■ REVIEW ARTICLE

The management of bone loss in revision total knee replacement

J. P. Whittaker,
R. Dharmarajan,
A. D. Toms

From Royal Devon and Exeter Hospital, Exeter, England

The management of bone loss in revision replacement of the knee remains a challenge despite an array of options available to the surgeon. Bone loss may occur as a result of the original disease, the design of the prosthesis, the mechanism of failure or technical error at initial surgery. The aim of revision surgery is to relieve pain and improve function while addressing the mechanism of failure in order to reconstruct a stable platform with transfer of load to the host bone. Methods of reconstruction include the use of cement, modular metal augmentation of prostheses, custom-made, tumour-type or hinged implants and bone grafting.

The published results of the surgical techniques are summarised and a guide for the management of bone defects in revision surgery of the knee is presented.

The National Joint Registry for the United Kingdom estimates that more than 62 000 replacements of the knee were carried out in 2007.[1] Although the clinical results of primary total knee replacement continue to be excellent, the number of revision procedures required will increase substantially.[2,3] The greatest challenge during revision surgery is the management of bone loss, which can occur as a result of the original disease process, the design of the prosthesis, the mechanism of failure or technical error at the initial procedure. Radiological assessment using standard anteroposterior and lateral views is known to underestimate bone loss[4] and further investigations must include oblique views, the use of image intensification or CT.[5-7]

Classification

Several systems of classification have been proposed for assessing bone loss prior to revision.[8-10] The most commonly-used is that of the Anderson Orthopaedic Research Institute (AORI)[9] which classifies the femur (F) and tibia (T) separately as follows:

Type-1 - Intact metaphyseal bone with minor defects which will not compromise the stability of a revision component.

Type-2 - Damaged metaphyseal bone. Loss of cancellous bone in the metaphyseal segment which will need to be filled with cement, augments or a bone graft at revision in order to restore the joint line. Defects can occur in one femoral condyle or tibial plateau (2A) or in both condyles or plateaux (2B).

Type-3 - Deficient metaphyseal bone. Bone loss which comprises a major portion of either condyle or plateau. These defects are occasionally associated with detachment of the collateral or patellar ligaments and usually require long-stemmed revision implants with bone grafts or a custom-made hinged prosthesis.

Surgical options

The options for the management of bone loss in revision knee surgery include: a) the use of cement, either alone or combined with screws and mesh, b) modular augmentation of the components with wedges or blocks of metal, c) the use of custom-made, tumour or hinge implants, and d) bone grafting with structural or morsellised graft.

When selecting the method of reconstruction and the materials for revision surgery, the potential for future further revision must be considered together with the life expectancy, functional demand and comorbidities of the patient. Restoration of bone stock is preferable, particularly if a future further revision is considered likely.

Cement performs poorly in the long term. It does not restrict deflection of the tibial tray and provides inferior load transfer with poor fatigue properties[11-13] which may in time lead to subsequent failure.[14] The use of cement in isolation during revision surgery should be reserved for AORI type-1 defects, small type-2

■ J. P. Whittaker, FRCS(Orth), Fellow
■ A. D. Toms, MSc, FRCS(Orth), Consultant Orthopaedic Surgeon
Exeter Knee Reconstruction Unit
Princess Elizabeth Orthopaedic Centre, Royal Devon & Exeter Hospital, Barrack Road, Exeter EX2 5DW, UK.

■ R. Dharmarajan, FRCS(Trauma & Orth), Consultant Trauma and Orthopaedic Surgeon
Cumberland Infirmary, Newtown Road, Carlisle CA11 9QW, UK.

Correspondence should be sent to Mr A. D. Toms; e-mail: Andrew.Toms@rdeft.nhs.uk

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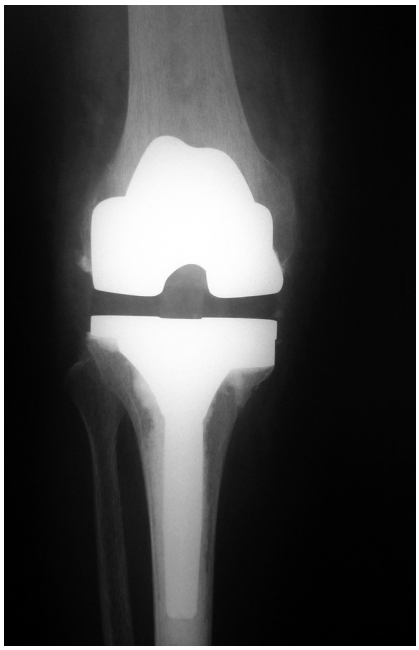

Fig. 1

Post-operative anteroposterior radiograph of the knee showing the use of a medial step wedge augment on the underside of the tibial baseplate.

defects of less than 5 mm or those which involve less than a quarter of the cortical rim. However, cement remains a good option in the short term and may be suitable for elderly or infirm patients. Elia and Lotke[15] found no difference between the use of cement and bone grafts for AORI type-1 and small type-2 defects in the short term, although they concluded that a bone graft had obvious biological advantages. The use of cement in combination with screws for bone defects of more than 5 mm has given excellent results at 13 years with no failures.[16] Lotke, Wong and Ecker[17] also described reasonable results with cement, but concluded that bone grafting was generally the choice for defects of more than 20 mm.

