The Role of Vibration and Drainage in Femoral Impaction Bone Grafting

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Abstract: Vibration is commonly used in civil engineering applications to efficiently compact aggregates. This study examined the effect of vibration and drainage on bone graft compaction and cement penetration in an in vitro femoral impaction bone grafting model with the use of 3-dimensional micro-computed tomographic imaging. Three regions were analyzed. In the middle and proximal femoral regions, there was a significant increase in the proportion of bone grafts with a reciprocal reduction in water and air in the vibration-assisted group \((P < .01)\) as compared with the control group, suggesting tighter graft compaction. Cement volume was also significantly reduced in the middle region in the vibration-assisted group. No difference was observed in the distal region. This study demonstrates the value of vibration and drainage in bone graft compaction, with implications therein for clinical application and outcome. **Key words:** impaction bone grafting, vibration, morselized allograft, compaction, micro-computed tomographic imaging.

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Impaction bone grafting (IBG) is a recognized technique to reconstitute the extensive areas of bone loss in the femur and acetabulum [1,2] often encountered in revision hip surgery. Morselized allograft continues to be the gold standard, providing good mechanical support and osteoconductive potential. The success of the procedure is reliant on sufficient compaction of the allograft to allow it to support the prosthesis under physiologic loading and to prevent excess subsidence and failure.

Impaction bone grafting is a technically demanding procedure with a steep learning curve. Determining when the graft is adequately compacted is potentially one of the most difficult factors for surgeons to judge intraoperatively. The concern of aggressive compaction leading to femoral fracture (with rates as high as 27% reported [3]) must be balanced against the risks of undercompaction of the graft and subsidence of the prosthesis postoperatively. This is compounded by the fact that there is no specific intraoperative indicator of graft compaction completion. The difficulty in obtaining this fine balance is reflected in the literature, in which a wide range of outcomes are reported. Results from the center from which the femoral IBG technique originated have shown excellent mid-term outcome, with 99% survival at an average 10-year follow-up (in 226 patients who underwent a femoral reoperation caused by symptomatic aseptic loosening as the end point) [4]. However, this has not always been the experience of other centers. In

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Bristol, of 79 patients who underwent hip arthroplasties on whom femoral IBG had been performed and followed up for just over 1 year, 9 (11%) showed evidence of significant subsidence [5]. This was defined as subsidence greater than 10 mm and in all cases occurred in the first 3 months after the operation. Six hips required subsequent re-revision. A series in Australia found a similar subsidence value of 9 mm (range, 2-37 mm) at 24 months [6].

Shear strength is commonly measured when evaluating the mechanical properties of bone grafts because the mode of bone graft failure after IBG is believed to be in shear. Techniques to improve the shear strength of allografts have concentrated on altering the composition and particle size of the impacted material. Important factors include washing [7,8], grading [8], the addition of synthetic materials [9-11] (eg, bone graft extenders), and the degree of cement penetration [12]. Since the development of the technique by Slooff et al in Nijmegen in the late 1970s for the acetabulum [1] and subsequently by Ling et al in Exeter in the UK in 1987 for the femur [2], there have been few modifications to either the technique itself or the instrumentation used for impaction.

The morselized allograft shares many characteristics with aggregate materials used in civil engineering applications [13]. The behavior of these aggregates under load has been studied extensively, and this knowledge can be applied to improve the mechanical characteristics of other aggregates, such as bone graft. Vibration is commonly applied to aggregates used in civil engineering applications to improve the compaction (assembly) of the aggregate particles and hence to increase the aggregate’s compressive and shear strengths [13]. A recent study investigated the effect of vibration and drainage during the impaction process on hoop strains (as a marker of fracture risk) and subsidence (as a marker of prosthesis stability). It demonstrated that vibration-assisted IBG leads to reduced peak loads and hoop strains in the femur during graft compaction and that the resulting graft is better able to resist subsidence of the prosthesis [14].

What remains unclear is the effect this technique has on graft compaction. Prosthetic stability can be affected not only by graft compaction but also by the degree of cement penetration. Greater cement penetration into the impacted graft through to the endosteal surface has been shown in vitro [15] and in vivo [16] to be mechanically advantageous. The mechanical advantage that cement penetration confers, however, is offset against a deleterious biological effect on allograft and cortical remodeling, as demonstrated by Frei et al [16] in an in vivo bone chamber model. Improving graft compaction is mechanically advantageous and, with a thicker bone graft mantle, creates a greater volume for potential bone remodeling.

