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This information is current as of August 19, 2006

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**Publisher Information**
The Journal of Bone and Joint Surgery
20 Pickering Street, Needham, MA 02492-3157
[www.jbjs.org](http://www.jbjs.org)
CURRENT CONCEPTS REVIEW

Impaction Bone-Grafting in Revision Joint Replacement Surgery

By Andrew D. Toms, MBChB, FRCS(Ed), MSc, FRCS(Tr+Orth), Ross L. Barker, FRCS, Richard Spencer Jones, MB, BS, FRCS, FRCS(Tr+Orth), and Jan Herman Kuiper, PhD

Investigation performed at the Robert Jones and Agnes Hunt Orthopaedic Hospital, Oswestry, Shropshire, England

The standard graft material for impaction bone-grafting is fresh-frozen femoral head allograft morselized to a particle size as large as is practical to ensure stability and allow new bone formation.

The graft must be sufficiently compacted to provide immediate mechanical stability; this requires containment of the graft and substantial impaction energy.

Diaphyseal bone fracture and excessive implant migration are the most common complications of the operation.

Impaction bone-grafting in revision total hip replacement has produced good medium-term results on both the acetabular and the femoral side.

The use of compacted morselized bone graft is a relatively new technique in revision knee surgery and requires longer-term follow-up with larger numbers of patients to assess its value.

Patients undergoing total joint replacement today tend to be younger and more active and to have higher expectations than the patients treated in the past, on whom the current ten to fifteen-year results are based. These younger patients are likely to live longer and place higher demands on their joint replacements. Ideally, an implant will function at an optimal level throughout the life of the patient. However, both total knee and total hip replacements have limitations and do not survive indefinitely. Some patients may require two or more revisions during their lifetime.

As implants fail, host bone is lost as a result of a combination of stress-shielding, osteolysis, instability, implant failure, and/or infection. This problem may be compounded by bone lost during removal of the failed implants. Substantial bone loss and bone defects are among the most challenging problems faced by surgeons performing revision surgery. Various techniques are available for dealing with bone loss, including filling with cement and use of modular metal augments in the knee, long-stemmed replacements in the hip, modular endoprostheses, and custom-made implants. However, it is important, particularly in a younger patient, to minimize bone loss and to try to restore bone stock. Of the many methods of reconstruction available to the surgeon performing a revision, only two techniques have the aim of reconstructing the bone stock: impaction bone-grafting and the use of structural allograft.

The objective of impaction bone-grafting is to achieve stability of an implant with the use of compacted, morselized bone graft and subsequently to allow the restoration of living bone stock by bone ingrowth. This is an attractive option, and the aim of restoring the bone stock to a condition close to what was present during the primary arthroplasty may be achievable. There is, however, a complex balance between the mechanical demands of achieving initial stability and the biology of long-term incorporation.

The outcome following revision arthroplasty has always been substantially worse than that after primary arthroplasty. Following removal of the primary implant, there is a fibrocellular membrane and a relatively smooth endosteal surface, and this causes a poor micro-interlock between bone and cement and results in early loosening. Impaction bone-grafting addresses this problem, which may in part account for some of the improvement in outcomes that has been observed with this technique.

Impaction bone-grafting in the acetabulum and the proximal part of the femur is a well-established technique, and it has recently been shown to provide both initial stability and longer-term restoration of bone stock in the distal part of the femur. The results of impaction bone-grafting in the proximal part of the tibia, which is more commonly affected by bone loss in total knee replacement, are difficult to interpret, and it has been suggested that initial stability, which is essen-
ential for both the short-term survival of the tibial implant and the long-term incorporation of the graft, cannot be achieved. In this article, we will review the literature regarding the biomechanical and biological characteristics of compacted morselized graft and examine the clinical results of the technique and its future development.

**History of Impaction Bone-Grafting**

In 1975, Hastings and Parker described a method similar to impaction bone-grafting to overcome the bone loss seen in patients with protrusio acetabuli secondary to rheumatoid arthritis. Three years later, McCollum and Nunley showed the potential of morselized allograft to treat bone-stock deficiency in protrusio acetabuli. In 1983, Roffman et al. reported the survival of bone chips under a layer of bone cement in a study of animals. The graft appeared viable, and new bone formed along the cement interface. Mendes et al. further developed the technique for use in primary hip arthroplasty with cement by reinforcing protrusio acetabuli with bone chips and mesh. Eight patients were followed for up to six years. There were no revisions, and histological examination confirmed bone-graft incorporation. In 1984, Slooff et al. modified the technique and described it as impaction bone-grafting. The defect was contained by mesh, and then bone graft was tightly packed before an acetabular cup was inserted into pressurized cement. Slooff et al. standardized the technique and developed special instrumentation. Impaction bone-grafting of the proximal part of the femur was initially developed by Ling et al. in 1991 and reported by Gie et al. in 1993. The efficacy of both of these techniques has been extensively supported by results from animal studies as well as histological, radiographic, and biomechanical studies.

