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Morphometric Predictors of Bone Fragility Suggest a Dichotomy in the Role of Osteons in the Resistance to Fracture of Human Cortical Bone

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MORPHOMETRIC PREDICTORS OF BONE FRAGILITY SUGGEST A DICHOTOMY IN THE ROLE OF OSTEONS IN THE RESISTANCE TO FRACTURE OF HUMAN CORTICAL BONE

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Introduction: Osteoporotic fractures have been historically associated with loss of bone mass;[1] however, other factors such as increased propensity to fall[2] and the quality[3] (e.g. fatigue microdamage, mineralization, collagen crosslinking and osteon morphology), the distribution of mass and architecture[4] of bone have also been implicated. Cortical bone obtained from the medial femoral neck (calcar) of femoral neck fracture patients was found to have significantly larger osteons, larger Haversian canals and a decreased number of osteons than patients that had not fractured[5]. It was hypothesized that these morphological differences may lower the fracture toughness of bone in the femoral necks of elderly women. The objective of this study was to investigate this hypothesis by examining the relationship between osteon morphology (osteon size, Haversian canal size, porosity and osteon density) and fracture toughness and to determine if the relationships are age related using cortical bone obtained from cadavers over an eight decade age range.

Materials and Methods: Sixty-one femurs and 38 tibias were obtained fresh from 35 male (avg. age 61.0 ± 19.4) and 26 female (avg. age 64.8 ± 20.0) cadavers with an age range of 22 to 94 years. Bulk sections of bone, 65 mm in length, were taken from the middiaphysis of the tibia and approximately 20 mm distal from the lesser trochanter of the femur as described previously[6]. Compact tension (mode I) and compact shear (mode II) fracture toughness specimens were wet machined from the medial and lateral cortices of the bulk specimens, tested, and tension (G_{Ic}) and shear (G_{IIc}) fracture toughness calculated as previously described[6]. After testing, a 200 mm thick, 2 mm wide and approximately 7 mm long transverse cross section was cut near the point of crack initiation from each fracture specimen using a low speed saw. Each piece was polished and stained with H+E for morphometric measurements using an image analysis system (Optimus, Edmunds, WA) and a transmitted light microscope (Olympus BH-2) under X40 magnification. Average measurements were taken from three different fields. In a selected field, the following were measured: total area of the selected field, total area of Haversian and Volkmann's canals and other pores; total area of osteons including Haversian canals; total number of osteons. The average area of a single pore (s.Po.Ar.), a measure of Haversian canal size, was calculated by the total area of pores per field divided by the number of osteons in the same field. Total porosity percentage (Po) was calculated by the total area of pores divided by the total field area. The average area of a single osteon (s.On.Ar.), or osteon size, was calculated by dividing the total osteon area by the number of osteons in the area. The osteon density (On.Dn.) was calculated by the total number of osteons divided by the selected field area. Statistical analysis of the results was performed using the JMP package (SAS Institute, Cary, NC). Generalized linear models (least-square procedures) were used to explain the relationships between the fracture toughness and morphological parameters. Statistical significance was set at $p < 0.05$.

Results: Tension (Fig. 1) and shear fracture toughness decreased with age while osteon density (Fig. 2) and porosity (Fig. 3) increased with age. Pore and osteon area did not change with age. When all variables investigated were considered together in the statistical model, the significant predictors of tension and shear fracture toughness were porosity (Po) (G_{Ic} and G_{IIc}: $p<0.0001$) and osteon density (On.Dn) (G_{Ic}: $p<0.0067$; G_{IIc}: $p<0.0021$). Porosity decreases toughness (Fig. 4) while osteon density increases toughness. When Haversian canal size (s.Po.Ar.) was considered separately, it was found that specimens with larger Haversian canals had lower toughness.

Discussion: Bone microstructure, namely porosity and osteonal features, has been of concern in numerous studies as a factor influencing fatigue and fracture characteristics of cortical bone. This research elucidates the underlying morphometric predictors of bone fragility as measured by fracture toughness. Our results show that both tension and shear fracture toughness decrease with age consistent with increased bone fractures with age reported in the literature. The most significant predictor of bone fragility was porosity followed by osteon density. These results elucidate a dichotomy in the role of the osteon in the resistance to crack growth. As the number of osteons increase, a longer and tougher path for crack propagation is created and fracture toughness increases. However, as osteons are created there is a corresponding increase in porosity which lowers toughness by reducing the net cross-sectional area. The combined effect of increased osteon density and porosity results in decreased toughness indicting the importance of bone porosity in the prediction of bone toughness. We also found that bone with larger Haversian canals are less fracture resistant and that Haversian canal size is not age related, consistent with other studies[7]. The increases in canal size may be related to some bone pathology ultimately leading to increased bone fragility and bone fractures (i.e. osteoporosis). Increases to Haversian canal size would indicate an imbalance between the resorption/formation (R/F) stages of bone remodeling where resorption is favored resulting in larger pores as discussed previously.[5,7] These results show that the widely reported increases in porosity in cortical bone with age are due primarily to increases in osteon density that occur with age rather than larger Haversian canal size. From a crack propagation perspective, the results of this study suggest that porosity has a greater influence on crack propagation than the size or density of the osteons. Therefore, with the exception of osteon area, the observations made in femoral neck fracture patients have merit in the long bones as well.

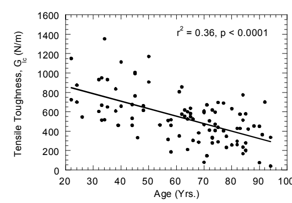

Fig. 1 Fracture toughness decreases with age.

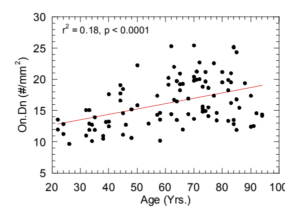

Fig. 2. Osteon density increases with age.

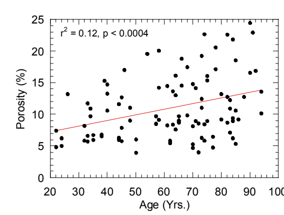

Fig. 3. Porosity increases with age.

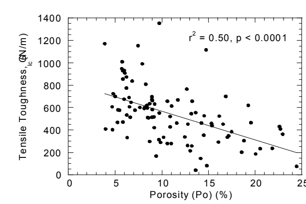

Fig. 4. Porosity reduces fracture toughness.

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