This study examined the effect of vibration and drainage on bone graft compaction and cement penetration in an in vitro femoral IBG model.

**Materials and Methods**

**Bone Graft Preparation**

Femoral heads were retrieved with the consent of patients undergoing elective or traumatic hip surgery at Southampton General Hospital and stored in a −80 freezer for more than 6 months. Only tissue that would otherwise have been discarded was used, with the approval of the local ethics committee (LREC 0091). Femoral heads were defrosted by soaking in warm normal saline. All soft tissue, osteophytes, and cartilage were removed using bone nibblers and an oscillating saw (Stryker, Howmedica, UK). The heads were cut into halves and milled using a 3-mm Aesculap bone mill. The resulting morselized graft was washed with normal saline to remove excess fat. Grafts from all femoral heads were mixed together to reduce the effects of patient variability. The same stock of morselized graft was used for both study groups.

**Instrumentation**

Standard “X-change” femoral IBG instrumentation (Stryker) consisting of distal and proximal tamps or phantoms attached to a slap hammer device was used in the control group. In the vibration-assisted group, a vibration hammer (Woodpecker vibration device, Minnesota Bramstedt Surgical Inc, St Paul, MN, USA; Fig. 1A) designed to aid femoral broaching was adapted to allow connection of impaction tamps/phantoms. Multiple holes were drilled through the flanks of the tamps into the central guidewire hole, providing drainage portals for fat, marrow, and fluid (Fig. 1C and D—standard and perforated phantoms).

Medium left third-generation composite femurs manufactured from short glass fiber-reinforced epoxy resin were used as the basis of the biomechanical model (Model No. 3303, Sawbones Europe, Malmo, Sweden). These models have been shown to approximate the mechanical properties of the human femur but with much less variability than that found in cadaveric material [17]. Twelve models of the femur were prepared (6 in each group): standard femoral graft compaction using “X-change” proximal and distal impactors and a slap...
hammer (Fig. 1B) for the control group) and vibration-assisted compaction with perforated impactors and a vibration hammer (Fig. 1A, C, and D) for the experimental group.

The models were widened to a canal diameter of 22 mm to closely resemble the appearance and composition of femurs encountered during revision hip arthroplasty surgery with loss of all cancellous bone and thinning of the cortex. The distal canal of each femur was occluded 25 mm beneath the anticipated position of the tip of the prosthesis using bone cement.

**Operative Procedure**

Impaction bone grafting was carried out using a standard protocol for the control and vibration-assisted groups with the “X-change” instrumentation (Stryker UK Ltd, Newbury, UK). Compaction of the graft was performed sequentially with a measured volume of graft introduced into the canal. Further portions of the graft were added to the femur, with the graft being compacted before the next portion of graft was added at each stage. Three sets of compaction using the distal impactors were performed before exchanging to the proximal impactors. In the control group, a standard technique of applying 20 blows per portion of graft was maintained. In the experimental group, the graft was compacted by application of the vibration hammer to the tamp/phantom for approximately 10 seconds. The end point of impaction in the control group was defined by there being no further movement of the tamp after 10 consecutive blows with the slap hammer, whereas that in the vibration-assisted group was defined by there being no further movement of the tamp despite force application to the vibration hammer. Preliminary experiments confirmed the end point in the vibration-assisted group to correlate with the end point in the control group (ie, after vibration-assisted compaction, the application of 10 blows using the slap hammer resulted in no further movement of the tamp). A single mix of bone cement (Smartset CMW, DePuy CMW Ltd, Blackpool, UK), prepared in a vacuum mixing system (Cemvac, DePuy CMW Ltd), was inserted retrograde using a revision nozzle and a cement gun and pressurized using a proximal cement seal. These were followed by the insertion of a 44 No. 2 Exeter (Stryker UK Ltd, Newbury, UK) femoral prosthesis (Fig. 2A).

**Micro-Computed Tomographic Imaging**

Micro-computed tomographic scans of the impacted bone grafted femurs were obtained using a bench-top micro-tomography system (X-TEK Systems Ltd, Tring, Hertfordshire, UK) with a photomultiplier detector. X-rays were generated using an electron gun accelerating voltage of 145 kV, a beam current of 45 μA, and a tungsten target. Owing to the model size, the femur was scanned in the proximal, middle, and distal sections. For the proximal scan, the femur was inverted; to permit this, it was mounted on a polyethylene tube with base and lid components that connected to the adjustable sample platform of the scanner. After being mounted on the sample platform, the femur was centered in the x-ray beam, the electron beam was focused, and the detector was calibrated under no-x-ray-beam and uninterrupted-x-ray-beam conditions. The samples were then scanned at 1600 angular positions integrating 16 frames at each. After the scanning process, the raw data were collected and reconstructed using Next Generation
Imaging version 1.4.59 software (X-TEK Systems Ltd) with an average voxel size of 120 μm.