The use of morselized bone graft in conjunction with total knee replacement was first described in 1988. The graft was morselized but not compacted and was bypassed by a long uncemented press-fit stem. In 1989, a similar technique was described and good graft incorporation and stable fixation were reported. This technique is different from the Slooff-Ling concept of impaction bone-grafting in the hip, in which the implant is cemented into and completely surrounded by compacted, morselized bone graft. Impaction bone-grafting for knee revision with a method consistent with the Slooff-Ling technique was first reported by Ullmark and Hovielius in 1996. They described a technique using a short-stemmed primary implant that was entirely surrounded by cement and compacted, morselized bone graft. Since then, a number of other stem configurations have been reported. The supporting evidence for these different techniques is largely based on small studies with short-term follow-up. The literature is inconclusive regarding the longer-term results of using morselized bone graft in the knee.

**Technical Aspects**

**Planning**

Revision arthroplasty requires thorough clinical and radiographic evaluation. Care must be taken to determine the degree of bone loss, the quality of the remaining bone, the presence of cortical continuity (containment), and the absence of infection. Biplanar views are essential; computed tomography and magnetic resonance imaging may at times be of value, particularly when there is massive bone loss or disruption of the normal anatomy. In general, even after ancillary studies have been reviewed, the bone loss tends to be greater and the bone quality tends to be worse than initially predicted. Careful preoperative assessment allows the selection and availability of appropriate implants and graft.

**Defect Classification**

The American Academy of Orthopaedic Surgeons (AAOS) classification (Table I) for the acetabulum and proximal part of the femur is based on the common patterns of component failure and is thus useful in terms of defect description and allows broad comparisons of results for a given type of defect. There is no evidence of its value with regard to predicting the survival of revision implants. The most commonly used classification for knee defects is the Anderson Orthopaedic Research Institute (AORI) system, which divides defects into three main categories, with F denoting the femur and T denoting the tibia (Table I).

**Graft Preparation**

**Material**

The original technique of impaction bone-grafting described by Slooff et al. involved use of morselized cancellous bone. The argument for using cancellous bone as the base material was that the open structure of cancellous bone would allow more rapid angiogenesis and that the apposition of cancellous trabeculae would enhance osteoclast-driven remodeling. The validity of this argument has been questioned; although cortical allograft might weaken during the resorption phase, it will still remain stronger than cancellous graft. In a clinical study of fifty patients treated with femoral revision with use of impaction bone-grafting, morselized cortical allograft was compared with morselized cancellous allograft. The cortical allograft provided better results in terms of clinical outcome, including thigh pain, and stem subsidence. However, this was a nonrandomized study with short-term follow-up, and the results warrant further investigation.

Several investigators have tried to optimize the mechanical performance of morselized bone graft under compaction by manipulating the particle size and the range of sizes (the grade) as well as by supplementing it with particles of other materials that are stronger and stiffer than bone. Kuiper et al. compared the early mechanical stability of various graft mixes, including human bone, bovine bone (which is stronger and stiffer), and human bone supplemented with hydroxyapatite. The mixes were further subdivided on the basis of particle size. A combination of relatively large particles (>2 mm) and a strong base material (e.g., bovine bone) achieved better mechanical stability. Addition of hydroxyapatite particles improved the particle-size distribution and strength of the human bone mix, but its effect on the biology is currently unknown.
Other investigators have confirmed that adding stronger or stiffer particles (such as ceramic particles or cortical bone) to the morselized bone improves the mechanical stability. The main questions pertaining to alternative materials are therefore not mechanical but biological.

**Morselization**

The size and grade of the bone particles is important to the early mechanical stability of the compacted morselized graft. The general consensus is that particles should be as large as practical to ensure stability—i.e., they should be the largest size that can be fitted between the host cortical bone and the tamp used to compact the morselized bone. That size is thought to be between 3 and 5 mm in diameter for proximal femoral revision. On the acetabular side, the ideal size is larger; research suggests that 8 to 10-mm-diameter chips provide the best initial stability. Another advantage of larger particles is that they result in a more porous and more permeable compacted graft. This is important because reduced porosity may make it more difficult for new bone to grow into the compacted mass. A study comparing bone ingrowth into noncompacted and compacted bone showed that increasing compaction reduces ingrowth. Furthermore, a comparison of bone ingrowth into compacted material with a not-ideal-grade particle-size distribution (an ideal distribution ensures, at each level, that voids between larger particles are open and not filled with smaller particles) with that in an ideal-grade particle mix showed increased ingrowth into the not-ideal-grade graft. In addition, larger voids facilitate cement penetration, which may contribute to improved initial mechanical stability.

