Repair of defects and containment in revision total knee replacement

A COMPARATIVE BIOMECHANICAL ANALYSIS

The treatment of bony defects of the tibia at the time of revision total knee replacement is controversial. The place of compacted morsellised bone graft is becoming established, particularly in contained defects. It has previously been shown that the initial stability of impaction-grafted trays in the contained defects is equivalent to that of an uncemented primary knee replacement. However, there is little biomechanical evidence on which to base a decision in the treatment of uncontained defects. We undertook a laboratory-based biomechanical study comparing three methods of graft containment in segmental medial tibial defects and compared them with the use of a modular metal augment to bypass the defect.

Using resin models of the proximal tibia with medial defects representing either 46% or 65% of the medial cortical rim, repair of the defect was accomplished using mesh, cement or a novel bag technique, after which impaction bone grafting was used to fill the contained defects and a tibial component was cemented in place. As a control, a cemented tibial component with modular metal augment was used in identical defects. All specimens were submitted to cyclical mechanical loading, during which cyclical and permanent tray displacement were determined.

The results showed satisfactory stability with all the techniques except the bone bag method. Using metal augments gave the highest initial stability, but obviously lacked any potential for bone restoration.

The management of bony defects of the tibia in revision total knee replacement (TKR) is controversial because of the variety of defects encountered and the relative lack of evidence from clinical trials or experimental studies on which to base a surgical decision. Defects may be reconstructed using various techniques including filling with cement, modular metal augment, structural allografts, custom implants, and compacted morsellised bone graft.

In addition to the provision of a stable, durable revision construct, the maintenance or improvement of bone stock to facilitate subsequent revision is an important additional goal. The use of compacted morsellised bone graft (CMBG) has been advocated for contained defects (Anderson Orthopaedic Research Institute (AORI) T1 defects) and localised metaphyseal defects, but compaction is only possible when defects are contained. For uncontained localised defects in metaphyseal bone (AORI T2a) modular metal augment are generally used, whereas major uncontained defects (AORI T3) may require custom implants, tumour-type prostheses or large structural allografts. Although the clinical results using modular metal augment are excellent, concerns about their use relate to potential bone loss and to fretting and dissociation of the modular components. Bone loss occurs because the use of a modular metal augment does not involve restoration of bone stock, and may actually require further resection of bone to accommodate the component.

Converting an uncontained defect into a contained one would allow the wider use of CMBG. In hip replacement this is achieved by covering the defect with surgical mesh. Although such a repair prevents the outflow of bone particles during compaction, it does not restore the mechanical function of the cortex, as can be judged from the large strains around defects contained using mesh. Additionally, a technique that works in the hip might not necessarily work in the knee. The existing clinical experience with CMBG for uncontained defects is based on the use of mesh. Knee prostheses need stable components to ensure the maintenance of the correct tension in the surrounding soft-tissue envelope; a loss of...
position has significant clinical consequences in the knee. An impaction-grafted proximal tibia needs the support of a cortical rim to ensure stability of the tibial tray. In the absence of full cortical support the question remains whether a cortex repaired using mesh provides the tibial tray with sufficient rim support to ensure stability. Alternative techniques that restore the containing function of the cortex and also provide support, such as rebuilding the cortex using a polymer, might be more appropriate. Such techniques may be particularly suitable for larger defects. The ideal material for repair of a defect would be a bioabsorbable mesh or bag which was as stiff as stainless steel mesh but which would ultimately become integrated, encouraging the formation of a new cortex. We have developed a bag technique that was an initial step towards the ultimate aim of the reconstruction of defects using bioabsorbable material.

This study addresses four specific questions: (1) Does a repaired cortex provide sufficient support for the tibial tray? (2) How does the initial stability of an impaction-grafted tray on a repaired cortex compare with that of a tray with a modular metal augment? (3) Does the method of repair of the cortex affect the initial stability of the tray? and (4) Does the size of the defect affect the initial stability of the tray after cortical repair?

Materials and Methods

Artificial cortical shells of proximal tibiae were produced from resin (SL5170, 3D systems Europe Ltd, Hemel Hempstead, United Kingdom) using a stereolithographic process. They were made with one of two defect configurations following the AORI classification: a small T2a (representing 46% loss of the medial cortical rim) and a large T2a (65% loss of the medial cortical rim; Fig. 1).

