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Fracture Toughness of Human Femoral Neck Cortical Bone is Reduced with Age and with Increased Osteon Eccentricity

Y. N. Yeni

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

FRACTURE TOUGHNESS OF HUMAN FEMORAL NECK CORTICAL BONE IS REDUCED WITH AGE AND WITH INCREASED OSTEON ECCENTRICITY

+*,**Yeni, Y N; *Norman T L
+* Dept of Mechanical and Aerospace Engineering and Orthopedics, West Virginia University, Morgantown, WV, USA
yeni@bjc.hfh.edu

INTRODUCTION Changes in the blood vessel formation patterns that result in formation of "giant" pores have been implicated in increased risk of hip fracture [1]. This might suggest that changes in the microstructural morphology would correlate with changes in mechanical properties of the tissue. However, the association of femoral neck fracture fragility (fracture toughness) with porosity or areas of remodeling was non-significant for tensile and only mild for shearing mode of fracture in a previous study that examined the fracture toughness of human femoral neck cortex [2]. In the previous study, average measurements of osteonal area, porosity and density were performed but the morphology of osteons, pores and their variability within a specimen were not considered. Also, no significant trend of fracture toughness with age was found for donors older than 50 years.

We examined the relationship of human femoral neck cortical bone fracture toughness with osteon and pore eccentricity (deviation from a circular shape), size, and variability of these parameters (coefficient of variation) within a specimen for a wider range of age. The eccentricity and size-variability of osteons/pores were of interest because of their similarity with fiber properties that determine mechanical properties of fiber composites similar to bone.

METHODS Thirty-eight femoral necks were obtained fresh from 24 men (age 58.0±18.0 years, range 22–90 years) and 14 women (age 70.8±19.0 years, range 24–90 years) cadavers. One-millimeter thick compact tension and compact shear specimens were wet-machined from the posterior and inferior cortices, respectively, using a computer numerical control (CNC) milling machine [2]. A precrack was placed 0.25 mm into the chevron notch of the specimens using a razor blade. The specimens were tested using an MTS (Minneapolis, MN) servohydraulic testing machine at a displacement rate of 0.02 cm/min. The strain energy release rate (fracture toughness) for mode I (G_I) and mode II (G_{II}) loading were calculated from critical load, compliance, specimen thickness and crack length using standard equations [2].

After mechanical testing, a 200–300-μm-thick cross-section was cut near the point of crack initiation from each fracture surface and stained with hemotoxylin-eosin. Histomorphometrical measurements were performed using the Image Analysis System (Optimas, Edmonds, WA) under 340 magnification. Area and circumference of each pore and osteon in the cross-section was recorded by tracing their boundaries on the digitized images. Osteonal area (On.Ar/B.Ar), osteon size (On.Ar), osteon density (On.Dn), porosity (Po), and Haversian pore size (H.Po.Ar) were calculated [1]. Aspect ratio (G/A) of each pore (G/A.Po) and osteon (G/A.On) was calculated as:

$$G/A = (A/\pi)^{1/2} / (P/2\pi)$$

where A and P are the area and the perimeter of an ellipse, respectively (G/A=1; the smaller the more elliptic rather than circular). The area and the perimeter are calculated as:

$$A=\pi ab \text{ and } P=\pi(a+b)$$

where a and b are the major and the minor radii of the ellipse. Note that the formula for perimeter is only approximate but considered valid for ellipses with low eccentricity. In addition to the average measurements for each specimen, the variability of these parameters within a specimen (eg: coefficient of variation of pore size, COV.H.Po.Ar, within a specimen) were calculated.

Wet density (ρ_w=wet weight/volume), dry density (ρ_d=dry weight/volume) and mineralization (%Min=(ash weight)/(dry weight)) were also calculated from the volume, wet weight, dry weight and ash weight of the remaining samples as explained previously [2].

Regression analyses were used to examine the correlations between fracture toughness, age and other parameters. Stepwise regression was used to determine the best independent predictors. Differences in the histomorphometrical and compositional parameters between cortices (between tensile and shear specimens) were examined using a paired t-test (SPSS, SPSS Inc.).