Augments attached to the underside of the tibial tray are a mechanically sound option[18] (Fig. 1). The advantages include ready availability and quick application but problems may arise from corrosion and from wear debris as a result of fretting between the tray and the augment. Angled wedge augments create shear stresses and fail to load the distal bone. Step wedge augments subject the underlying interface to compression forces, but may require further resection of bone to accommodate them. Hockman, Ammeen and Engh[19] found that modular augments alone failed to address bone loss effectively in 48% of cases and noted an improved rate of survival when modular augments were combined with structural allograft. Good results have been described using augments to manage bone loss, and Rand[20] has reported good or excellent results in 100% of cases with no complications. Although they also achieved good results using wedge augments, Brand et al[18] have suggested that this technique is most suitable for severe peripheral tibial defects in elderly, low-demand patients. Typically, augments are used for type-1 defects, type-2 defects of 5 mm to 10 mm, or segmental defects with bulk allograft in larger defects. The use of augmentation has been advised when 40% or more of the projected implant-bone interface is unsupported by host bone[21] resulting in an inability to achieve stability of the trial implants, or if peripheral defects involve 25% or more of the cortical rim.

Large defects (Fig. 2) may require the use of custom-made or rotating-hinge implants (Fig. 3). Pour et al[22] described the use of the latter in reconstruction of the knee and achieved a survival rate of 68% at five years, but the authors cautioned against their use in active or younger patients. Advocates of custom-made prostheses suggest that they are mechanically-sound and survive well.[23,24] However, the accurate pre-operative assessment of bone loss is difficult and a custom-made prosthesis may not, therefore, fit well. In these cases, more bone may have to be resected to achieve stable function. Custom-made prostheses are expensive and take time to manufacture. They are best used when the alternative options are limited.

The use of bone graft allows the augmentation of the residual bone stock. The ability to contour the graft at operation and the capacity of the graft to transfer load in a physiological manner are significant advantages. The disadvantages of allografts include unpredictable union, the theoretical transmission of viral, bacterial and prion disease[25,26] and their availability, which is not universal.

Both autograft and allograft are available in either structural or morsellised forms. The use of autograft in reconstruction of the knee has been debated.[21] Success has been achieved with smaller bone defects, whether centrally contained[27-29] or peripherally uncontained,[29-31] although higher rates of failure have been seen in the presence of instability and large bone defects.[32] Structural allograft, typically used for the reconstruction of large defects, has shown variable early results,[33-35] with reports of nonunion and collapse of the graft because of resorption.[32] Tsahakis, Beaver and Brick[36] found that the early results of structural grafting are reliable, with a rate of union of 100%, but commented on the potential concerns of rapid dissolution, possibly due to immune reaction. Laskin[32] had a success rate of 67% and concluded that structural bone grafting should only be used for small circumscribed defects. In the medium term, however, the results are better with a survival of 92% at five years and 72% at ten years, when failure is defined as the need for additional surgery related to the allograft or an improvement of less than 20 points in the modified Hospital for Special Surgery knee score.[37] Ghazavi et al[38] have described the results of using a massive structural allograft in uncontained defects of more than

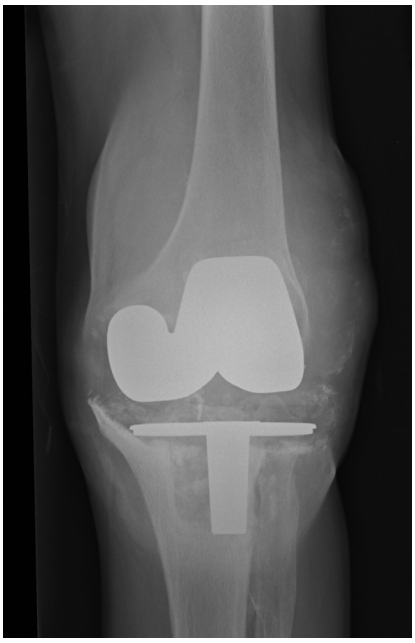

Fig. 2a

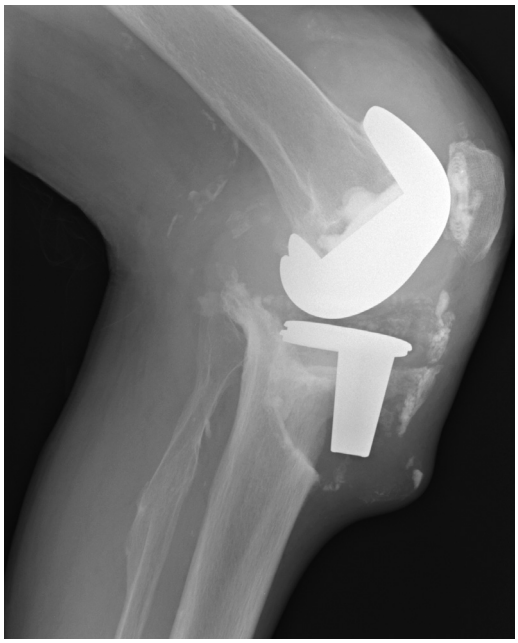

Fig. 2b

Pre-operative a) anteroposterior and b) lateral radiographs of the knee showing severe (type-3) tibial bone loss in a failed knee replacement.