**Micro-Computed Tomographic Analysis**

The reconstructed images were visualized using Volume Graphics Studio Max 1.2.1 software (Volume Graphics, Heidelberg, Germany), and 3-dimensional views (Fig. 2B) were created along with axial, sagittal, and coronal slices. Segmentation tools allowed the extraction of cement, bone graft, and femoral sawbone components individually (Fig. 3A-D). Along with the 3-dimensional view of the individual component, a histogram plotting the number of voxels against gray-scale values was created. The sawbone, air, water, bone graft, and cement were all scanned separately using identical image settings to determine the gray-scale range for the individual components. Regions from the distal, middle, and proximal thirds of the femur were analyzed. Subvolumes, 2 cm in height and 2 cm apart, commencing from the tip of the prosthesis were selected and represented the distal, middle, and proximal regions of interest (ROIs). Referencing from the stem tip ensured that reproducible volumes were selected and excluded any variation introduced from the depth of stem insertion (Fig. 4A-D).
Based on the determined gray-scale ranges for separate components, the total number of voxels representing the cement and bone graft for the distal middle and proximal regions for the control and experiment groups was quantified. The cement volume was expressed both as a percentage of the total ROI and in millimeters cubed (the resolution of the scan determined the dimension of the voxel from which the volume in millimeters cubed could be calculated). The segmented bone graft volume also represented proportions of air and water; therefore, all 3 components were quantified separately and measured as a percentage of the total segmented volume. This also had the additional advantage of eradicating any difference in the segmented volume size under analysis.

**Statistical Analysis**

Statistical analysis of the data was performed using Student's t test and 2-sample unequal variance (GraphPad Instat Software, GraphPad Software, Inc, San Diego, CA, USA).

**Results**

**Computed Tomographic Calibration of Air, Water, Bone Graft, and Cement Properties**

The gray-scale ranges, derived from scanning components separately, were 0 to 25 for air, 25 to 50 for water, 40 to 100 for bone graft, and 90 to 120 for cement. The range of 50 to 100 was taken to determine the bone graft volume in the absence of water (Fig. 5).

**Regional Analysis of Cement Volume and Bone Graft Proportions**

**Distal ROI. Cement volume:** The volume of bone cement represented in the distal ROI was 1.21 cm³.
Bone graft proportions: The distal ROI was composed of a mean 96.2% (SD, 1.5%) bone graft, that of 3.1% (SD, 1.2%) water, and that of 0.4% (SD, 0.3%) air in the control group as compared with its composition being 94.9% (SD, 3.3%) bone graft, 3.9% (SD, 2.2%) water, and 1.2% (SD, 1.2%) air in the vibration-assisted group (Fig. 6). This difference was not statistically different ($P = .72$).

Bone graft proportions: The middle ROI was composed of a mean 81.9% (SD, 6.0%) bone graft, that of 12.5% (SD, 3.1%) water, and that of 5.5% (SD, 3.1%) air in the control group as compared with its composition being 91.8% (SD, 2.3%) bone graft, 6.7% (SD, 1.5%) water, and 1.2% (SD, 1.0%) air in the vibration-assisted group (Fig. 6). This difference was statistically different ($P < .01$).

Bone graft proportions: The proximal ROI was composed of a mean 63.8% (SD, 3.1%) bone graft, that of 22.5% (SD, 1.8%) water, and that of 13.5% (SD, 1.9%) air in the control group as compared with its composition being 68.8% (SD, 3.1%) bone graft, 19.4% (SD, 2.1%) water, and 10.8% (SD, 1.9%) air in the vibration-assisted group (Fig. 6). The increase in the proportion of bone graft along with a drop in the proportions of water and air in the vibration-assisted group as compared with the control group was significant in all cases (bone graft, $P < .05$; water, $P < .05$; air, $P < .05$).

**Discussion**

We have shown that in a femoral IBG model, the application of vibration combined with perforated impactors to allow drainage leads to improved bone graft compaction as compared with the standard technique and instrumentation used in present-day clinical practice.