RESULTS Po, On.Ar/B.Ar, COV.H.Po.Ar, G/A.H.Po, COV.G/A.H.Po, Avg.On.Ar, COV.On.Ar, COV.G/A.On *were not different between the posterior* (7.01±3.31 %, 47.6±12.0 %, 0.716±0.203, 0.789±0.0275, 0.0760±0.0187, 33.3±8.4 $*10^{-3}$ mm^2, 0.425±0.117, 0.0475±0.0139, respectively) *and inferior cortices* (5.96±3.68 %, 48.1±10.3 %, 0.732±0.231, 0.784±0.0241, 0.0854±0.0187, 30.4±7.5 $*10^{-3}$ mm^2, 0.435±0.110, 0.0461±0.0116, respectively) ($0.05<p<0.8$). *Posterior cortex had a greater* ρ_w, ρ_d, Avg.H.Po.Ar and Avg,G/A.On (1.90±0.065 g/cm^3, 1.67±0.065 g/cm^3, 2.9±1.2 $*10^{-3}$ mm^2, 0.880±0.0182, respectively) *than the inferior cortex* (1.81±0.123 g/cm^3, 1.56±0.109 g/cm^3, 2.3±1.3 $*10^{-3}$ mm^2, 0.875±0.0115) ($0.0001<p<0.05$) *whereas* On.Dn and %Min *were less in the posterior* (13.1±4.36 /mm^2, 66.4±5.96 %) *than in the inferior cortex* ($p<0.03$).

A weak but significant decrease of tensile fracture toughness with age was noted (Fig. 1) whereas shear fracture toughness did not vary significantly with age ($p>0.7$).

Tensile fracture toughness increased with increasing G/A.On (r=0.372, p=0.022), i.e., bone tissue with more circular osteons were more resistant to tensile crack growth than those with more elliptical osteons (Fig. 1). G_I also increased with increasing wet and dry density (r=0.670, $p<0.001$ and r=0.641, $p<0.001$, respectively). Other parameters of microstructural morphology and composition had a varying degree of non-significant correlation with G_I ($0.12<p<0.94$). Stepwise regression with age, showed that dry density and donor age were the best independent predictors of G_I (r^2_{adj}=0.36, $p_{model}<0.001$, $p_{\rho d}<0.001$, $p_{age}<0.02$).

Shear fracture toughness decreased with increasing porosity (r=-0.344, p=0.034) and increased with increasing dry density (r=0.348, p=0.032). Other parameters of micro-morphology and composition had a varying degree of non-significant correlation with G_{II} ($0.12<p<0.97$).

Osteon density increased (r=0.344, p=0.034) while G/A (r=-0.489, p=0.002), wet density (r=-0.403, p=0.012) and dry density (r=-0.360, p=0.026) decreased with age in the posterior cortex of the neck. Haversian pore size increased (r=0.398, p=0.013) with age in the inferior cortex where G_{II} specimens were machined.

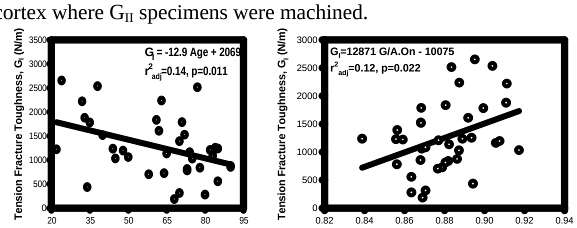

Figure 1a) Fracture toughness of the posterior aspect of human femoral neck cortex decreases with age and **b)** increases if osteons are more circular than elliptical.

DISCUSSION We have demonstrated, for the first time, that the fracture resistance of human femoral neck cortex decreases with age. The reduction in fracture resistance with age may be associated, in part, with the tendency of osteons to become less circular with age. This is consistent with sharper flaws being sources of higher stress concentration. The non-circular shape of osteons being due to an osteonal orientation oblique to the fracture axis is unlikely as this would increase rather than decrease toughness. Although bone density decreased with age, it contributed to increased susceptibility of the neck cortex to fracture independent from age.

A significant correlation between G_{II} and age was not observed. However, increasing Haversian pore size with age and decreasing fracture toughness with porosity found for the inferior cortex are consistent with the proposal that increasing number of large canals in the cortex may contribute to the fragility of femoral neck [2].

Overall, our data support that reduction of femoral neck cortex fracture toughness due to changes in the geometry of remodeling units contributes to the fragility of the femoral neck. Additional factors may be needed to increase the explained variability in fracture toughness.

REFERENCES [1] Bell et al., 1999, Bone, 24: 57. [2] Yeni&Norman, 2000, Bone, 26: 499.

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** Bone and Joint Center, Henry Ford Hospital, Detroit, Michigan, USA