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A New Approach to Quantify Trabecular Resorption Adjacent to Cemented Knee Arthroplasty

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Abstract

A new micro-computed tomography (μ CT) image processing approach to estimate the loss of cement-bone interlock was developed using the concept that PMMA cement flows and cures around trabeculae during the total knee arthroplasty procedure. The initial mold shape of PMMA cement was used to estimate the amount of interdigitated bone at the time of implantation and following *in vivo* service using *enbloc* human postmortem retrievals. Laboratory prepared specimens, where there would be no biological bone resorption, were used as controls to validate the approach and estimate errors. The image processing technique consisted of identifying bone and cement from the μ CT scan set, dilation of the cement to identify the cement cavity space, and Boolean operations to identify the different components of the interdigitated cement-bone regions. For laboratory prepared specimens, there were small errors in the estimated resorbed bone volume fraction ($\text{reBVfr} = 0.11 \pm 0.09$) and loss in contact area fraction ($\text{CAfr} = 0.06 \pm 0.15$). These values would be zero if there were no error in the method. For the postmortem specimens, the resorbed volume fraction ($\text{reBVfr} = 0.85 \pm 0.16$) was large, meaning that only 15% of the cement mold shape was still filled with bone. The loss of contact area fraction ($\text{CAfr} = 0.84 \pm 0.17$) was similarly large. This new approach provides a convenient method to visualize and quantify trabecular bone loss from interdigitated regions from postmortem retrievals. The technique also illustrates for the first time that there are dramatic changes in how bone is fixed to cement following *in vivo* service.

Introduction

Maintaining implant fixation during *in vivo* service of total joint replacements is critical to prevent aseptic loosening and need for revision. There has been longstanding interest in using postmortem retrievals to understand the *in vivo* function of joint replacements and to explore potential loosening mechanisms (Bishop et al., 2009; Charnley, 1979; Kwong et al., 1992; Maloney et al., 2002; Rao et al., 2010). For cemented fixation, identifying patterns of bone resorption at the cement-bone interface could improve our understanding of how

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implants loosen and also point to alternative designs or surgical techniques to improve long term fixation. Cemented knee arthroplasty utilizes doughy PMMA cement that infiltrates the bone bed and flows around trabecular bone prior to self-polymerization. The cement creates a mold around the individual trabeculae (Miller et al., 2010) and could serve as a means to identify the original state of the cement-bone interface prior to any biological changes during *in vivo* service.

In this work, we developed a new micro-computed tomography (μ CT) image processing approach to estimate the state of cement-bone interlock at the time of implantation and following *in vivo* service using *enbloc* retrievals from the tibial components of knee replacements. Laboratory prepared specimens, where there would be no biological bone resorption, were used as controls to validate the approach and estimate errors. We asked two research questions. Can the amount of resorbed bone be estimated using the ‘mold shape’ created by viscous cement flowing and curing around trabeculae? Based on the initial mold shape, how much bone resorbs from postmortem retrievals?

Methods

Specimen Preparation

Laboratory-prepared samples were created from a fresh-frozen proximal tibia (male, age 51) that was prepared for a total knee replacement by performing a trans-axial cut at the subchondral level, followed by lavage with suction on the cut bone surface. The bone was warmed to 32 deg C and standard viscosity PMMA cement (Simplex, Stryker Orthopaedics, Mahwah, NJ) was applied to the bone surface in a doughy state using digital pressure and pressing motion with a spatula prior to placement of a flat surrogate metal ‘tibial tray’ (without stem). The amount of cement applied was chosen to approximate that used for the postmortem retrievals. Two *enbloc*, postmortem cemented tibial components were used to create samples for the ‘postmortem’ group. These were derived from: (1) an age 82 male after 6 years of service with a NexGen CoCr metal tray (Zimmer Inc., Warsaw, IN, USA), and (2) an age 78 male after 10 years of service with an AMK CoCr metal tray (Depuy Orthopaedics, Warsaw, IN, USA). The laboratory-prepared and postmortem constructs were sectioned through the tibial tray in the sagittal and frontal planes to create specimens with 8mm $\times$ 8mm cross sections containing cement, bone, and the interdigitated cement-bone interface. Cement-bone specimens were randomly selected from the underside of the tibial tray for the laboratory-prepared (n=10) and postmortem retrieval (n=20) groups. Donor bones were provided by the Anatomical Gift Programs at SUNY Upstate Medical University and Case Western Reserve University.