Freshly-frozen femoral heads, harvested during primary total hip replacements and stored at -80°C, were morsellised using a bone mill (Noviomagus; SMT, Nijmegen, The Netherlands) which produced bone particles with an effective diameter of 3.0 mm and a uniformity of 1.8. Uniformity, a soil mechanics term, is a measure of the spread of sizes of a particulate sample. A uniformity of 1 is obtained when all particles are equal; soil with a uniformity < 5 is considered 'uniform'; a uniformity > 15 is considered 'well graded', meaning a wide range and spread of particle size is present.

In order to investigate whether a repaired cortex offers tray support, two sizes of pressfit condylar (PFC Sigma Knee System, DePuy International Ltd, Leeds, United Kingdom) tibial trays were used. The first was a small tray (size 2) that fitted within the cortical rim. It received no rim support and was therefore supported by compacted graft only. The second was a large tray (size 4) and was supported by the repaired cortex along its entire edge. A 13 mm diameter stem with a 30 mm tip was used in all cases, creating a total stem length of 69 mm measured from the undersurface of the tray.

In order to investigate the role of graft containment and the type of repair, four methods were compared (Fig. 2):

1. Mesh. The defect was contained by the use of a stainless steel mesh, which was fixed to the model tibia using unicortical screws.
2. Cement. A film of bone cement (CMW3, DePuy CMW, Blackpool, United Kingdom) was applied across the defect to contain the graft.
3. Bone bag. A new technique using a closed polyester mesh bag filled with CMBG, tensioned and fixed in place across the defect using unicortical screws. This method aimed to provide graft containment and direct tray support.
4. Metal augment. A size 4 tray with a 15 mm modular metal step augment was used to repair a tibia with a T2b defect. This is currently accepted as standard clinical practice and therefore served as a control.

Surgical technique. A cement restrictor was inserted into the medullary canal of each tibial model, to a depth that left a minimum gap of 2 cm between the restrictor and the tip of the intended stem. A central guide wire was then attached to the restrictor. Morsellised bone graft was introduced and compacted in an incremental manner to produce a firm distal graft, which was compacted to a predetermined height. The proximal graft bed was then prepared around a trial stem, with space for a 2 mm thick cement mantle around the stem. Bone cement (CMW3, DePuy) was prepared and injected into the space for the stem and placed on top of the compacted graft. Finally, the tibial component was implanted and held firmly in place until the cement had polymerised. The implanted models were left at room temperature for 24 hours to allow the cement to cure fully, before being frozen at -22°C for a minimum of 24 hours.
For each of the three methods of cortical repair, six specimens were prepared. These were divided equally between the two tray sizes (n = 3 each) and the two defect sizes (n = 3 each), ensuring that each combination of repair method, tray size and defect size occurred at least once. Two control specimens were prepared with an augmented tray. Therefore, a total of 20 specimens were prepared.

**Mechanical testing.** Prior to mechanical testing the specimens were thawed overnight at room temperature. An aluminium frame containing six linear displacement transducers with spring-return (S8FLP10A; Sakae, Kawasaki-city, Japan) was fixed to the proximal tibia, such that the tip of each transducer was in contact with the tibial tray. Three transducers were located proximally, recording movement in the distal direction, two posteriorly measuring in the anterior direction, and one medially measuring in the lateral direction (Fig. 3). This allowed the relative movement between tibia and tray to be measured in all six degrees of freedom. Specimens were mounted on a 5 kN servo-hydraulic testing machine (ESH Testing Ltd, Brierley Hill, United Kingdom) and loaded cyclically at a frequency of 1 Hz. A series of three load cases were applied. The first two were normal forces, directed posteriorly along the tibial axis, one acting on the centre of the medial tibial condyle and one on the lateral. The third was a shear force directed anteriorly and acting on the centre of the posterior side of the tray. A total of 100 cycles of each load case were applied per series, each time superimposed on a static pre-load of 10 N. In the first series, the peak normal load was 500 N and the peak shear force 100 N. This ratio of normal to shear was chosen to mimic that measured by Taylor and Barrett. For each consecutive series, peak normal loads were increased by 500 N and peak shear loads...
by 100 N up to a maximum normal load of 2000 N and shear load of 400 N, approximately 2.7 times normal body weight. This is larger than previously reported peak loads. Movement data from the displacement transducers and force data from the testing machine’s load cell were digitised and stored in a personal computer for subsequent analysis.