Allograft bone is most commonly morselized by hand, to produce so-called croutons, or with commercially available bone mills. Most currently available mills produce particles close to the ideal size for proximal femoral revision (3 to 5 mm in diameter); however, bone-nibblers produce a better size of graft for the acetabular side.

Implants supported by compacted morselized bone graft can migrate as a result of shear within the layers of the compacted graft. Shear strength of the graft layer is improved by using morselized graft with a range of particle sizes, which cannot be produced with commercially available mills. However, using a range of particle sizes reduces graft permeability, since the pores between the larger particles will be filled with smaller particles. As argued above, a reduction in permeability may reduce bone ingrowth, but this can be offset by the improved mechanical resistance to shear. More work is needed to clarify the interaction between these mechanical and biological factors.

**Rinsing**

Fluid plays an important role in compaction. In soil, the moisture content is optimum for compaction when there is enough moisture to lubricate the particles, facilitating relative movement, but not so much that pressures develop in the fluid and keep the particles apart. One of the mechanical...
The strength of the graft may be enhanced by rinsing, which further improves implant stability by improving the shear resistance of graft compaction, plastic deformation and intergranular motion achieved by repetitive vigorous impaction. During the process of graft compaction, plastic deformation and intergranular motion occur, leading to denser packing and a permanent decrease in volume. Only following compaction is the morselized cancellous graft strong enough to carry the load imposed by the patient. In vitro studies have confirmed the importance of compaction: the migration distance of hip stems and tibial trays associated with impaction grafts can be largely predicted from the density of the compacted graft—i.e., the degree of compaction achieved. The degree of compaction is mainly influenced by the impaction vigor (the energy applied per impact) and the number of cycles. Gie et al., in their original paper on impaction grafting in the femur, recommended “vigorous impaction” and commented on the impressive stability that can be achieved with such a technique. Although more vigorous impaction creates a more compacted graft bed with improved resistance to mechanical loading, it also has a downside. Studies have shown intraoperative fracture of the femur to be the most common complication of the technique. The impaction energy required for the graft bed to achieve sufficient weight-bearing capacity is determined not only by the impaction vigor and the number of blows, but also by the material properties of the graft, the particle size and grading and the fat content. Using stronger and stiffer material, larger particles, and better grading and removing fat are all strategies that surgeons could employ to reduce the impaction effort and the probability of intraoperative fracture.

**Prosthetic Selection**

Confined compression tests of compacted morselized bone chips have suggested that morselized bone graft would be subject to ongoing postoperative deformation. As a consequence of this, it was thought that a suitable prosthesis should be able to accommodate both recoverable and permanent deformation in the graft. The nature of compacted bone graft makes some additional packing of the graft after cyclical loading inevitable. This was shown in a cadaver study in which the mean subsidence was 0.27 mm for 5000 cycles with use of a servohydraulic test frame. Animal experiments have confirmed that early implant stability in the proximal part of the femur is mainly an effect of surgical technique. Use of a double-tapered polished stem in the proximal part of the femur (as advocated by the originators of the technique) appears to be suitable as such a stem can achieve secondary stability after subsidence. However, this is now an area of debate, and good results have been obtained with use of other stem designs, as will be described below. There are no clear data on which to base a choice for a particular implant for the acetabulum or knee.

**Cemented Compared with Uncemented Prostheses**

An in vitro study of goat femora showed that a cemented femoral stem is more stable in conjunction with impaction bone-grafting than an uncemented stem. It was hypothesized that this was due to penetration of the cement into the graft forming a construct with better mechanical properties. Another study supported the use of cement in combination with morselized graft, but the authors concluded that, although cement penetration into the graft could be improved with increased cement pressurization, this had no effect on the fixation strength of the revision.

**Rehabilitation**

Postoperative weight-bearing is controversial; the argument for delaying weight-bearing is based mainly on poorly supported mechanical considerations. Some authors have advocated immediate weight-bearing, and have included it in their treatment protocols, on the grounds that if there is going to be subsidence it is probably better for it to occur before osseointegration is under way. If weight-bearing is delayed until incorporation has occurred, patients may have to be restricted for up to thirty-two months. A comparison of cup migration following unrestricted and restricted weight-bearing showed that implants in patients who were allowed unrestricted weight-bearing settled into their final position faster. The implants did not, however, migrate more. In addition, the patients who were allowed unrestricted weight-bearing were more satisfied.