3 cm. After a mean of 50 months they had a rate of success of 77%, with a Kaplan-Meier probability of survival of the graft at five years of 67%. From the same unit, Backstein, Safir and Gross[39] noted satisfactory results after five years when using structural allograft in 58 patients with uncontained bone defects which were too large to be reconstructed with metal augments. They observed radiological allograft-host union in 98%, although allograft-related complications required additional intervention in 21%. Parks and Engh[40] investigated the biological incorporation of structural bone graft from the femoral head at a mean of 41 months. They observed dead bone graft centrally with new bone at the periphery of the allografts. Consideration must be given to alternative methods of reconstructing large bone defects in revision knee replacement when evaluating these results.

Morsellised impaction grafting, which has been widely accepted in revision surgery of the hip,[41] has been used sparingly in revision replacement of the knee. It may be used to treat contained defects and uncontained defects which can be converted into contained defects by the use of wire mesh (Fig. 4). Reconstruction involves occlusion of the canal and compaction of morsellised graft over a guide wire to produce a stable reconstruction of the cortical tube into which an implant can be cemented. This reconstitutes bone stock and in the long term incorporation of the graft occurs, with remodelling of bone by creeping substitution. The technique has been extensively supported in animal models and by histological,[42,43] radiological and biomechanical studies.[44,45] Several centres have published clinical studies of revision replacement of the hip using impaction bone grafting, showing good restoration of bone with evidence of subsidence but no loosening.[46,47]

There is a wide variety of opinion in the use of morsellised bone graft in the knee, particularly with regard to case selection, technique and the outcomes achieved. Some series have shown radiological evidence of remodelling of cancellous bone graft with no clinical failure or instability, although the numbers involved were small.[48,49] These studies described a technique which involved the use of washed morsellised allograft combined with uncemented long-stemmed components and restricted post-operative weight-bearing. More recently, Whiteside[50] described the use of morsellised graft, even in the presence of type-3 cortical defects, in 105 patients with a follow-up of between five and ten years, again with uncemented long-stemmed implants. The results were excellent with only one case of aseptic tibial loosening. Concern has been raised about the use of morsellised bone graft and the predictability of its initial and clinical stability,[51] although biomechanical[52] and clinical studies[53] have addressed this. In order to achieve stability, many authors have used long press-fit stems which, although they ensure greater initial stability, largely bypass the graft, unloading it and causing stress shielding.[12,54] This inhibits its early incorporation, which otherwise remains a major advantage of morsellised over large structural grafts.

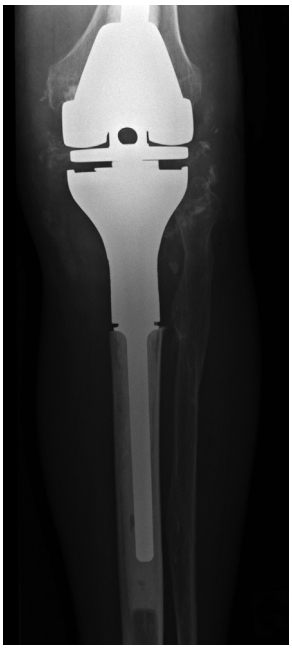

Fig. 3

Post-operative anteroposterior radiograph showing the reconstruction of severe tibial bone loss by a hinged prosthesis.

Published reports of the use of morsellised graft in the knee need careful interpretation of both technique and results. Several authors[48,50,55,56] have used morsellised bone graft without impaction, again employing long uncemented press-fit stems. Whiteside[49] has also reported radiological and histological results which confirm evidence of union and active bone formation.

The experience of Bradley[56] has established the place of morsellised bone graft as a practical biological solution capable of achieving good results. He described 19 revision replacements of the knee using impaction bone grafting with stems of between 8.5 cm and 10.5 cm in length in all cases. These were uncemented in 14 cases, cemented in five and used additional structural allograft in three. His overall results were good with only one failure. In this case cement augmentation had been used and he did not use this combination again.

The combination of morsellised graft and a long stem engaging the distal cortex causes a decrease in loading of the graft by up to 38%.[54] Experimental evidence from *in vivo* studies has shown that incorporation of the graft can be improved by early loading and the use of short stems.[57] Longer stems may increase toggling or tilting movement.[58] This method therefore differs substantially from the Slooff-Ling technique,[59] as used by Ullmark and Hovelius,[60] in which the whole stem was surrounded by graft including its distal tip.