**Data analysis.** From the tray movement data, permanent maximum total displacement after 100 cycles and cyclic maximum total displacement, were calculated from the mean of the final ten cycles separately for each load case and load series. Maximum total displacement is the total displacement between the tray and the model tibia at the position where relative movement is maximal, and is comparable to the maximum total point movement measured in radiostereophotogrammetric studies of tray migration. The maximum total displacement generated during cyclic loading can be divided into a permanent and a cyclic portion. The cyclic maximum total displacement is the difference between displacement at load peak and pre-load level. The permanent maximum total displacement is the remaining displacement after 100 cycles of load, compared with the starting position.

After testing for equal variances using Bartlett’s test, a one-way analysis of variance (ANOVA) model was used to analyse differences in maximum total movement, using appropriate constructs to test the effect of rim support and the method of repair, and to compare with the controls. The Benjamin-Liu step-down procedure was used to test for significant differences between the three individual methods of repair. For all analyses, a probability of \( p = 0.05 \) was assumed to indicate statistical significance. All results are given as mean values with 95% confidence intervals (CI). All statistical analyses was performed with SYSTAT 11 (Systat Software Inc., Richmond, California).

**Results**

All specimens with small T2a defects survived the complete loading protocol up to normal loads of 2000 N without gross subsidence. Three specimens with a large T2a defect failed during medial loading of 2000 N (Table I). In these cases, tray movements were large and we decided to stop the tests prematurely. The statistical analysis was based on the movements at loads of 1500 N, the highest level sustained by all specimens. When comparing movement caused by the three load cases, we found that normal loading of the medial condyle, which was the side of the defect, invariably gave the largest movements. Hence, we present only the results for this load case, which represents the worst-case scenario.

A general pattern was found of small cyclic movements superimposed on a larger permanent movement. The first few cycles gave a large permanent displacement, after which further permanent migration occurred at a decreasing rate (Fig. 4).

Irrespective of the method of cortical repair, the mean permanent and mean cyclic displacements of the small impaction-grafted trays without rim support was more
Table II. Mean (95% confidence interval) permanent and cyclical maximal displacement for trays on repaired cortices compared to augmented trays, measured in mm

<table>
<thead>
<tr>
<th>Experimental group</th>
<th>Permanent displacement</th>
<th>Cyclical displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trays on repaired cortices (large defects and rim support, n = 6)</td>
<td>0.88 (0.28)</td>
<td>0.41 (0.13)</td>
</tr>
<tr>
<td>Augmented trays (n = 2)</td>
<td>0.29 (0.48)</td>
<td>0.19 (0.23)</td>
</tr>
</tbody>
</table>

* difference significant (p < 0.05, 1-way analysis of variance)

Table III. Mean (95% confidence interval) permanent and cyclical maximal displacement for trays on cortices repaired by different methods, measured in mm

<table>
<thead>
<tr>
<th>Repair method</th>
<th>Permanent displacement</th>
<th>Cyclical displacement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bag (n = 6)</td>
<td>1.67 (0.28)</td>
<td>0.92 (0.13)</td>
</tr>
<tr>
<td>Cement (n = 6)</td>
<td>0.55 (0.28)</td>
<td>0.36 (0.13)</td>
</tr>
<tr>
<td>Mesh (n = 6)</td>
<td>1.27 (0.28)</td>
<td>0.71 (0.13)</td>
</tr>
</tbody>
</table>

* difference significant (1-way analysis of variance followed by Benjamin-Liu step-down procedure, p < 0.05)

Graph showing the effect of the mean maximum total displacement for large and small defects for each type of reconstruction on movement. For repairs with a bag there is a significant difference between the large and small defects (p = 0.002), but not for the other repairs (p > 0.27). All one-way analysis of variance, with error bars representing 95% confidence intervals.