**Experimental Findings**

**Biomechanics**

The scientific basis and engineering aspects of impaction bone-grafting are poorly understood. This is confirmed by the incorrect use of the term *impaction*, which refers to one body...
coming forcibly into contact with another and not to the process in impaction bone-grafting, which is actually compaction. The term impaction bone-grafting should really only be used to describe the Sloop-Ling technique; the process itself is actually compaction of morselized bone graft. Structurally, the use of bone graft in this way can be studied with utilization of soil mechanics and compaction mechanics. The graft itself can be described as a particulate material and, more specifically, as a friable agglomerate or aggregate

Even within the engineering sciences, compaction and the behavior of particulate materials under relatively simple stress states are not well understood

Combine this with the degree of viscoelasticity and plasticity exhibited by bone, and a situation arises in which the ability to apply scientific knowledge is limited.

In purely mechanical terms, short-term initial stability should be achievable in a predictable fashion with the use of an ideal graft mix that has been defatted and is optimally compacted and cemented in situ. Unfortunately, these parameters are not all clearly defined; they all interact and, as already discussed, they also affect the biology and long-term incorporation of the graft.

Biology

The medium to long-term results depend on the biological interaction between the graft and the host bone. If the reported benefit of impaction bone-grafting—i.e., reconstitution of bone stock—is to be realized, then some or all of the graft bone must be replaced with new host bone. This is clearly a biological process, although it depends on a certain degree of mechanical stability.

One of the earliest reports providing insight into the biology of impaction bone grafts was a case study of the histological findings in a femur retrieved 3.5 years after morselized, compacted allograft had been used to fill two large cortical defects during a revision

The histological evaluation showed that the allograft chips had been largely replaced with living cortical bone over >90% of the total surface area of the sections studied. Importantly, the cement-tissue interface resembled that seen after primary arthroplasty, with some direct osteoid-cement contact and areas of foreign-body giant-cell reaction.

The allograft used in impaction bone-grafting is nonvascularized; it is therefore unclear how successful incorporation is achieved

Bone ingrowth may be encouraged by three main mechanisms:

1. Osteoinduction. Morselization increases the surface area and may release important growth factors.
2. Osteoconduction. The compacted graft acts as a scaffold.
3. Mechanical loading. This produces deformation that stimulates bone formation.

In reality, an interaction between important biological factors and important mechanical factors determines the effectiveness of the host-graft union

Biological factors include the quality of the bone graft, its post-harvesting treatment, and the vascularity of the host cavity. Mechanical stability is probably the most important factor, in conjunction with the mechanical strain experienced by the graft. Therefore, the avoidance of stress-shielding combined with early weight-bearing should enable faster graft incorporation. Evidence for this was provided by a study on the effects of mechanical loading on compacted morselized graft in rabbit tibia

In that study, the loaded graft showed more new bone ingrowth than did graft that was not loaded. The authors concluded that the ability of compacted bone graft to allow mechanical stimulation of new bone formation was the principal reason for the success of this technique. The assertion that early and physiological loading is important for active graft incorporation was further supported by a study of goats

That study showed that the amount of bone graft that became incorporated was greater in the loaded group than it was in the nonloaded group. Despite these results, the need to load allograft and by how much is still controversial. Autograft packed into simple cysts in children unites without problems, but often the graft remains unloaded. It might be that allograft needs the initial stimulus of uniform loading to encourage vascularity. In contrast, the earliest studies on morselized bone-grafting in revision knee surgery involved use of long, uncemented interference-fit stems, which transfer the load distal to the graft; yet excellent graft incorporation was seen

Long stems have been shown to unload the graft by as much as 38%

Maybe ingrowth would be more predictable and would occur faster if short stems were used. Only longer-term, large clinical trials can demonstrate if there is a benefit from increasing load transfer to the graft.

Bone morphogenetic proteins (BMPs) could enhance the osteogenic properties of bone. Recent studies of a canine model of hip replacement suggested that BMPs (in particular OP-1 and rhBMP-2) can enhance bone ingrowth into bone defects behind acetabular cups

Perhaps more relevant for impaction bone-grafting is a rabbit bone chamber study that demonstrated the potential of OP-1 to compensate for the delaying effect of graft compaction on bone ingrowth

However, the same investigators did not find a beneficial effect of OP-1 once the compacted graft was actively loaded by the walking animal

Fibrous tissue ingrowth may provide adequate stability, suggesting that complete osseous remodeling might not be necessary for a good clinical result

This hypothesis has been supported by retrieval studies indicating that complete graft incorporation was not a prerequisite for clinical success if the resulting construct provided mechanical stability

An observational study of stable implants showed remodeling and graft incorporation, and the authors concluded that a stable construct could be provided by fibrous tissue ingrowth in areas of unincorporated graft

The hypothesis that osseointegration does occur is supported by histological evidence confirming the process of incorporation

A goat model has also been used to analyze the histological findings at set intervals after impaction bone-grafting

At three weeks, the histological analysis showed changes of active bone-remodeling and revascularization, progressing to incorporation of two-thirds of the graft at six weeks. The twelve-week specimens showed almost total graft
incorporation, with the graft mostly being replaced with normal viable bone in the revascularized areas. Complete consolidation and revascularization of the graft were observed in all specimens at twenty-four and forty-eight weeks.

