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Biomechanical analysis of impending femoral neck fractures: The role of percutaneous cement augmentation for osteolytic lesions

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ABSTRACT

Background: Management of impending pathologic femoral neck fractures includes internal fixation, arthroplasty and megaprostheses. The study aim was to determine the augmentative effect of cement injection for minimally invasive treatment of femoral neck lesions.

Methods: Twenty-seven cadaveric femora received a simulated osteolytic lesion previously shown to decrease the femur's failure load by 50%. Specimens were allocated to three groups of nine and loaded to failure in simulated single-leg stance: (1) percutaneous cementation + internal fixation (PCIF); (2) percutaneous cementation (PC); and (3) internal fixation (IF). Lesion-only and augmented finite element models were virtually loaded and stresses were queried adjacent to the lesion.

Findings: PCIF resulted in the largest failure load though the increase was not significantly greater than the PC or IF groups. Inspection of the PC and PCIF specimens indicated that the generation of a cement column that spanned the superior and inferior cortices of the femoral neck increased failure loads significantly. Finite element analysis indicated that IF and PCIF constructs decreased the stress adjacent to the lesion to intact femur levels. Cementation without superior-to-inferior femoral neck cortical contact did not restore proximal femoral stress toward the intact condition.

Interpretation: Internal fixation alone and internal fixation with or without cementation produce similar levels of mechanical augmentation in femora containing a high-risk lesion of impending fracture. A cement injection technique that produces a cement column contacting the superior and inferior femoral neck cortices confers the highest degree of biomechanical stability, should percutaneous cementation alone be performed.

1. Introduction

Surgical management of impending pathologic femoral neck fractures includes internal fixation, arthroplasty and tumor megaprostheses (Chandrasekar et al., 2009; Favorito and McGrath, 2001; Schneiderbauer et al., 2004). Metastatic disease involving the axial and appendicular skeleton negatively impacts prognosis and life expectancy. Therefore, surgical methods should effectively address mechanical and tumorgenic pain while preserving function and limiting the postoperative rehabilitative course.

Percutaneous cement augmentation of metastatic lesions of the spine is an effective treatment modality with benefits in pain reduction and functional preservation (Eleraky et al., 2011; Konig et al., 2012). At our National Cancer Institute (NCI) designated center we have expanded the role of this technique to reinforce pathologic lesions of the appendicular skeleton. Potential benefits include improved mechanical stability of internal fixation constructs, pain reduction and the potential for "tumor kill" by the exothermic reaction of polymethylmethacrelate (PMMA) cement. Prophylactic fixation with cement augmentation is also less invasive than endoprosthetic reconstruction and may have improved hospitalization times and faster recovery; however this comparison has yet to be demonstrated. Although good clinical outcomes have been reported with cement augmentation (Dutka et al., 2006; Mrozek et al., 2005), its biomechanical effects have yet to be elucidated and have recently been the source of multiple investigations (Beckmann et al., 2011; Sutter et al., 2010).

Our hypothesis was that percutaneous cementation of internally fixed impending femoral neck fractures would increase the load bearing capacity of the construct (defined in terms of failure load) compared to internal fixation alone. We employed a human cadaveric biomechanical study to test this hypothesis with the purpose of comparing the load to failure of three constructs: 1) cement alone; 2) internal fixation with cement augmentation; and 3) internal fixation alone. This information

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may afford insight regarding the augmentation strategy for patients at high-risk of femoral neck fracture.

2. Methods

2.1. Specimen preparation

Twenty-seven (n = 27), un-matched femora were dissected from fresh-frozen cadavers (average age: 58.4 years (10.1 SD) (range: 42–80 years)), leaving the bone devoid of soft tissue. Anterior–posterior (AP) and lateral radiographs were taken to confirm a lack of pre-existing bony disease or trauma. Bone mineral density (BMD) values were assessed by dual energy X-ray absorptiometry (DEXA) (Lunar Prodigy Advance, GE Healthcare, Madison, WI) with average values of 0.834 g/cm^2 (0.162 SD) and an average T-score of −1.3 (range: −4.1–1.6). The physical dimensions of each femur were measured (Tables 1 and 2) and included: femur length, femoral neck cross sectional area (modeled as an ellipse), and neck cross sectional moment of inertia (CSMI). Hip axis length (HAL) and neck-shaft angle were measured on AP radiographs (Image J, NIH, Bethesda, MD).