There is also debate about the use of stems and the choice of stem length with long stems reported to enhance fixation and alignment.[61,62] However, as has been noted previously, they increase proximal stress shielding. Excellent mid-term results have been reported in 84% of patients[61] using long stems when revising for aseptic loosening. However, the use of large stems results in increased bone loss and decreased proximal loading. Stern et al,[58] in a biomechanical study, found that longer stem tibial implants were associated with increased micromovement of the tibial tray. Radnay and Scuderi[63] advised that the length of the stem should be determined by the integrity of the residual bone and the diameter of the intramedullary canal. They suggested cementing a short stem or a longer stem of narrow diameter for host bone of poor quality, and using a long press-fit stem engaging the diaphysis for patients with bone of better quality.

There are only a few reports of genuine impaction bone grafting[64] in revision knee replacement.[53,60,65] Ullmark and Hovelius[60] achieved good short-term stability, commenting that the biological advantages of morsellised bone graft in the knee had already been established by Samuelson,[48] and with their limited clinical experience concluded that the technique was encouraging. Van Loon et al[51] described their experience of morsellised impaction grafting in the knee with histological follow-up at four years. Grafting was performed for bone loss in both the femur (F2B) and tibia (T2B) using the Slooff-Ling technique,[59] with a short stem cemented into the graft. Histological examination showed good incorporation of the graft in the femur, although this was not seen in the tibia. New cortical bone was found in the tibia around the containing mesh but approximately three-quarters of the tibial graft failed to become incorporated with an area of central necrotic graft. They concluded that impaction grafting in the tibia did not provide sufficient initial stability and that this led to poor incorporation of the graft. They discouraged the use of the technique in the tibia, but recommended it as a promising method in the femur.[51] Heyligers et al[65] published a technical note on impaction grafting of both the tibia and the femur at the knee. Primary implants with short stems were used and the results were presented in 11 knees (ten tibial reconstructions) in nine patients, with a mean follow-up of 23 months. Of the 11 knees, the tibial defect was classified as T1 in one, T2A in five, T2B in four and F2 in one. The initial results appeared to be promising, with no subsidence, no radiolucencies and no resorption of the graft. Their technique was similar to that used by Ullmark and Hovelius,[60] in keeping with the Slooff-Ling philosophy.[59] However, full post-operative weight-bearing was only allowed in four patients, with five immobilised in casts for between six weeks and three months.

Mechanical studies have suggested that a short-stemmed tibial tray surrounded by impacted bone graft will be stable if the cortical rim provides adequate support. A long stem should be used if there is a cortical defect.[52] Lotke et al[53]

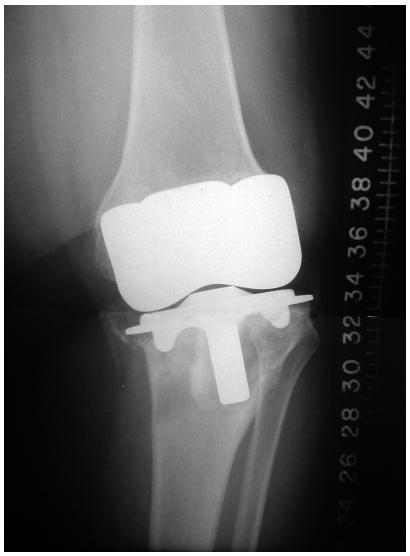

Fig. 4a

Fig. 4b

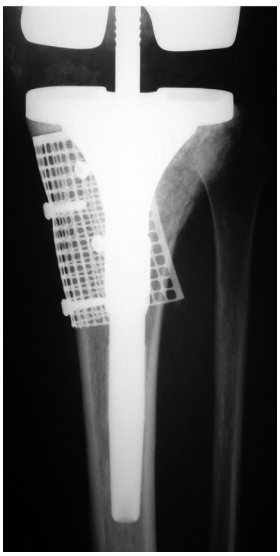

Fig. 4c

a) Pre-operative anteroposterior scaled radiograph used to template the bone defect in preparation for impaction bone grafting with the use of a wire mesh to contain the defect, b) intra-operative photograph of tibial impaction bone grafting for a type-2 defect. A wire mesh has been used on the medial side and morsellised allograft bone has been impacted around a central metal post within the proximal tibia, and c) post-operative anteroposterior radiograph showing the wire mesh secured to the medial tibia with screws and impacted morsellised bone graft in the proximal tibia.

and Lotke, Carolan and Puri[66] recorded promising early results of impaction grafting using a similar method to that of the Slooff-Ling technique[59] in 45 patients, 11 of whom required mesh for an uncontained defect. They reported no mechanical failure at a mean follow-up of 3.8 years and noted progressive incorporation of the bone graft on the post-operative radiographs.