Image Processing

Micro-CT scans at 16 μ m resolution (Scanco 40, Wayne, PA) were obtained for each specimen in air, and a sub region of 4mm $\times$ 4mm cross-section were used for analysis (Figure 1A). Figure 1B shows a small 2-D representation of the cement-bone interface. MIMICS (Materialise, Leuven, Belgium) was used to identify bone, isolated bone (not connected to the supporting trabecular bone bed, Figure 1C), and cement (Figure 1D) using thresholding and region growing operations. Bone thresholding was performed using uniform thresholding, meaning that the same lower threshold level (480 mg/cc HA equivalent) was used for all bone images. An 8 voxel dilation followed by an 8 voxel erosion (MIMICS ‘close’ operation, Figure 1E) was used to identify the cement mold shape or ‘cement cavities’. This process filled cavities with a width up to 256 μ m. Finally, Boolean operations (Figure 1F) were used to identify interdigitated bone and estimated resorbed bone.

We developed several parameters to describe the local cement-bone morphology. Interdigitation depth described the initial extent of cement penetration into the bone (see Figure 2). Interdigitated (inBV), isolated (isBV), and resorbed bone volume (reBV) (see Figure 1) were normalized to the cross sectional area of the specimen. Resorbed BV fraction (reBVfr) was defined as $\text{reBV}/(\text{reBV}+\text{inBV}+\text{isBV})$. The estimated initial contact area fraction (esCAfr) between cement and bone was determined for the initial ‘mold state’ plus the adjacent support bone (orange in Figure 1). The current CAF (curCAfr) was determined using all post-resorption bone components. The esCAfr and curCAfr were normalized to cross sectional area. The loss in CAF was calculated as: $(\text{esCAfr}-\text{curCAfr})/\text{esCAfr}$. For the validation study using laboratory prepared specimens where there is no resorption, if there were no gaps between interdigitated cement and bone, then: $\text{reBV}=0$, $\text{reBVfr}=0$, and loss of CAF=0.

Two sample t-tests with Bonferroni correction for multiple sampling were used to determine if the morphology parameters were different for the laboratory prepared and postmortem specimens.

Results

For the validation study with laboratory prepared specimens (Figure 2), there were small errors in the estimated resorbed bone volume fraction ($\text{reBVfr}=0.11\pm0.09$) and loss in contact area fraction ($\text{CAF}=0.06\pm0.15$) (Table 1). The estimated initial interdigitation depth was very similar for the lab-prepared and postmortem groups, indicating that the initial state of cement infiltration was comparable. For the postmortem specimens, the amount of estimated resorbed bone was often quite dramatic (Figure 3, shown in blue). The initial estimated cement-bone contact area fraction (esCAfr) was also similar for the two groups. In contrast, the resorbed volume fraction (reBVfr) for the postmortem specimens was 0.85 ± 0.16 , meaning that only 15% of the cement mold shape was still filled with bone. In addition, the loss of CAF was also extensive (0.84 ± 0.17).

It is interesting to note that the amount of bony resorption could vary widely in different regions from the same donor bone (Figure 4). This example shows three samples from the medial plateau region of the donor bone with six years *in vivo* service. Some interdigitated regions were almost completely resorbed while others maintained robust interdigitation.

Discussion

The results of this study suggest that the mold shape left by cement that flows around trabeculae can be used to estimate the original trabecular volume in the interdigitated region. Errors with this method are on the order of 10% and are likely due to the fact that cement does not flow in perfect apposition with the bone and small gaps may be present after the cement cures. Further, the cement shrinks upon polymerization (Gilbert et al., 2000), and this could also cause small gaps at the interface. The results also show that bony resorption can be extensive following *in vivo* service with resorbed bone volume fractions of 85% and loss of cement-bone contact area fractions of 84%.

There have been a number of different approaches used to quantify the interlock between cement and bone. At the apparent level, Mann and coworkers (Mann et al., 1997) identified the quantity of interdigitated bone using the apparent density of the interlocked bone multiplied by the depth of interdigitation. Maher and McCormack (Maher and McCormack, 1999) defined a random undulating parameter to describe the interlock between cement and bone using two-dimensional images of sections from lab-prepared cemented hip replacements. Arola and coworkers (Arola et al., 2001) developed an estimate of the

apparent volume of interdigitation using concepts from surface profilometry. The new approach presented here builds on these earlier concepts through use of 3D high-resolution micro-CT imaging and the ability to estimate the relative amounts of interdigitation in the initial postoperative condition and following bone remodeling with *in vivo* use.