Each femur received a high-risk pathologic lesion in the femoral neck using a methodological approach previously reported by our group (Fig. 1) (Alexander et al., 2013). "High-risk" was defined according to the clinically relevant and implemented Mirels score (Mirels, 1989) and Harrington's criteria (Harrington, 1986). As our study was cadaveric in nature, "pain" as a scoring metric was not included. Lesions were created to satisfy a Mirels score of nine by being osteolytic (3 points), encompassing greater than 2/3 of the femoral neck diameter (3 points), and located in the proximal femur (3 points). Harrington's proposed criteria of lesion size greater than 25 mm and axial cortical involvement of greater than 50% were incorporated in the lesion as well. The neck lesion was created through a foveal approach and a curved curette was used to remove the trabeculae within the neck region such that the lesion encompassed 2/3 of the femoral neck width. This was confirmed with AP and lateral fluoroscopy images. A 25 mm diameter cortical insult was created in the outer cortex of the calcar. The defect was centered over the inferomedial femoral neck above the lesser trochanter. A high-speed burr was use to thin the cortical bone by 50% within the 25 mm circle. The same author created all lesions to promote reproducibility of the technique (G.E.A.). The generated high-risk lesion has recently been reported by our group to reduce the failure load of the femur in simulated single leg stance by 50% relative to matched control femora (Alexander et al., 2013). The specimens were wrapped in saline-soaked gauze and stored at −70 °C in sealed plastic bags.

2.2. Experimental design

Specimens were allocated to one of three groups for biomechanical evaluation: (1) percutaneous cementation + internal fixation (PCIF, n = 9); (2) percutaneous cementation alone (PC, n = 9); and (3) internal fixation alone (IF, n = 9). A sample size and power analysis (SPSS v.20, IBM, Armonk, NY) was performed using the mean and variance of failure load data collected from specimens destructively tested in our prior work (Alexander et al., 2013). Assuming an expected range in failure load between groups of 30%, a sample size of n = 9 per treatment group powered the study at the β = 0.853 level. Specimen allocation was such that each treatment group was statistically equivalent with regard to BMD/T-Score, donor demographics and physical dimensions (Tables 1 and 2).

2.3. Implants

A stainless steel fracture fixation system (Talon™ Compression Hip Screw, Orthopaedic Designs North America, Inc., Tampa, FL) was utilized for fixation of PCIF and IF specimens. In these groups, the femoral diaphysis was accessed and reamed until appropriate cortical contact and diaphyseal fill was achieved via a lateral, trochanteric approach. Femoral preparation was performed using the manufacturer's instrumentation and technique recommendations. After insertion of the nail, lag screws were implanted with the tip of the screw positioned 5 mm distal to subchondral bone in the "center–center" position as qualitatively assessed on AP and lateral radiographs (Baumgaertner et al., 1995). The neck-shaft angle of all implanted devices was 125° and the implant's deployable splines were not utilized.

2.4. Cementation of the high risk lesion

Under fluoroscopic guidance, the anterior femoral neck was penetrated with a sharp trochar providing access to the defect. After removal of the trochar, with the cannula still inserted in the lesion, a Kyphon balloon (Medtronic, Memphis, TN) was inserted and inflated with radio-opaque contrast to fully expand the balloon maximally within each specimen-specific sized lesion (Fig. 2). Polymethyl methacrylate cement (PMMA) (Kyphon® HV-R®, Medtronic) was introduced into the defect via the cannula. After filling the defect, the balloon insufflated within the lesion to force the cement to interdigitate into the surrounding cancellous bone. The balloon was then removed and any void created by the balloon was filled with cement. This process was repeated until circumferential cancellous interdigitation was achieved on AP and lateral radiographs (Fig. 2). In the PCIF treatment arm, cementation was performed after internal fixation.

2.5. Biomechanical testing

Prior to testing, the femurs were thawed overnight at 4 °C and stored at room temperature for at least 3 h. Each femur was shortened by 50% and 5 in. of the distal femur was potted in 1.5″ diameter polyvinylchloride (PVC) pipe in a custom-designed aluminum fixture with high strength resin (Bondo body filler, 3M, St. Paul, MN). We employed a biomechanical testing model similar to previous investigations (Alexander et al., 2013; Olsen et al., 2011; Ropars et al., 2008; Stoffel et al., 2008; Wheeler et al., 1997). The distal end of each specimen was secured to a custom-designed testing fixture and rigidly affixed to the base of a servoelectric load frame (Test Resources,

Table 1
Comparison of donor demographics between the PC, PCIF and IF treatment groups. Mean (SD).

Treatment group	Donor demographic				
	Age (yrs.)	Height (in.)	Weight (lbs.)	BMD (g/cm^2)	T-score
Percutaneous cement (PC)	59.6 (8.4)	65.9 (3.8)	252.8 (108.1)	0.8 (0.2)	−1.5 (1.4)
Cement + internal fixation (PCIF)	56.4 (12.8)	67.9 (13.0)	218.3 (70.7)	0.9 (0.2)	−1.3 (1.5)
Internal fixation (IF)	59.2 (9.5)	66.8 (4.0)	262.4 (68.2)	0.9 (0.2)	−1.2 (1.5)
P-value					
PC vs. PCIF	0.550	0.236	0.435	0.752	0.773
PC vs. IF	0.938	0.635	0.823	0.585	0.634
PCIF vs. IF	0.608	0.513	0.197	0.811	0.856