Discussion

This study aimed to address the controversy concerning the best method of containment of a defect when using CMBG in the tibia. First, we found that both permanent and cyclical movements of tibial trays on reconstructed cortices were less than half those of trays without rim support. This strongly suggests that reconstructed cortical rims do indeed provide support for the tibial tray upon loading. A similar reduction in permanent and cyclical movement was found earlier for tibial trays on intact cortices, suggesting that repaired cortices provide the same relative contribution to stability as do intact cortices.

Second, we found that permanent and cyclical movement of impaction-grafted tibial trays on reconstructed rims was on average twice that of metal-augmented trays. However, the grafted trays achieved levels of stability reported for primary TKR and we specifically used a short stem and a rigorous testing regime in order to illustrate a worst-case scenario for CMBG. A direct comparison between our results and those of earlier studies comparing metal-augmented trays and alternative methods of repair is difficult because in our study no cancellous bone was present, but rather compacted bone instead. However, the superiority of metal augments over alternative repair methods such as cement alone echoes the findings of an earlier study that compared methods to repair wedge-shaped defects. In a later study of stepwise defects, which more closely mimic the geometry of our defects, no difference in stiffness was found between repair by cement or metal blocks. However, it should be appreciated that in our study not only was the
cortical rim repaired but the defect was grafted, whereas in the earlier study the cement repair covered the complete defect area. The fact that morsellised cancellous bone is at least 20 times less stiff than polymethylmethacrylate cement (10 MPa to 100 MPa vs 2.3 GPa to 3.5 GPa[16,17]) may explain why, in our study, modular augment blocks provided superior stability compared to alternative methods of cortical repair.

Third, we found significant differences in the stability provided by the three methods of repair, with cement giving most initial stability, followed by the more traditional mesh repair, and the experimental bag repair being the least supportive. The superiority of cement repair is probably due to its combination of a relatively high elastic modulus and full cortical thickness, thereby providing true cortical repair and direct support to the tray. The metal mesh was more flexible and did not restore the cortical thickness, hence not providing as much direct support. However, it still gave sufficient constraint to allow compaction of the morsellised bone graft. The lower stability achieved with the experimental bone bag repair suggests that deformation of the bags during compaction may have prevented effective compaction of the morsellised bone contained by it.

Using cement to repair the cortex gave the most stable impaction-grafted construct in this study. Although the use of cement to repair large defects in the tibia has been reported, this normally involves filling the defect with cement. In our study, only the cortex at the site of the defect was repaired, giving a relatively thin cement layer with a thickness of 4 mm. This was sufficient to give stable support. However, the cortical shell at the human proximal tibial epiphysis, where defects occur, is typically less than 1.5 mm, much thinner than that of our model tibiae. In clinical practice, therefore, the layer of bone cement to repair a cortical defect will be much thinner than the 4 mm in our study. Such a thin layer is likely to fracture during compaction or upon joint loading. In one of our specimens, such a failure occurred at a load of 2000 N, highlighting this danger even in the case of thicker repairs. Moreover, the presence of a cement patch in the cortex might preclude the formation of a neocortex. An advantage of mesh over cement repair is that formation of a neocortex adjacent to wire mesh is possible, as demonstrated in a previous histological study.

Although mesh repair of cortical defects gave less stable trays than obtained with a cement repair, tray movements were within the range reported for primary uncemented knee prostheses. Moreover, this type of repair can be applied in clinical practice. Mesh repair of cortical defects before bone grafting has been used in several clinical studies of revision TKR. Although all have a relatively short follow-up, with a maximum of four years, none of the authors mention problems due to a lack of early stability.

Finally, the variation in the size of the defect between 46% and 65% of the medial cortical rim had a significant effect on stability only where the repair was undertaken using the bone bag method. This was also the least stable method overall. For the other two types of reconstruction we found no effect of defect size on tray stability, suggesting that both cement and mesh should be equally suitable for smaller and larger defect repairs. As mentioned previously, the thin cortex at the tibial rim is likely to make a repair of cortices with cement difficult to apply in clinical practice. However, mesh repair is being used. In three clinical studies, mesh repair was used to repair various sizes of defect without demonstrating any effect of defect size on failure rates, underlining the findings in the present study[2,24,25]. However, a case study has reported failure of graft incorporation under a tibial tray following mesh containment of an extensive bilateral cortical defect (T2b). Hence, although mesh repair may give sufficient stability for unilateral defects, this does not necessarily translate to bicondylar defects.