The numerous techniques for bone grafting and their varied results suggest that the ideal method of restoring bone stock at the knee has not yet been achieved. If the bone graft is to be incorporated, there must be initial mechanical stability of the construct and no subsequent migration. Whether this is possible in the tibia has been questioned.[51]

Future developments

New innovations include the use of metaphyseal filling metal cones. These may help the surgeon to achieve improved stability of the implant in patients with larger bone defects, particularly in the presence of diminished or sclerotic bone stock. The use of these cones in combination with new materials such as porous tantalum[63] may offer improved metaphyseal fixation.[63,67-70] Porous tantalum combines a high coefficient of friction, a volumetric porosity of 70% to 78%[71] and encourages accelerated bone ingrowth,[71] which can be potentially enhanced further by additional coatings.[72]

Although these cones may provide structural support they will not reconstitute bone stock and need to be cemented to the prosthesis to ensure stable fixation. The medium- and long-term outcome of this technique is unknown. In the short-term, porous tantalum metaphyseal tibial implants have demonstrated good results when used for severe bone loss in the tibia (type-2B and type-3 defects). In a series of 15 patients with a mean follow-up of 34 months, the Knee Society clinical scores improved from 52 points pre-operatively to 85 points at the latest follow-up with more of the metaphyseal tibial implants demonstrating radiological signs of migration or loosening.[73]

Theoretical improvements in achieving bone ingrowth may be seen with agents such as recombinant bone morphogenetic proteins (BMP)-7 (osteogenic protein (OP)-1) and BMP-2[74,75] used to enhance osteo-induction or osteogenesis. However, other animal studies have not shown benefits with the use of BMP-7 (OP-1) when the animal was allowed to load the graft[76-78] and there are no clinical data to recommend their use in revision knee surgery. In animal studies, alterations in the graft mix have been used to improve the mechanical stability of a graft/stem construct, although the effect of this *in vivo* is not known. Biomechanical and animal studies have suggested that improved stability can be achieved with cancellous bone particles of more than 2 mm[79] with the further addition of stiffer particles such as ceramics, cortical bone, bovine bone and hydroxyapatite.[79-83]

Summary

Biological solutions have obvious advantages, particularly for the younger active patient who requires a revision procedure. Reconstruction with bone graft has merit, but the

final choice of technique will depend on the age and level of activity of the patient, the extent and distribution of bone loss, the quality of the remaining bone, the experience of the surgeon and the availability of bone graft and implants. This review of the literature supports the following techniques for reconstruction. Cement or bone graft should be used with a primary implant for small cavitary defects involving less than one quarter of the cortical rim, with consideration being given to the use of revision prostheses with metal augments when larger segmental defects or greater involvement of the rim are encountered. For type-2 defects, either cement alone or compacted morsellised bone graft with mesh may be used for small defects. For larger defects of 5 mm to 10 mm, reconstruction can be performed either with metal augments alone or in combination with compacted morsellised bone graft. With further bone loss, particularly on the femoral side, the use of a contoured fresh-frozen femoral head or metal augments may be considered, while bearing in mind that the size of the augment is limited to 15 mm when attached to the prosthesis. Type-3 defects generally require reconstruction with a tumour-type prosthesis, although a structural bulk allograft, a custom-made prosthesis or a trabecular metal cone may be appropriate. The combination of ligamentous instability and bone loss demands a constrained prosthesis. The use of a short, cemented stem is recommended when there is good cortical support or a well-supported augment. As the size of defect increases or the degree of support decreases, a longer stem should be used. In older patients, we prefer to use a narrow cemented stem, reserving the use of a press-fit stem for when the distal bone is of better quality. Traditionally, tumour prostheses and hinged prostheses have been cemented as they tend to be used in older patients.

