Expensive, only used in severe cases</td>
</tr>
<tr>
<td>Meneghini et al.88</td>
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</table>

Table 2
Protocol for bone defect management in revision total knee arthroplasty63

<table>
<thead>
<tr>
<th>Defect</th>
<th>Treatment options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contained</td>
<td>Cement</td>
</tr>
<tr>
<td>&lt;5 mm</td>
<td>Cement + screw</td>
</tr>
<tr>
<td>5–10 mm</td>
<td>Impaction morselised allografting, structural allografting</td>
</tr>
<tr>
<td>&gt;10 mm</td>
<td></td>
</tr>
<tr>
<td>Mild uncontained</td>
<td>Cement</td>
</tr>
<tr>
<td>&lt;5 mm</td>
<td>Cement + screw</td>
</tr>
<tr>
<td>5–10 mm</td>
<td>Impaction allograft bone, metal augment</td>
</tr>
<tr>
<td>&lt;50% femoral condyle or tibial plateau</td>
<td></td>
</tr>
<tr>
<td>Moderate uncontained</td>
<td>Metal augment, structural allografting, Modular prosthesis</td>
</tr>
<tr>
<td>&gt;5 mm and &gt;50% femoral condyle or tibial plateau, intact ligament</td>
<td></td>
</tr>
<tr>
<td>Severe uncontained</td>
<td>Metal augment, structural allografting, megaprosthetics, tantalum augment</td>
</tr>
<tr>
<td>Lateral ligaments involved</td>
<td></td>
</tr>
</tbody>
</table>
52. Verdonst N, Schreurs BW, Van Unen JM, Slooff TJ, Huiskes R. Cup stability after acetabulum reconstruction with morsellized grafts is less modular dependent when larger grafts are used. Trans Orthop Res Soc 1999;24:867.