This was a laboratory study, designed to address specific concerns regarding the repair of cortical defects and the subsequent containment and stability of tibial CMBG. A number of assumptions and simplifications have been made. The first concerns mechanical loading. In order to load the trays, a combination of two unilateral axial loads and a (smaller) central shear load were chosen. The two unilateral loads were chosen because they would test tray stability more severely than central loading. Such unilateral loads are commonly observed in patients with these implants, as quantified by the use of fluoroscopy. The absolute load level and the ratio of shear to axial load that we have adopted mimics the levels recorded in vivo during walking.

A second limitation is our restriction to measuring short-term early stability only and ignoring the in vivo osseous response. We consider this limitation justified because at the hip initial stability is thought to be the factor that dictates the in vivo response. A third limitation is our use of synthetic tibial models instead of cadaver tibiae. Artificial bone models have the advantage of minimising the confounding variables from differences in bone geometry and properties, which can be considerable. The stereolithographically produced proximal tibiae used in our study were also used in an earlier investigation of impaction grafting for tibial trays and validated against commercially-available artificial tibiae for biomechanical testing purposes. A particular advantage of the stereolithographic process for the present study was the ability to reproducibly make tibial models with identical cortical defects.

A final limitation was that we restricted our study to trays with short stems. These stems were chosen to emphasise any difference between the methods of repair. However, in an earlier study we demonstrated that a longer stem significantly improves the stability of impaction-grafted trays on an intact cortical rim. It seems reasonable to assume that the same would apply for trays on repaired cortical rims. Further support for this assumption comes from a biomechanical study comparing the influence of distal
stem/canal fit on the stability of uncemented revision trays on cortical rims with either an unrepaired AORI T2a defect or a T2a defect reconstructed with a metal augment. That study found no difference between trays on unrepaired and repaired cortices, provided a line-to-line or oversized stem was used. Hence, using longer stems is likely to improve the stability of impaction-grafted trays beyond that measured in this study, and will reduce the influence of the method of repair or of the defect size.

The repair of a tibial defect at the time of revision TKR should be based on clinical and biomechanical evidence. In our study, the stability achieved by the control repair method - a tray with a modular metal augment, well seated on the cortical rim - was better than the other methods tested. In clinical practice, a five- to ten-year follow-up shows that the use of such trays to treat patients with type 2 defects can have a survival rate of 92% at 11 years. Although trays with modular metal augments would therefore seem a good choice to treat such defects, they do not have the potential to improve bone stock. On the contrary, their insertion frequently requires bone to be removed.

CMBG provides a bone-restoring revision option for tibial trays. In an earlier study we showed that the initial stability of impaction-grafted trays on contained defects was comparable to that of primary uncemented tibial trays, provided the tray was properly seated on the rim, and especially when a long stem was used. In this study, we demonstrated that the initial stability of impaction-grafted trays on cortices with AORI T2a defects repaired using bone cement or metal mesh was similar, in range to that found in primary uncemented tibial trays. Although the trays on cortices repaired using cement were more stable in this study, we doubt whether this would translate to clinical practice, and therefore consider mesh repair the preferable option. Mesh repair is being used in clinical practice, and therefore consider mesh repair the preferable option.

Our experimental method for the repair of significant tibial defects (AORI T2a small and large) arising at revision TKR could be successfully managed using compacted morsellised bone graft when this is appropriately contained. We can recommend the use of morsellised bone graft contained with a mesh to provide this containment. However, the choice of this biological method of reconstruction over the mechanically superior modular metal augments should be based on the potential benefits to the patient. In the elderly patient with poor bone stock the increased stability of modular metal augments is attractive. Conversely, in a younger patient who faces the prospect of several revisions in their lifetime, the use of CMBG to reconstitute the tibia offers important long-term benefits. Initial stability can be further optimised by cortical rim support and the use of a longer stem.

References


The authors wish to thank Depuy UK for their support of this research. No benefits in any form have been received or will be received from a commercial party related directly or indirectly to the subject of this article.