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References

1. **No authors listed.** National Joint Registry. http://www.njrcentre.org.uk/ (date last accessed 12 June 2008).
2. **Kurtz S, Ong K, Lau E, Mowat F, Halpern M.** Projections of primary revision hip and knee arthroplasty in the United States from 2005 to 2030. *J Bone Joint Surg [Am]* 2007;89-A:780-5.
3. **Dixon T, Shaw M, Ebrahim S, Dieppe P.** Trends in hip and knee joint replacement: socioeconomic inequalities and projections of need. *Ann Rheum Dis* 2004;63:825-30.
4. **Mulhall KJ, Ghamrawi HM, Engh GA, et al.** Radiographic prediction of intraoperative bone loss in knee arthroplasty revision. *Clin Orthop* 2006;446:51-8.
5. **Nadaud MC, Fehring TK, Fehring K.** Underestimation of osteolysis in posterior stabilized total knee arthroplasty. *J Arthroplasty* 2004;19:110-15.
6. **Vyskocil P, Gerber C, Bamert P.** Radiolucent lines and component stability in knee arthroplasty: standard versus fluoroscopically-assisted radiographs. *J Bone Joint Surg [Br]* 1999;81-B:24-6.
7. **Miura H, Matsuda S, Okazaki K, et al.** Validity of an oblique posterior condylar radiographic view for revision total knee arthroplasty. *J Bone Joint Surg [Br]* 2005;87-B:1643-6.
8. **Engh GA, Ammeen DJ.** Classification and preoperative radiographic evaluation: knee. *Orthop Clin North Am* 1998;29:205-17.
9. **Engh G.** Bone defect classification. In: Engh GA, Rorabeck CH, eds. *Revision total knee arthroplasty.* Williams and Wilkins, 1997:63-120.
10. **Nelson CL, Lonner JH, Rand JA, Lotke PA.** Strategies of stem fixation and the role of supplemental bone graft in revision total knee arthroplasty. *J Bone Joint Surg [Am]* 2003;85-A(Suppl 1):52-7.
11. **Dennis DA.** Repairing minor bone defects: augmentation and autograft. *Orthopedics* 1998;21:1036-8.
12. **Brooks PJ, Walker PS, Scott RD.** Tibial component fixation in deficient tibial bone stock. *Clin Orthop* 1984;184:302-8.
13. **Saha S, Pal S.** Mechanical properties of bone cement: a review. *J Biomed Mater Res* 1984;18:435-62.
14. **Sierra RJ, Conney WP 4th, Pagnano MW, Trousdale RT, Rand JA.** Reoperations after 3200 revision TKAs: rate, etiology and lessons learned. *Clin Orthop* 2004;425:200-6.
15. **Elia EA, Lotke PA.** Results of revision total knee arthroplasty associated with significant bone loss. *Clin Orthop* 1991;271:114-21.
16. **Ritter MA, Keating EM, Faris PM.** Screw and cement fixation of large defects in total knee arthroplasty: a sequel. *J Arthroplasty* 1993;8:63-5.
17. **Lotke PA, Wong RY, Ecker ML.** The use of methylmethacrylate in primary total knee replacements with large tibial defects. *Clin Orthop* 1991;270:288-94.
18. **Brand MG, Daley RJ, Ewald FC, Scott RD.** Tibial tray augmentation with modular metal wedges for tibial bone stock deficiency. *Clin Orthop* 1989;248:71-9.
19. **Hockman DE, Ammeen D, Engh GA.** Augments and allografts in revision total knee arthroplasty: usage and outcome using one modular revision prosthesis. *J Arthroplasty* 2005;20:35-41.
20. **Rand JA.** Bone deficiency in total knee arthroplasty: use of metal wedge augmentation. *Clin Orthop* 1991;271:63-71.
21. **Cuckler JM.** Bone loss in total knee arthroplasty: graft augment and options. *J Arthroplasty* 2004;19(Suppl 1):56-8.
22. **Pour AE, Parvizi J, Slenker N, Purtill JJ, Sharkey PF.** Rotating hinged total knee replacement: use with caution. *J Bone Joint Surg [Am]* 2007;89-A:1735-41.
23. **Springer BD, Sim FH, Hanssen AD, Lewallen DG.** The modular segmental kinematic rotating hinge for nonneoplastic limb salvage. *Clin Orthop* 2004;421:181-7.
24. **Harrison RJ Jr, Thacker MM, Pitcher JD, Temple HT, Scully SP.** Distal femur replacement is useful in complex total knee arthroplasty revisions. *Clin Orthop* 2006;446:113-20.
25. **Buck BE, Malinin TI.** Human bone and tissue allografts: preparation and safety. *Clin Orthop* 1994;303:8-17.
26. **Delloye C, Cornu O, Druez V, Barbier O.** Bone allografts: what they can offer and what they cannot. *J Bone Joint Joint Surg [Br]* 2007;89-B:574-80.
27. **Scuderi GR, Insall JN, Haas SB, Becker-Fluegel MW, Windsor RE.** Inlay autogenic bone grafting of tibial defects in primary total knee arthroplasty. *Clin Orthop* 1989;248:93-7.
28. **Ries MD.** Impacted cancellous autograft for contained bone defects in total knee arthroplasty. *Am J Knee Surg* 1996;9:51-4.
29. **Watanabe W, Sato K, Itoi E.** Autologous bone grafting without screw fixation for tibial defects in total knee arthroplasty. *J Orthop Sci* 2001;6:481-6.
30. **Franceshina MJ, Swienckowski JJ.** Correction of varus deformity with tibial flip autograft technique in total knee arthroplasty. *J Arthroplasty* 1999;14:172-4.
31. **Nagumo A, Ishibashi Y, Tsuda E, Toh S.** A reversed tibial flip autograft technique for correcting over-valgus knee after high tibial closing-wedge osteotomy in total knee arthroplasty. *J Arthroplasty* 2006;21:771-4.
32. **Laskin RS.** Total knee arthroplasty in the presence of large bony defects of the tibia and marked knee instability. *Clin Orthop* 1989;248:66-70.
33. **Dorr LD.** Bone grafts for bone loss with total knee replacement. *Orthop Clin North Am* 1989;20:179-87.
34. **Zatsepin ST, Burdygin VN.** Replacement of the distal femur and proximal tibia with frozen allografts. *Clin Orthop* 1994;303:95-102.
35. **Dorr LD, Ranawat CS, Sculco TA, McKaskill B, Orisek BS.** Bone graft for tibial defects in total knee arthroplasty. *Clin Orthop* 1986;205:153-65.
36. **Tsahakis PJ, Beaver WB, Brick GW.** Technique and results of allograft reconstruction in revision total knee arthroplasty. *Clin Orthop* 1994;303:86-94.
37. **Clatworthy MG, Ballance J, Brick GW, Chandler HP, Gross AE.** The use of structural allograft for uncontained defects in revision total knee arthroplasty: a minimum five-year review. *J Bone Joint Surg [Am]* 2001;83-A:404-11.
38. **Ghazavi MT, Stockley I, Yee G, Davis A, Gross AE.** Reconstruction of massive bone defects with allograft in revision total knee arthroplasty. *J Bone Joint Surg [Am]* 1997;79-A:17-25.
39. **Backstein S, Safir O, Gross A.** Management of bone loss: structural grafts in revision total knee arthroplasty. *Clin Orthop* 2006;446:104-12.
40. **Parks NL, Engh GA.** Histology of nine structural bone grafts used in total knee arthroplasty. *Clin Orthop* 1997;345:17-23.
41. **Board TN, Rooney P, Kearney JN, Kay PR.** Impaction allografting in revision total hip replacement. *J Bone Joint Surg [Br]* 2006;88-B:852-7.
42. **Nelissen RG, Bauer TW, Weidenhielm LRA, LeGolvan DP, Mikhail WE.** Revision hip arthroplasty with the use of cement and impaction grafting: histological analysis of four cases. *J Bone Joint Surg [Am]* 1995;77-A:412-22.