On the acetabular side, the histological changes have been likened to fracture-healing. A study of samples taken after twenty-one revision arthroplasties with impaction bone-grafting revealed a process of endochondral ossification in the graft bed. Clearly, there is still controversy about both the nature and the need for graft incorporation. It may be that fibrous ingrowth can provide an acceptable degree of stability in the long term if full osseointegration does not occur.

**Clinical Results**

**Hip**

**Acetabulum (see Appendix)**

Professor Slooff and the Nijmegen unit have been pioneers in the area of the acetabulum. In their experience with fifty-six patients who underwent acetabular revision between 1979 and 1986, only five had required repeat revision at the time of follow-up, at an average of 11.8 years. The defect was type II in thirty-seven hips and type III in twenty-three. The failures were due to septic loosening in two hips and aseptic loosening in three. Progressive radiolucent lines were noted in an additional three hips that were asymptomatic. Overall, the survival rate, with aseptic loosening as the end point, was 94% at 11.8 years. In addition, these authors reported the results for forty-two patients who underwent impaction bone-grafting (performed during a revision in nineteen) when they were under the age of twenty. Four years, but the authors recommended caution when using this procedure in detail, but emphasized that it is highly technique-dependent. Clinical follow-up with use of hip scores is widespread and may well be appropriate, although it has not yet been validated in this specific area of impact bone-grafting. Radiographic assessment is difficult and may well be unreliable for the evaluation of graft incorporation and remodeling. Although there is no doubt about the importance of massive migration, it is not clear whether minor subsidence is a sign of future problems. Similarly, the presence of radiolucent lines has been universally reported, but their implications for the survival of an individual implant is unclear. The only clear clinical recommendation to enhance long-term survival is to create a situation where the load from the cup is transmitted directly to the graft.

**Femur (see Appendix)**

The Exeter group reported their short-term results (at eighteen to forty-nine months) after the use of fifty-six stems. There were two intraoperative fractures and three dislocations but no repeat revisions due to aseptic loosening. Radiographic analysis of thirteen stems followed for more than three years revealed that 71% of the zones showed no radiolucency. Trabecular remodeling was reported as being frequently visible, although the authors commented that the relevance of the radiographic changes are uncertain. In one study of 226 hips followed for a minimum of five years, the survival rate, with a femoral reoperation due to symptomatic aseptic loosening as the end point, was 99% at ten years. Of the twelve hips that underwent another surgical procedure because of aseptic failure, ten (4% of the total cohort) had the operation because of a femoral fracture. This finding prompted the authors to recommend the use of a longer stem in hips with substantial compromise of the bone stock around the tip of a primary stem. Mid-term studies at two other centers in which the Exeter stem and technique were used also demonstrated good outcomes. In one of those studies, in which twenty-one hips were followed for an average of five years, no repeat revisions had been done during the follow-up period, although four stems showed massive subsidence. In the other study, eighty-seven hips had been followed for an average of 3.6 years after revision, and the rate of repeat revision was 3.5% (three hips) and the rate of subsidence of >5 mm was 2.5% (two hips). The authors mentioned patient selection and the experience of the operating surgeon as the keys to success.

The originators of the technique maintain that part of the success of impaction bone-grafting is due to the Exeter stem’s design, which allows it to engage and consequently maintain radial loading of the cement and graft. However, success has also been reported with other designs. In one study of thirty-one hips treated with another double-tapered polished stem, the authors concluded that impaction bone-grafting was a successful way of dealing with femoral bone loss. At the time of follow-up, at an average of thirty-one months, the modified Harris hip score had improved by 45 points, the rate of patient satisfaction was 97%, the technique-related fracture rate was 16% (five hips), and the subsidence rate was approximately 50% (fifteen hips, with ten stems subsiding <5 mm, four subsiding 6 to 8 mm, and one subsiding >10 mm). The subsidence noted with collarless, polished, tapered designs has been mentioned as a potential cause of postoperative pain, dislocation, and failure.