This study has demonstrated that the compaction of aggregates, such as bone graft, can be improved with better alignment of the particles to allow denser packing and greater interparticulate surface area contact. In doing so, the volume in between the particles, consisting of air and fluid, is reduced. In the field of civil engineering, this has been shown to occur with the application of vibration [13,18]. Vibration gives the particulate material a better chance to come into denser packing provided that the void space reduction is allowed by adequate drainage of the fluids in the void space. In the presence of excess fluid in a contained space, compaction effort is transmitted not only to the bone graft but also to the fluid, resulting in poorer impaction of the graft particles [8]. Drainage is used widely for in situ densification of loosely deposited sand to alleviate the risk of soil liquefaction under earthquake loading. Improved closer packing increases the interparticulate contacts and the shear strength of the particulate material [19,20].

In this study, the proportion of bone graft in the vibration-assisted group was increased in both the proximal and middle regions of the femur, with a concomitant decrease in the proportions of air and water. These findings are consistent with improved denser packing and compaction of the graft. In the distal region, there was no difference in the proportions of bone graft, air, and water between the 2 groups. This has been supported by a previous femoral IBG study on cadaveric femurs that also demonstrated increased graft compaction in the region where the distal impactors were used [12]. There are several possibilities for this. The distal impactors have a much smaller surface area in contact with the bone graft; therefore, the vibrating area will have less contact and, consequently, less effect on realigning the bone graft particles. An axial compressive force is transmitted during distal impaction rather than a radial compressive force (which occurs with the tapered proximal impactors). Consequently, the bone graft distally is often very well compacted using the standard technique, therefore making it more difficult to detect a significant improvement. Finally, the length of the column of the distal graft impacted is much less than that in the proximal impaction, resulting in the dissipation of fluid around the sides and top of the distal impactors—thus nullifying the potential benefits from the addition of drainage holes to distal impactors.
It is important to note that the improvement in bone graft compaction has not only a mechanical advantage but also a potential biological advantage. Greater bone graft compaction should result in less cement penetration into the interparticulate spaces, leaving a greater bone graft mantle for neovascularization and bone remodeling to take place. Studies have demonstrated a positive correlation between increased cement penetration and delayed revascularization of the endosteal surface—essential for graft incorporation and remodeling [21].

The cement volume in the middle region of the femur was reduced, which correlated with the improved graft compaction also observed in this region, in the vibration-assisted group. Similarly, in the distal region, where there was no difference in graft compaction, the cement volume also remained unchanged between the 2 groups. However, in the proximal region, the cement volume remained the same despite an increase in the percentage of bone graft, suggesting inferior compaction in comparison with the middle region. Possible explanations include the fact that the proximal bone graft not only sustains the fewest impactions/exposure to vibration but also is the most difficult to contain, an essential requirement for good graft impaction.

Therefore, overall, across the 3 regions, there was no increase in cement volume in the vibration-assisted group. A previous study that used this technique demonstrated that prosthetic stability is enhanced, with less subsidence observed after cyclical loading [14]. Therefore, with no increase in the cement volume, we postulate that the improved prosthetic stability is a direct result of improved bone graft compaction.

The underlying principle of IBG is to achieve stability of the implant and subsequently allow the restoration of living bone stock by bone ingrowth. However, in achieving good mechanical stability, the environment for the biological remodeling of the graft may be compromised. Examples include (a) washing (this removes fat, increasing shear strength of the bone graft, but also removes growth factors and cytokines that encourage ingrowth and new bone formation [7,8]), (b) compaction energy (the energy imparted during impaction has a positive correlation with the shear strength of the graft but a negative correlation with bone ingrowth [22]), and (c) cement penetration. The vibration technique has improved compaction of the bone graft, producing a greater bone graft mantle with improved support for the femoral prosthesis. A thicker graft mantle unaffected by the thermal reaction and detrimental effects of bone cement may result in improved endosteal blood supply, neovascularization, and, ultimately, bone remodeling and incorporation. However, further in vivo studies are required to establish this and the longer-term effects this technique has on bone incorporation and remodeling.

This study has demonstrated that vibration combined with perforated tamps to allow drainage of excess fluid significantly improves bone graft compaction as compared with the current surgical technique. Further characterization of the vibration hammer and perforated tamps, including the effects of vibration frequency and amplitude, air pressure, and the number, size, and position of the holes in the tamps, is required to determine optimum compaction conditions. These results offer new clinical approaches and therapeutic implications therein to a significant orthopedic problem.

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**References**