43. Ullmark G, Linder L. Histology of the femur after cancellous impaction grafting using a Charnley prosthesis. *Arch Orthop Trauma Surg* 1998;117:170-2.

44. Schimmel JW, Buma P, Versleyen D, Huiskes R, Slooff TJ. Acetabular reconstruction with impacted morselized cancellous allografts in cemented hip arthroplasty: a histologic and biomechanical study on the goat. *J Arthroplasty* 1998;13:438-48.

45. Malkani AL, Voor MJ, Fee KA, Bates CS. Femoral component revision using impacted morsellised cancellous graft: a biomechanical study of implant stability. *J Bone Joint Surg [Br]* 1996;78-B:973-8.

46. Elting JJ, Mikhail WE, Zicat BA, et al. Preliminary report of impaction grafting for exchange femoral arthroplasty. *Clin Orthop* 1995;319:159-67.

47. Capello WN. Impaction grafting plus cement for femoral component fixation in revision hip arthroplasty. *Orthopedics* 1994;17:878-9.

48. Samuelson KM. Bone grafting and non-cemented revision arthroplasty of the knee. *Clin Orthop* 1988;226:93-101.

49. Whiteside LA. Cementless fixation in reconstruction of massive tibial bone loss in revision total knee arthroplasty. *Clin Orthop* 1989;248:80-6.

50. Whiteside LA. Cementless fixation in revision total knee arthroplasty. *Clin Orthop* 2006;446:140-8.

51. van Loon CJ, Buma P, De Waal Malefijt MC, van Kampen A, Veth RP. Morselized bone allografting in revision total knee replacement: a case report with a 4-year histological follow-up. *Acta Orthop Scand* 2000;71:98-101.

52. Toms AD, McClelland D, Chua L, et al. Mechanical testing of impaction bone grafting in the tibia: initial stability and design of the stem. *J Bone Joint Surg [Br]* 2005;87-B:656-63.

53. Lotke PA, Carolan GF, Puri N. Impaction grafting for bone defects in revision total knee arthroplasty. *Clin Orthop* 2006;446:99-103.

54. Bourne RB, Finlay JB. The influence of tibial component intramedullary stems and implant-cortex contact on the strain distribution of the proximal tibia following total knee arthroplasty: an in vitro study. *Clin Orthop* 1986;208:95-9.

55. Hofmann AA. Morselized allografting in revision TKA. *Orthopedics* 1999;22:877-8.

56. Bradley GW. Revision total knee arthroplasty by impaction bone grafting. *Clin Orthop* 2000;371:113-18.

57. van Loon CJ, de Waal Malefijt MC, Buma P, et al. Autologous morselised bone grafting restores uncontained femoral bone defects in knee arthroplasty: an in vivo study in horses. *J Bone Joint Surg [Br]* 2000;82-B:436-44.

58. Stern SH, Wills RD, Gilbert JL. The effect of tibial stem design on component micromotion in knee arthroplasty. *Clin Orthop* 1997;345:44-52.

59. Gie GA, Linder L, Ling RS, et al. Impacted cancellous allografts and cement for revision total hip arthroplasty. *J Bone Joint Surg [Br]* 1993;75-B:14-21.