Other investigators have therefore used stems with features to minimize subsidence, such as a matte finish or a collar. In one such study, fifty-eight hips treated with a Charnley stem were followed for an average of 56.7 months, at which...
time the rate of repeat revision was 3.5% (two of fifty-seven)⁸⁹. Ullmark et al. compared the results in fifty-seven hips that had been treated with impaction bone-grafting and either a Lubinus or a Charnley prosthesis. The results in the two groups were similar, with a rate of mechanical failure of 4% at sixty-four months, but the hips with the Lubinus prosthesis showed better trabecular remodeling⁹⁰. One of the largest studies consisted of a cohort of 181 cemented revisions performed with a Charnley Elite stem and impaction bone-grafting⁹¹. The overall prosthetic survival rate was 97.2% at four years. In another series, of twenty-nine revisions performed with a stem with a calcar-bearing design, the survival rate, with aseptic loosening as the end point, was 92% at six years⁹². This study revealed a high intraoperative and postoperative fracture rate of 21% (six of the twenty-nine patients).

Femoral fracture and subsidence are frequently reported as the most common serious complications of femoral impaction bone-grafting. The fracture rate has been highlighted as a concern in a number of studies⁹³⁹⁴. In one large series of 108 femora in which a stem had been implanted, the intraoperative fracture rate was 27% (twenty-nine) and the postoperative periprosthetic fracture rate was 15% (sixteen)⁹⁵. This complication is probably at least in part a reflection of the deficient femoral bone stock that made impaction bone-grafting the treatment of choice in these patients. To reduce the risk of femoral fracture, a longer stem bypassing the defect or extramedullary augmentation of the femur with a strut graft or plate has been suggested⁹⁶. Recent work in our biomechanics laboratory showed that, compared with a standard stem, a long stem reduces strain at a cortical defect by 31% and a strut graft or plate reduces it by approximately 50%⁹⁷.

With regard to subsidence, the nature of compacted bone graft makes some additional packing of the graft during cyclic loading inevitable. One particular question is whether subsidence of a polished double-tapered stem could be beneficial. Subsidence inside the cement mantle might cause the mantle to expand radially, inducing radial stresses in the compacted bone graft that could stimulate graft-remodeling. In a prospective, randomized study of twenty-four patients, a comparison of migration of Exeter and Charnley Elite stems was performed with radiostereometric analysis⁹⁸. These stems differ fundamentally in geometry and in the way that they load the bone cement. The Exeter stems migrated an average of 1.3 mm in the first year, whereas the Charnley Elite stems migrated an average of 0.2 mm. The Exeter stems continued to subside in the second year, by an additional 0.42 mm, but the Charnley stems did not. The authors detected no relationship between the amount of subsidence of either stem and the radiographic appearance of the proximal part of the femur. No additional effect of the subsidence of the Exeter stem on the remodeling process was seen on radiographs. The authors concluded that radial compression of the cement produced by a double-tapered design such as the Exeter stem is not the essential stimulus for bone-remodeling. The frequency of massive subsidence (>10 mm) was as high as 11% in one series, of seventy-nine revisions with impaction bone-grafting⁹⁹. However, early massive subsidence may be due to a failure to attain initial stability and has been associated with malalignment of the stem.

Overall, the clinical results of impaction bone-grafting in the femur have been good, but there have been large variations between different centers. Stem selection is an unresolved issue; however, minor subsidence appears to be unimportant with respect to the long-term survival of the implant and the remodeling of the graft.

Knee

It should not be assumed that the technique of impaction bone-grafting used in the hip achieves the same results in the knee, as the biomechanics of the knee are very different. Even within the knee, a distinction should be made between the tibia and the femur, in which different patterns of bone loss occur and different loading conditions exist. The aim of revision surgery is to address the failure mechanism, producing a stable platform with good load transfer to the underlying bone, while relieving pain, maintaining the joint line, and restoring function⁹⁰. Failures of total knee replacements occur most commonly on the tibial side. This is thought to be due to compressive failure of trabecular support⁹¹, resulting from the effects of stress-shielding. It has been clearly shown that stress-shielding of the proximal part of the tibia results from the metal-backed tibial tray and stem reducing the maximum compressive stress on the underlying bone by 16% to 39%, depending on the loading conditions⁹²⁹³. Bone loss does not only occur as a result of failure; it may also result from the primary condition or occur at the time of the primary arthroplasty because of excessive resection or technical error. Older implant designs, particularly hinged knee prostheses, required larger bone cuts and had longer stems, automatically creating a situation of both cortical and cancellous loss. Revision surgery may exacerbate any bone loss, and great care is required when freeing the failed prosthesis, with the posterior femoral condyles being particularly at risk.

The clinical results of revision surgery are difficult to interpret⁹⁴⁹⁵. Published reports have often grouped different failure modes and patient groups together, and thus results have ranged from an 89% rate of good outcomes⁹⁶ to a 30% rate of successful outcomes⁹⁷ and complication rates have been as high as 30%⁹⁸. However, results are improved by the use of revision-specific systems⁹⁹.

