A MODEL OF ENERGY DISSIPATION IN THE POST-YIELD DEFORMATION OF BONE

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INTRODUCTION

Bone fracture is a major concern for elderly because the toughness of aged bone becomes more susceptible to impact load.(6) It has been well documented that the post-yield behavior of bone determines the major part of the toughness of bone.(3,4) As a natural composite material, bone primarily comprises a hard mineral phase (mainly hydroxyapatite crystals) and a more compliant collagenous matrix (90% type I collagen).(5) From composite materials perspectives, the biomechanical properties of bone may be the function of the quality and spatial arrangement of its constituents. Some of previous studies have suggested that microcrack accumulation is a major mechanisms in energy absorption during the post-yield deformation of bone.(2,7-9,11-13) On the other hand, some studies indicate that the age-related changes in the collagen network may contribute significantly to the toughness of bone.[Wang, 2001 #101; Wang, 2002 #244; Zioupos, 1999 #253] Moreover, in a recent study Thomason et al. reported that a recoverable bond in the collagen molecules may contribute to the energy dissipation in the post-yield deformation of bone.(10) To elucidate the role of collagen in the post-yield deformation of bone, we proposed in this study that the microdamage accumulation leads to the surface energy dissipation during the post-yield deformation of bone, whereas the degradation and deformation in the collagen network are the major mechanisms in the inelastic and viscoelastic energy consumption.

ANALYTICAL TREATMENT

Figure 1 shows a typical strain-stress curve of bone in monotonic testing schemes. From the curve, the initial elastic modulus (E_0) can be determined by estimating the slope of the linear portion of the curve AB. The yield point (σ_y) separates the elastic and post-yield deformation of bone. After yielding, bone begins to show permanent deformation, which is characterized by a residue strain, ε_p. During the post-yield deformation (from B to C), bone loses its stiffness significantly (E_1). However, bone exhibits a significant viscoelastic behavior after yielding in terms of an unloaded and reloaded hysteresis. The toughness of bone (U_T) is usually defined as the area under the strain-stress curve (shaded area of ABCE). Hence, U_T can be divided into three components: the elastic energy (the area under unload curve-CED), viscoelastic energy (*i.e.*, the hysteresis area of CDC), and the plastic energy by the permanent deformation of bone (*i.e.*, the area of ABCD). In this study, we propose that: 1) the decreased elastic modulus with increasing post-yielded deformation of bone is due to microcrack accumulation because elastic modulus of bone is dominated by the mineral phase; 2) the irreversible energy consumption is induced by the denatured collagen around the microcracks; and 3) the viscoelastic behavior of bone during the post-yield deformation is contributed by the reversible collagen deformation.

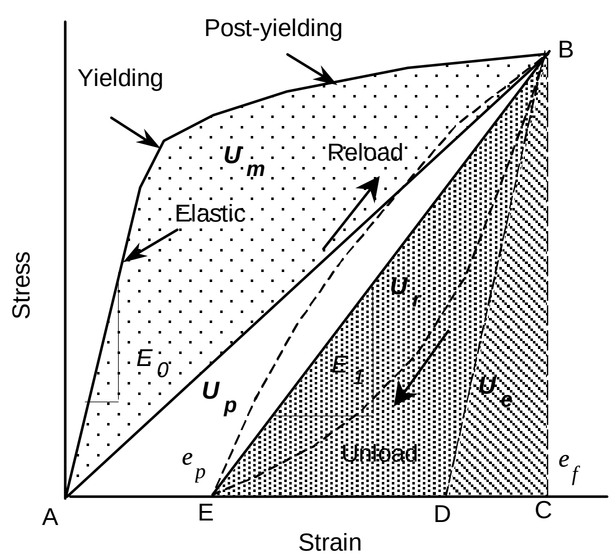

Figure 1. Determination of the energy dissipation in post yield of bone

Figure 2 shows a schematic representation of the model of the above assumptions. As shown in this figure, there would be two types of microdamages: microcracks (on the order of microns) and the nano

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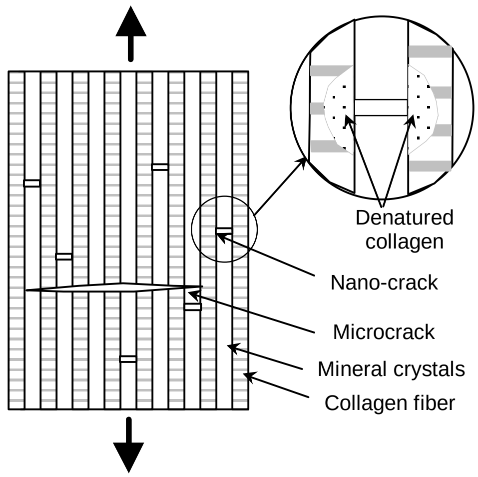