60. Ullmark G, Hovelius L. Impacted morselised allograft and cement for revision total knee arthroplasty. *Acta Orthop Scand* 1996;67:10-12.

61. Haas SB, Insall JN, Montgomery W 3rd, Windsor RE. Revision total knee arthroplasty with use of modular components with stems inserted without cement. *J Bone Joint Surg [Am]* 1995;77-A:1700-7.

62. Rand JA, Ilstrup DM. Survivorship analysis of total knee arthroplasty: cumulative rates of survival of 9200 total knee arthroplasties. *J Bone Joint Surg [Am]* 1991;73-A:397-409.

63. Radnay CS, Scuderi GR. Management of bone loss: augments, cones, offset stems. *Clin Orthop* 2006;446:83-92.

64. Slooff TJ, Huiskes R, van Horn J, Lemmens AJ. Bone grafting in total hip replacement for acetabular protrusion. *Acta Orthop Scand* 1984;55:593-6.

65. Heyligers IC, van Haaren EH, Wuisman PI. Revision knee arthroplasty using impaction grafting and primary implants. *J Arthroplasty* 2001;16:533-7.

66. Lotke PA, Carolan GF, Puri N. Technique for impaction bone grafting of large bone defects in revision total knee arthroplasty. *J Arthroplasty* 2006;21(4 Suppl 1):57-60.

67. Mabry TM, Hanssen AD. The role of stems and augments for bone loss in revision knee arthroplasty. *J Arthroplasty* 2007;22(Suppl 1):56-60.

68. Nasser S, Poggie RA. Revision and salvage patella arthroplasty using a porous tantalum implant. *J Arthroplasty* 2004;19:562-72.

69. Nehme A, Lewallen DG, Hanssen AD. Modular porous metal augments for treatment of severe acetabular bone loss during revision hip arthroplasty. *Clin Orthop* 2004;429:201-8.

70. Bush JL, Wilson JB, Vail TP. Management of bone loss in revision total knee arthroplasty. *Clin Orthop* 2006;452:186-92.

71. Bobyn JD, Stackpool GJ, Hacking SA, Tanzer M, Krygier J. Characteristics of bone ingrowth and interface mechanics of a new porous tanatalum biomaterials. *J Bone Joint Surg [Br]* 1999;81-B:907-14.

72. Garbuz DS, Hu Y, Kim WY, et al. Enhanced gap filling and osteoconduction associated with alendronate-calcium phosphate-coated porous tantalum. *J Bone Joint Surg [Am]* 2008;90-A:1090-100.

73. Meneghini RM, Lewallen DG, Hanssen AD. Use of porous tantalum metaphyseal cones for severe tibial bone loss during revision total knee replacement. *J Bone Joint Surg [Am]* 2008;90-A:78-84.

74. Bragdon CR, Doherty AM, Rubash HE, et al. The efficacy of BMP-2 to induce bone ingrowth in a total hip replacement model. *Clin Orthop* 2003;417:50-61.

75. Barrack RL, Cook SD, Patrón LP, et al. Induction of bone ingrowth from acetabular defects to a porous surface with OP-1. *Clin Orthop* 2003;417:41-9.

76. Tägil M, Jeppsson C, Aspenberg P. Bone graft incorporation: effects of osteogenic protein-1 and impaction. *Clin Orthop* 2000;371:240-5.

77. Tägil M, Jeppsson C, Wang JS, Aspenberg P. No augmentation of morselized and impacted bone graft by OP-1 in a weight-bearing model. *Acta Orthop Scand* 2003;74:742-8.

78. Buma P, Arts JJ, Gardeniers JW, Verdonschot N, Schreurs BW. No effect of bone morphogenetic protein-7 (OP-1) on the incorporation of impacted bone grafts in a realistic acetabular model. *J Biomed Mater Res B Appl Biomater* 2007:231-9.

79. Kuiper JH, Merry JC, Cheah K, Richardson JB. Graft composition influences early mechanical stability in impaction grafting. *Trans EORS* 1996;6:45.

80. Brewster NT, Gillespie WJ, Howie CR, et al. Mechanical considerations in impaction bone grafting. *J Bone Joint Surg [Br]* 1999;81-B:118-24.

81. Bolder SB, Verdonschot N, Schreurs BW, Buma P. The initial stability of cemented acetabular cups can be augmented by mixing morsellized bone grafts with tricalciumphosphate/hydroxyapatite particles in bone impaction grafting. *J Arthroplasty* 2003;18:1056-63.

82. van Haaren EH, Smit TH, Phipps K, et al. Tricalcium-phosphate and hydroxyapatite bone-graft extender for use in impaction grafting revision surgery: an in vitro study on human femora. *J Bone Joint Surg [Br]* 2005;87-B:267-71.

83. Arts JJ, Gardeniers JW, Welten ML, et al. No negative effects of bone impaction grafting with bone and ceramic mixtures. *Clin Orthop* 2005;438:239-47.