The published experience with impaction bone-grafting in revision knee surgery is limited. The use of morselized bone graft has been variable in terms of patient selection, technique, and results. Reports have been mainly clinical, with small numbers of patients and only short-term follow-up⁹⁶. It is thus necessary to analyze the literature carefully. Three main techniques for using morselized bone graft in the knee have emerged: (1) use of short stems surrounded by graft and cement; (2) use of diaphyseal fluted stems, which bypass the graft and engage the cortex; and (3) use of long thin stems surrounded by graft and/or cement but not engaging the diaphysis.

Early descriptions of the use of morselized bone graft in
revision knee surgery did not include compaction of the bone, and long uncemented press-fit stems were used\textsuperscript{20,21,101}. These studies demonstrated radiographic evidence of graft-remodeling without clinical failure or instability. Subsequent histological evidence confirmed union and active bone formation even though the graft had been bypassed by a long stem\textsuperscript{102}. As discussed earlier, the presence of a long stem engaging the distal cortex decreases the loading of the graft by up to 38\%\textsuperscript{103}. There is also substantial experimental evidence from in vivo studies showing that graft incorporation can be improved by increased loading and that, surprisingly, longer stems may actually increase the toggling or tilting motion of the implant\textsuperscript{104}. In a recent report of the two-year results in thirty-three patients who had undergone insertion of diaphyseal fit stems with morselized bone-grafting and compaction of the graft, there were no failures and remodeling and incorporation were noted on radiographic evaluation\textsuperscript{22}. Although compaction was used, the authors stated that the graft was not employed in a manner to support the implants structurally and the graft was therefore bypassed with distal stem fixation. In all of the above examples, surgeons used long press-fit stems because of concern about the unpredictable initial stability when morselized bone graft was utilized. Unfortunately, this practice reduces one of the major advantages of morselized bone grafts—i.e., early incorporation compared with large structural grafts. These reports establish the place of morselized bone graft as a biological and practical solution capable of achieving good results in the knee, but the techniques that were used failed to emulate the essential experience in the hip, which is that graft alone, when sufficiently compacted, can achieve a stable bed for an implant without the use of a bypassing stem. The use of morselized bone graft in conjunction with a short-stemmed primary implant was first described in 1996\textsuperscript{26}. Good results were reported for three patients who had been followed for eighteen to twenty-eight months. At the Nijmegen unit, a four-year histological follow-up was carried out for a single patient in whom both the femur (type-FIIB defect) and the tibia (type-TIIB defect) had been treated with the modified Slooff-Ling technique—i.e., with a stem surrounded by graft and cement\textsuperscript{105}. The histological analysis showed good graft incorporation in the femur, but approximately three-quarters of the graft on the tibial side was not incorporated and the central portion of the tibial graft was necrotic. The authors discouraged the use of the technique in the tibia but recommended it as a promising method in the femur. They concluded that impaction bone-grafting in the tibia could not provide enough initial stability and that this had led to a relatively unstable situation and hence to poor graft incorporation. Recent work at our biomechanics laboratory showed that sufficient initial stability is attainable on the tibial side by using specifically developed impaction bone-grafting instrumentation\textsuperscript{106}. Short-stemmed implants with no cortical support were tested under maximal physiological loads, and levels of stability equivalent to those reported for primary total knee replacements were found\textsuperscript{107}. Failures on the tibial side may therefore reflect inadequate biology (a sclerotic, poorly vascularized bone bed) or inadequate graft compaction (a failure of technique or instrumentation) or an interaction between the two. Since 1999, the Nijmegen unit has performed additional studies of morselized bone-grafting for distal femoral defects. These include a review of the current status of management of femoral bone loss\textsuperscript{108}, a mechanical study of human cadaveric knees\textsuperscript{109}, an in vivo study of horses\textsuperscript{110}, and a short-term clinical study\textsuperscript{111}. The findings in the mechanical study supported the concept that morselized bone graft, even in an uncontaminated situation, improved the structural resistance against loading on the femoral side. The in vivo study confirmed that the technique was biomechanically sound, with complete graft incorporation by six months\textsuperscript{112}. Clinical results were good, and the authors advocated the use of impaction bone-grafting, in combination with total knee arthroplasty with cement, for small-to-medium contained and uncontained distal femoral bone defects.