Figure 2. Schematic representation of microscopic failure at molecular level

cracks (on the order of nanometers). The former generates new surfaces in both the mineral and collagen phase, whereas the latter creates new surface only in the mineral phase. In terms of bone histomorphometry, the former corresponds to the microcracks seen in the stained sections of bone, whereas the latter is most probably manifested by the diffuse microdamages. For nano cracks, collagen around the crack tips is readily damaged by the stress concentration at the tips. Thus collagen denaturation (unravel due to breaking of hydrogen bonds) is anticipated by the mechanical stresses. Since such collagen denaturation is irreversible, the energy consumed by breaking these hydrogen bonds is most likely related to the irreversible deformation of bone (plastic deformation). Moreover, since more collagen fibers participate in carrying the load as microdamages cumulate, the mechanical behavior of bone reflects more characteristics of the behavior of collagen.

To distinguish between these three different forms of energy dissipation, a specially defined load-unload scheme can be used (Figure 1). Briefly, the elastic modulus (E) during post-yield deformation may be determined as an average value based on the slope of line BE. The energy due to microcrack formation may be calculated as the area of ABA under the stress-strain curve (U_m). The elastic energy may be calculated as the area of EBCE under the curve (U_r). The increment of elastic energy (U_r - U_e). could be considered as the released elastic energy due to the microcrack accumulation, which is dominated by the mineral phase of bone. Moreover, the plastic energy may be calculated as the area of ABEA under the curve (U_p).

EXPERIMENTS

To verify whether collagen denaturation increases with the extent of post-yielding deformation of bone, tensile specimens obtained from a human cadaveric femur were deformed in elastic, at yielding point, and pre-fracture levels. The percentage of denatured collagen molecules with respect to the total collagen amount was determined using a selective digestion technique described elsewhere.(1) The HPLC analysis of the specimens acquired from the bone samples revealed that the amount of collagen denaturation in bone (%DC) increased with the extent of post-yield deformation. In the elastic deformation region, the amount of denatured collagen (about 12%) is similar to the control specimens (unloaded). After yielding, %DC began to increase (approximately 18%) and more than doubled at the fracture (around 26%).

SUMMARY

This study proposed that the post-yield behavior of bone most likely involves three distinct mechanisms: microcrack formation, denaturation of collagen, and recoverable collagen deformation (viscoelasticity). By distinguishing different paths of energy dissipation during post-yield deformation of bone, one can study changes in both the collagen and mineral phases that may contribute to the decreased toughness of aged or disease bone tissues.

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REFERENCES

1. Bank RA, Krikken M, Beekman B, Stoop R, Maroudas A, Lafeber FP and te Koppele JM: A simplified measurement of degraded collagen in tissues: application in healthy, fibrillated and osteoarthritic cartilage. *Matrix Biol* 5:233-43, 1997
2. Burr DB, Forwood MR, Fyhrie DP, Martin RB, Schaffler MB and Turner CH: Bone microdamage and skeletal fragility in osteoporotic and stress fractures. *J Bone Miner Res* 1:6-15., 1997
3. Courtney AC, Hayes WC and Gibson LJ: Age-related differences in post-yield damage in human cortical bone. Experiment and model. *J Biomech* 11:1463-71., 1996
4. Fondrk MT, Bahniuk EH and Davy DT: A damage model for nonlinear tensile behavior of cortical bone. *J Biomech Eng* 5:533-41., 1999
5. Katz JL: Hard tissue as a composite material. I. Bounds on the elastic behavior. *J Biomech* 5:455-73, 1971
6. Martin B: Aging and strength of bone as a structural material. *Calcif Tissue Int* Suppl 1:S34-9; discussion S39-40, 1993
7. Norman TL, Yeni YN, Brown CU and Wang Z: Influence of microdamage on fracture toughness of the human femur and tibia. *Bone* 3:303-6., 1998
8. O'Brien FJ, Taylor D, Dickson GR and Lee TC: Visualisation of three-dimensional microcracks in compact bone. *J Anat* 413-20., 2000
9. Pidaparti RM and Liu Y: Bone stiffness changes due to microdamage under different loadings. *Biomed Mater Eng* 3:193-203, 1997
10. Thompson JB, Kindt JH, Drake B, Hansma HG, Morse DE and Hansma PK: Bone indentation recovery time correlates with bond reforming time. *Nature* 6865:773-6., 2001
11. Vashishth D, Koontz J, Qiu SJ, Lundin-Cannon D, Yeni YN, Schaffler MB and Fyhrie DP: In vivo diffuse damage in human vertebral trabecular bone. *Bone* 2:147-52., 2000
12. Yeh OC and Keaveny TM: Relative roles of microdamage and microfracture in the mechanical behavior of trabecular bone. *J Orthop Res* 6:1001-7., 2001
13. Zioupos P: Accumulation of in-vivo fatigue microdamage and its relation to biomechanical properties in ageing human cortical bone. *J Microsc* Pt 2:270-8., 2001