There are several limitations to this study. Only two postmortem retrievals were used and it is possible that other retrievals will have different amounts of resorbed and residual interdigitated bone. We have sectioned (but not quantitatively analyzed) shorter and longer term implants and they all exhibit the characteristic loss of interdigitation shown here. Bone resorption from interdigitated regions with cemented hip replacements also has been reported by our group (Mann et al., 2010). A reasonable sample population with a wide range of years in service will be needed to answer important questions of temporal changes of bone resorption. The errors from our lab prepared specimens were not negligible, but were small relative to the magnitude of resorption in the retrievals. If errors were systematic (constant across all conditions), the average resorbed bone volume fraction would be 74% (85%-11% error) and the contact area fraction would be 78% (84%-6% error). However, it is difficult to know the systematic error for each specimen and the error for each will likely be different. For constructs with small amounts of resorption, care should be taken in interpreting results. It is possible that other forms of cement porosity at the trabeculae-cement interface could confound results. For example, trapped fat or fluid could form in the cement along the interface. In addition, if the original trabecular were very thick, the dilation and erosion procedure might not be sufficient to capture all of the morphology. Thresholding of the bone was conducted using a fixed gray scale value. It is possible that more complex thresholding algorithms could capture details of the bone morphology (Waarsing et al., 2004).

The finding that some regions can maintain good interlock, while others resorb within the same donor bone, suggests that resorption may not be a biocompatibility or thermal necrosis issue. For the example shown (Figure 3), the greatest residual interdigitated bone was located below the center of the medial condyle. It is possible that femoro-tibial contact stresses are transferred through this region, thereby maintaining trabecular stress at physiologic levels. Spatial and temporal mapping of the interdigitation patterns with a much larger series would be very useful to understand how fixation via cement-bone interdigitation changes following *in vivo* service.

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Figure 1.

A series of Boolean operations was performed using micro-CT images of 4mm×4mm subregions (A, shown as shaded region) of the cement-bone interface. The micro-CT images (B) were converted to image masks for bone, isolated bone (C) and cement (D). A dilation followed by erosion operation (E) was used to identify the cement cavity (F), the interdigitated bone, and the estimated resorbed bone. Isolated bone was defined as bone that was not in contact with the bone below the cement-bone interface. In contrast, interdigitated bone was bone that is contiguous with the bone below the cement-bone interface, but also was in the space defined by the cement with close operation (E).

Figure 2.

3-D reconstruction of the cement-bone interface from a laboratory prepared specimen illustrating the trabecular bone structure with interdigitated cement (A). The interdigitation depth for each sample was calculated as the average of measurements from four sampling quadrants as illustrated in panel A. The actual interdigitated bone (B) had a similar morphology when compared to the estimated interdigitated bone (C) calculated using the cement mold shape.

Figure 3.

3-D reconstruction showing estimated resorbed bone following 10 years in service. Cement cavities with small regions of isolated bone (red) are evident in the inset image (right). Following bony remodeling, there appears to be trabecular pedestal support of the cement layer. The specimen was taken from a region under the tibial tray with cross sectional area dimensions of 4 mm $\times$ 4mm.

Figure 4.

Samples from same donor bone (6 yrs in service) reveal a wide range of bony resorption. Blue shows estimated resorbed bone volume (ReBV). The estimated resorbed bone volume fraction (ReBV fr) and current contact area fraction (CAfr) values are shown.

Table 1

Morphology results of postmortem vs. lab-prepared specimens.

Morphology Parameter	Lab Prepared (n=10)	Postmortem (n=20)	p-value
Interdigitation depth (mm)	2.67 (0.54)	2.95 (0.65)	0.49
Interdigitated BV (inBV, mm ³ /mm ²)	0.20 (0.05)	0.06 (0.11)	0.0039
Isolated BV (isBV, mm ³ /mm ²)	NA	0.003(0.005)	---
Resorbed BV (reBV, mm ³ /mm ²)	0.02(0.02)*	0.28 (0.15)	<0.0001
Resorbed BV fraction (reBV fr)	0.11(0.09)*	0.85 (0.16)	<0.0001
Estimated initial contact area fraction (esCAfr, mm ² /mm ²)	4.78 (1.43)	4.72 (2.14)	0.396
Current contact area fraction (curCAfr, mm ² /mm ²)	4.36 (1.01)	0.84 (1.29)	<0.0001
Loss of CAfr	0.06 (0.15)*	0.84 (0.17)	<0.0001

Values indicated by a * would be zero if there were zero error with this method.