To our knowledge, the largest clinical study in which primary implants with short stems were used in conjunction with morselized compacted bone graft included nine patients (eleven knees) followed for an average of twenty-three months\textsuperscript{113}. Of the eleven knees, one had a TI tibial defect; five, TIIA; four, TIIB; and one, FIIB. The initial results were promising, with no subsidence, radioluencies, or graft resorption. However, only four patients were allowed full weight-bearing postoperatively; five were treated with cast immobilization for six weeks to three months. The authors of two recent publications used the third concept of stem fixation—i.e., long thin stems\textsuperscript{114,115}. Both reports emphasized the use of mesh for containment and commented on the need for formal instrumentation, which has proved to be important for the acetabulum and the proximal part of the femur and is now starting to become available for the knee. In the first report, eight patients had no failures at two years\textsuperscript{116}. It is important to note that these patients had substantial bone defects, all of which were classified as FIIB, FIII, TIIB, or TIII. The authors also emphasized that this is a technically difficult procedure that is both time-consuming and labor-intensive. In the second study, in which the results of seventeen revisions were reviewed at an average of seventeen months (range, six to forty months), tibial radioluencies were seen in three cases, there was one supracondylar femoral fracture, and there was one infection\textsuperscript{117}. This study again supports the assertion that compacted morselized bone graft can be used for load-bearing in knees with severe bone loss. **Overview**

Total joint replacement has been established to have a high success rate, particularly in elderly and low-demand patients. As a result, there has been a move toward operating on a wider population, some of whom will demand more from their implants. All implants to date have had a finite useful life, and bone loss is associated with all of the major causes of failure. The numbers of patients requiring complex revision surgery can be expected to mirror the current increase in the numbers of primary procedures. Bone loss will continue to be the ma-

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\textsuperscript{102} Slooff-Ling technique

\textsuperscript{107} An in vivo study of horses

\textsuperscript{110} Clinical results were good, and the authors advocated the use of impaction bone-grafting, in combination with total knee arthroplasty with cement, for small-to-medium contained and uncontained distal femoral bone defects.

\textsuperscript{112}Clinical results were good, and the authors advocated the use of impaction bone-grafting, in combination with total knee arthroplasty with cement, for small-to-medium contained and uncontained distal femoral bone defects.

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\textsuperscript{117} This study again supports the assertion that compacted morselized bone graft can be used for load-bearing in knees with severe bone loss.
Impaction bone-grafting is a useful technique for dealing with bone loss. The main advantage is long-term reconstitution of bone stock, with obvious implications for any subsequent surgery. The technique allows the surgeon to fashion the graft to the defect at the time of surgery. The addition of cortical support in the form of meshes, strut grafts, and plates makes the technique applicable to a range of revision scenarios involving various degrees of bone-stock deficiency. Once the bone stock has been reconstituted, the remainder of the procedure is performed with standard implants and current cementing techniques. Load transfer between the implant and bone is likely to be more physiological with use of these standard stems than it is with the more complex revision stem designs.

The procedure is technically demanding; time-consuming; and, like all revision surgery, is associated with a high complication rate. As such, it requires special equipment and training. Results from different centers using the same equipment and prostheses and with comparable patient groups have varied substantially, as illustrated above. Although good medium-term results have been reported after these procedures in the hip, many questions remain unanswered at the present time.

The use of bone graft to reconstitute deficient bone stock may be the main attraction of compacted bone-grafting, but at the same time it could prove to be a major disadvantage. Fresh-frozen allograft is associated with inherent risks of disease transmission and bacterial infection. It is of unpredictable quality and, because it is not clear what constitutes a poor graft, there is no method of ensuring a consistently high-quality graft. Compacted morselized bone graft can be realized clinically in the proximal part of the tibia. There is a complex interaction among the biomechanics of the specified joint, the mechanics of the graft, the science of compaction, and the inherent constraints of arthroplasty implants. Our understanding of how to optimize these interactions is currently limited.

Appendix

Tables summarizing clinical studies of impaction bone-grafting with implantation of acetabular and femoral total hip components are available with the electronic versions of this article, on our web site at jbjs.org (go to the article citation and click on “Supplementary Material”) and on our quarterly CD-ROM (call our subscription department, at 781-449-9780, to order the CD-ROM).

Andrew D. Toms, MBChB, FRCS(Ed), MSc, FRCS (Tr+Orth)
35 Simpsons Walk, Horsehay, Telford, Shropshire TF4 2PA, England. E-mail address: toms@at-rj.freeserve.co.uk
Ross L. Barker, FRCS
Richard Spencer Jones, MB, BS, FRCS, FRCS/(Tr+Orth)
Jan Herman Kuiper, PhD
Robert Jones and Agnes Hunt Orthopaedic Hospital, Oswestry, Shropshire SY10 7AG, England.

The authors did not receive grants or outside funding in support of their research or preparation of this manuscript. They did not receive payments or other benefits or a commitment or agreement to provide such benefits from a commercial entity. No commercial entity paid or directed, or agreed to pay or direct, any benefits to any research fund, foundation, educational institution, or other charitable or nonprofit organization with which the authors are affiliated or associated.

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