Mechanisms of Failure of the Cement-Bone Interface from En-bloc Retrieved Cemented Knee Replacements

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Introduction: Aseptic loosening is a leading cause of revision of total knee replacements (TKR) and excessive early migration of the tibial component portends failure (1). Progressive radiolucencies at the cement-bone interface from follow-up x-rays have also been associated with the loosening process (2), suggesting that the integrity of this interface is important for long-term fixation. The observations of progressive migration and interface radiolucencies suggest that both mechanical and biological factors contribute to the loosening process. In this study, we used post-mortem retrieved knee replacements from well-fixed components where there was substantial bony remodeling at the cement-bone interface. Mechanical tests to failure were performed on small samples of the cement-bone interface from the tibial tray to determine the mechanisms of failure. We hypothesized that (1) failure would localize to the cement-bone interface, that (2) the interface strength would be greater in compression than tension, and (3) interface strength would be proportional to the amount of bony support.

Methods: Two radiographically well-fixed, en-bloc retrieved cemented tibial components were obtained from the author’s institution’s (82-year-old male with NexGen [Zimmer] at 6 years in service, and a 75-year-old female with Scorpio [Stryker] at unknown time in service). The tibial components including tray, cement, and bone were mounted in a holding device and sectioned into approximately 10mm slabs in the sagittal plane using a water-irrigated, silicone carbide saw. The slabs were cut into small rectangular test specimens; cuts were made to exclude the keel so that loading could be made orthogonal to the plane of the interface (Fig 1). A total of 35 specimens (17 compression/18 tension) were created (35 to 92 mm² cross-sectional area).

Specimens were imaged at 16um using a μCT scanner (Fig 1) to document interface morphology. The bone volume fraction (bone volume/total volume, BV/TV) of the trabecular bone distal to the cement-well layer as well as the bone density was determined. The amount of contact between the cement and bone was determined using a μCT-based stereology approach. The contact index (CI) was determined for each specimen by projecting a grid of lines across the cement-bone interface and dividing the number of contact points between cement and bone by the number of projection lines.

The specimens were stained with alizarin red for better visualization of the interface and lightly coated with black spray paint to enhance contrast for digital image correlation (DIC) analysis. Specimens were bonded to a top fixture with epoxy and to a base fixture using PMMA cement. Mechanical tests to failure in compression and tension were conducted in displacement control with failure defined as a 20% decrease in load from a previous peak. Images of the interfaces were captured during loading and micro-motion at the cement-bone interfaces were quantified using DIC techniques. Peak strength and energy to failure were calculated. Half of the specimens from each donor bone were tested to failure in each in compression and tension. Two-sample t-tests were used to compare tension and compression results. Linear regression was used to assess relationships between bone morphology and interface strength.

Results: The cement-bone interface often contained regions of apposition between the cement and bone, usually at the extent of cement penetration into the bone (Fig 1). There was evidence of extensive bone resorption from the cement, and occasionally, fibrous tissue between the cement and bone. In tension, failure typically occurred at the interface between cement and bone (Fig 2). In compression, failure generally occurred in the trabeculae below the cement-bone interface (mean 3.5mm). The cement-bone interface moved under compression (closed), but did not fail.

![Figure 1](Diagram of tray/cement/bone specimen in experimental setup (left). MicroCT of a post mortem retrieved tibial tray component (right)).](Diagram of tray/cement/bone specimen in experimental setup (left). MicroCT of a post mortem retrieved tibial tray component (right)).

![Figure 2](Relative contributions of cement, bone, and cement-bone interfaces to the failure process in tension (left) and compression (right). Interface strain (**) was normalized to a gage length of 1.](Relative contributions of cement, bone, and cement-bone interfaces to the failure process in tension (left) and compression (right). Interface strain (**) was normalized to a gage length of 1.)

The strength of the cement-bone interface was approximately three times greater (P=0.0003) in compression (2.9±1.9 MPa) when compared with tension (0.90±0.63 MPa). The energy to failure was significantly greater (P=0.005) in compression (1.14±1.26 MPa-mm) than in tension (0.24±0.30 MPa-mm). Specimens with a higher BV/TV had a greater strength in compression (r²=0.46, P=0.0027) (Fig 3), but there was no corresponding relationship in tension (r²<0.001, P=0.97). Similarly, specimens with greater CI had greater strength in compression (r²=0.47, P=0.0025), but not in tension (r²=0.06, P=0.78). It is interesting to note that specimens with more bone (higher BV/TV), did not have more cement-bone contact (r²=0.019). Using multiple linear regression analysis, both CI and BV/TV contribute positively to compressive strength (r²=0.74, P=0.0001).

![Figure 3](Trabecular bone volume fraction (BV/TV) distal to the cement was positively correlated with strength in compression (hypothesis 3).](Trabecular bone volume fraction (BV/TV) distal to the cement was positively correlated with strength in compression, but not in tension.)

Discussion: Failure did not always localize to the cement-bone interface (hypothesis 1). In tension, failure always occurred at the interface, while in compression, failure occurred in the trabeculae below the interface. Maintenance of this trabecular region would seem important to prevent migration and loosening of the tibial component. With compressive loading, it appears that the quantity of bone beneath the cement layer and the amount of bony contact between the cement and bone will influence the strength of the cement-bone interface (hypothesis 2). Not surprisingly, the ability to support tensile loads at the cement-bone interface is much lower than compressive loads and may contribute to the loosening process for situations where there is eccentric loading on the component (hypothesis 3).

For these two well-fixed components, the morphology of the cement-bone interface following in vivo service is substantially changed from the morphology present at the completion of surgery. Both components appear to support the cement layer under the tibial tray at the extent of cement penetration into the bone, while there is extensive bone resorption in regions where the bone originally interdigitated with cement.


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