3-2-2008

Viscoelastic Failure Properties of Cortical Bone are Reduced by Bone Mineralization

Timothy L. Norman
Cedarville University, tnorman@cedarville.edu

Suzanne Smith

Christopher Brown

Viscoelastic Failure Properties of Cortical Bone are Reduced by Bone Mineralization

Timothy L. Norman[1,2], Suzanne Smith[2], Christopher Brown[2]
[1]Engineering and Computer Science, Cedarville University, Cedarville, OH; [2]Orthopaedics, West Virginia University, Morgantown, WV
tnorman@cedarville.edu

Introduction: Adequacy of biological fixation for cementless femoral implants depends on numerous factors including the initial primary fixation of the implant [1-5] achieved via press-fit. However, contact stresses at the time of implant insertion result in creep, viscoelastic time-dependent deformation under constant load [6]. Creep due to hoop stress may threaten initial stability by reducing the contact area for load transfer between bone and implant before new bone growth can occur [7] and can also result in longitudinal fracture of the bone. Previous studies have shown that post-yield properties decline with increases in mineral content [8,9]. The objective of this study was to investigate the relationships between bone viscoelastic behavior and mineralization under simulated press-fit (transverse) loading. It was hypothesized that the viscoelastic properties of bone are diminished as bone becomes more mineralized.

Materials and Methods: Nine fresh human femora were obtained from 7 male and 2 female cadavers (mean age 39 ± 13 years). From these femora, a total of 14 right circular cylinders 19 mm in length, with a 19 mm inner wall diameter and a mean wall thickness of 2 ± 0.05 mm were wet machined and tested as described previously [10]. Four unidirectional strain gages were mounted on the outer surface of the specimen on the anterior, posterior, lateral and medial aspects; all gages were oriented to measure hoop strain. A test fixture applied internal pressure to the specimen while it was submerged in saline at 37° C [11]. A multi-phase loading protocol was followed to observe creep behavior [12] (Fig. 1). Creep strain was calculated as the difference between hoop strain measured at the beginning and at the end of the one-minute loading phase. Creep strain and creep rate were determined for each constant pressure phase by linear regression analysis of creep strain data during the last 40 seconds of the one-minute load phase. Time-to-failure and viscoelastic strain at failure at prescribed stress levels were also recorded. After testing, a remaining portion from each quadrant of each tested specimen was ashed in a muffle furnace at 600°C to determine mineral percentage according to previously published procedures [13]. Simple regression analysis was used to identify relationships between mineral percentage and bone viscoelastic parameters including creep rate, permanent strain, time-to-failure and viscoelastic failure strain. JMP™ (SAS Institute, Cary, NC) was used to perform the analysis. Statistical significance was set at $p < 0.05$.

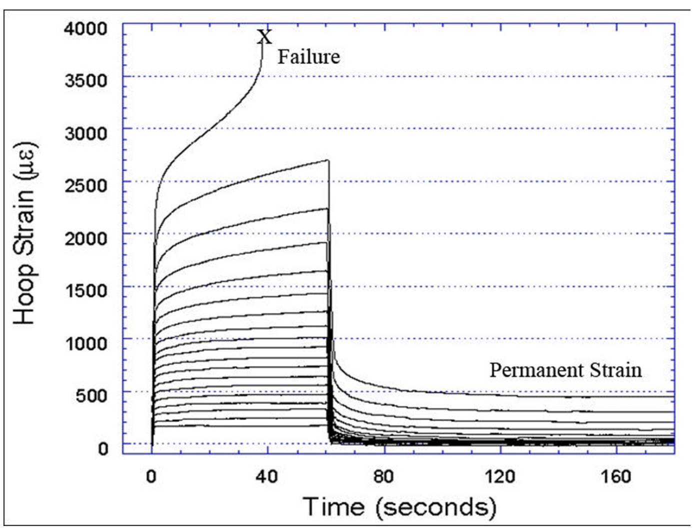

Figure 1. Multiphase loading illustrating creep, creep rate, failure and permanent strain.

Results: Statistical analysis revealed that there was no significant difference between the mineral percentages of the four cortices, so the data were pooled yielding a total of 56 specimens analyzed. Results revealed no significant relationship between mineral percentage and creep strain or the rate of creep. However, there were significant relationships between mineral percentage and maximum strain and strain at failure (Fig. 2). Results indicated that the more mineralized bone had lower maximum strain at the prescribed stress intervals and failed at lower maximum strain levels. There was also a marginally significant relationship between mineral percentage and time-to-failure ($p<0.07$), indicating that the more mineralized bone failed sooner under constant stress.

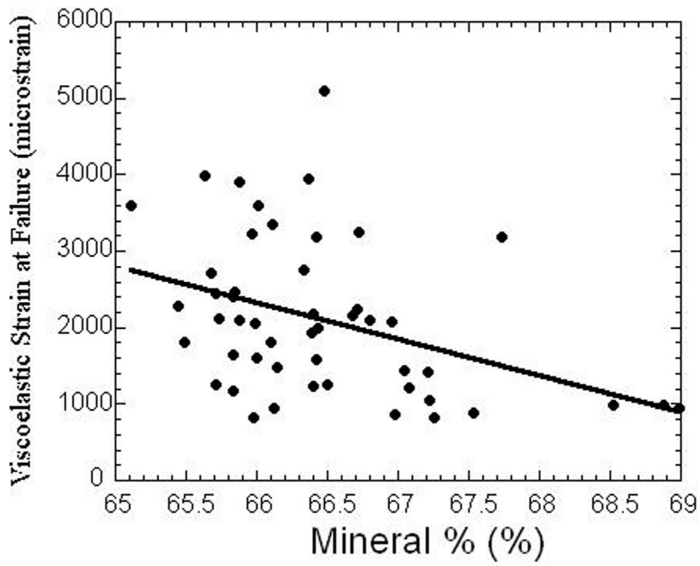

Figure 2. Variation in viscoelastic failure strain with mineral percentage.

Discussion: At the ultrastructural level, bone consists of collagen fibers cross-linked with mineral crystals to provide mechanical integrity for tension, compression and shear loading primarily in the long bone direction. Several studies have been conducted and models developed to understand the static, fatigue and viscoelastic behavior of bone in the longitudinal direction. Few studies have investigated the transverse viscoelastic behavior of bone despite its significance in joint replacement. This study, using a simulated press-fit loading environment, provides information on the dependence of transverse viscoelastic properties on mineral percentage. Results of this study indicated that time-dependent failure of human cortical bone in the transverse, or hoop, direction is significantly related to mineral percentage. Specifically, the maximum strain at failure during prolonged loading is reduced. The clinical significance of this study is related to the treatment of bone with antiresorptive agents that result in a more mineralized bone [14]. According to these results, treatment with antiresorptive agents could potentially reduce the maximum strain allowable in the hoop direction of a press-fit stem.

References: 1) Ling, Clin. Orthop. 1978. 2) Engh, Clin. Orthop. 1983. 3) Morscher, Clin. Orthop. 1983. 4) Robertson et al., Clin. Orthop. 1988. 5) Poss et al., Noncemented Total Hip Arthroplasty, 1988. 6) Norman et al., J. Biomech. Eng. 2006. 7) Blaha, The Adult Hip, 1998. 8) Les, J. Ortho. Res. 2002. 9) Currey, J. Biomech. 2004. 10) Brown et al., J. Biomech. Eng. 2002. 11) Brown et al., Exp. Tech. 2000. 12) Fondrk et al., J. Biomech. 1988. 13)Yeni et al., Bone 1998. 14) Mashiba et al., Bone 2001.