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Tensile behavior of cortical bone: Dependence of organic matrix material properties on bone mineral content

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Abstract

A porous composite model is developed to analyze the tensile mechanical properties of cortical bone. The effects of microporosity (volksman's canals, osteocyte lacunae) on the mechanical properties of bone tissue are taken into account. A simple shear lag theory, wherein tensile loads are transferred between overlapped mineral platelets by shearing of the organic matrix, is used to model the reinforcement provided by mineral platelets. It is assumed that the organic matrix is elastic in tension and elastic–perfectly plastic in shear until it fails. When organic matrix shear stresses at the ends of mineral platelets reach their yield values, the stress–strain curve of bone tissue starts to deviate from linear behavior. This is referred as the microscopic yield point. At the point where the stress–strain behavior of bone shows a sharp curvature, the organic phase reaches its shear yield stress value over the entire platelet. This is referred as the macroscopic yield point. It is assumed that after macroscopic yield, mineral platelets cannot contribute to the load bearing capacity of bone and that the mechanical behavior of cortical bone tissue is determined by the organic phase only. Bone fails when the principal stress of the organic matrix is reached. By assuming that mechanical properties of the organic matrix are dependent on bone mineral content below the macroscopic yield point, the model is used to predict the entire tensile mechanical behavior of cortical bone for different mineral contents. It is found that decreased shear yield stresses and organic matrix elastic moduli are required to explain the mechanical behavior of bones with lowered mineral contents. Under these conditions, the predicted values (elastic modulus, 0.002 yield stress and strain, and ultimate stress and strain) are within 15% of experimental data.

Keywords: Cortical bone tissue; Tensile behavior; Bone mineral content (BMC); Organic phase; Composite modeling

1. Introduction

Examining the tensile stress–strain behavior of bone tissue with different mineral contents is helpful to understand diseased conditions (e.g., osteoarthritis, osteopetrosis), in which the ratio of mineral to organic matrix content is affected (Li and Aspden, 1997). Previous models to explain the mechanical behavior of bone (other than elastic modulus) have used the phenomenon of microscopically observable damage to explain the mechanical properties of bone (Fondrk et al., 1999; Gao et al., 2003). This approach does not provide an insight into why the post-yield slope of the stress–strain curves with different mineral contents should be the same as that of decalcified bone (Kotha and Guzelsu, 2003a).

In our previous studies, we have used a simple shear lag theory with overlapped platelets to model the tensile mechanical behavior of bone tissue (Kotha and Guzelsu, 2000, 2002, 2003a; Kotha et al., 2000). This type of analysis has also been conducted by Jager and Fratzl

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(2000). The microporosity (volkman's canals, osteocyte lacunae, canaliculi and blood vessels) that affects the mechanical properties of bone tissue (Sevostianov and Kachanov, 2000) has not been considered in these models (Kotha and Guzelsu, 2002, 2003a). In this study, we incorporated two additional refinements to our previous models, namely: (1) the mechanical properties of the organic phase are affected by mineral content, and (2) the mechanical properties of bone tissue are affected by microporosity (Sevostianov and Kachanov, 2000). This approach allowed us to model the mechanical behavior of bones with lower mineral content, which were obtained by fluoride treatments (Kotha and Guzelsu, 2003a; Table 1) with better accuracy than our previous model (Kotha and Guzelsu, 2003a). The entire tensile stress–strain curve, the elastic modulus, the microscopic and macroscopic yield points, the ultimate stresses, and strains of bone tissue are presented as a function of bone mineral content (BMC).

2. Theoretical model

2.1. Basic principles of the model

Using our previous model (Kotha and Guzelsu, 2003a), predictions of tensile elastic moduli and ultimate strains in bones with lower mineral contents (fluoride treated) were almost 30% off from their corresponding experimental values (Kotha and Guzelsu, 2003a). In our previous model, even after taking into account the microporosity, using mean-field methods similar to those used by Sevostianov and Kachanov (Sevostianov and Kachanov, 2000), predicted values were not improved. In this study, we model the tensile mechanical properties of bone by taking into account: (1) the dependence of organic matrix mechanical properties on mineral content; (2) the load transfer between the overlapped mineral platelets (Jager and Fratzl, 2000; Ji and Gao, 2004; Kotha and Guzelsu, 2003a), and (3) the effect of microporosity.

To model the elastic modulus of organic matrix as a function of mineral content, the following relationships were tried: (i) a constant (independent of mineral content); (ii) a linear relationship (two constants) and (iii) a non-linear relationship (three constants). By matching experimental measurements to model predictions, we show that a non-linear relationship allows us to predict the mechanical properties of bone samples with reduced mineral content much better than a constant or a linear relationship. Presently, a relationship between the organic matrix and mineral content cannot be explicitly modeled, because the following phenomena that determine the extent of straight-jacketing of collagen molecules/microfibrils (McCutchen, 1975) by the bone mineral are not known: (i) the rearrangement and changes in orientation of collagen molecules/microfibrils due to removal of some mineral–organic interactions as mineral content is lowered and (ii) changes in lattice confinement of collagen molecules and/or microfibrils and their interactions in bones with different mineral contents (Lees, 1981; Bonar et al., 1985).

In this study, the mineral–organic composite (moc) without microporosity is referred to as *moc*. Within the *moc*, the organic matrix mechanical properties depend on mineral content before yield. In the *moc*, load transfer between overlapped platelets is due to shear stress, τ_o, in the organic matrix. Therefore, our previous model, formulas for *moc* can be obtained by modifying the relationships derived previously (Kotha and Guzelsu, 2003a). In the *moc*, increasing loads parallel to the x-axis (along the long axis of bone, Fig. 1(a)) are transferred between overlapped platelets by shear. On applying load to bone tissue, increasing organic matrix shear stresses (τ_o) allows the mineral platelets to bear increased normal stresses in the x direction (Jager and Fratzl, 2000; Gao et al., 2003; Ji and Gao, 2004; Kotha and Guzelsu, 2003a). Under increasing load, organic matrix shear stress reaches its yield value, τ_{oy}, at the ends of the platelets (τ_{oy}, shear yield stress of organic) (Fig. 1b). This is the microscopic yield point of bone tissue as the stress–strain behavior of bone begins to deviate from linearity at this point. With a further increase of loads in the x direction, the organic phase yields in shear over the entire surface of the platelet. After this point, referred as macroscopic yield point, mineral platelets cannot contribute to the load bearing capacity of

Table 1
Experimental values of control and fluoride treated bone samples: control 12 days in 0.15 M KCl at pH = 7.5; fluoride 3 days in 1.0 M KF at pH = 7.5; fluoride 12 days in 1.0 M KF at pH = 7.5 (Kotha and Guzelsu, 2003b)

Group	Number of samples	Elastic modulus (Gpa)	Yield stress (MPa)	Yield strain (%)	Ultimate stress (MPa)	Ultimate strain (%)
Control	9	19.3 (2.9)[a]	100.5 (19.1)[a]	0.698 (0.025)[a]	103.3 (16.6)[a]	2.88 (1.22)[a]
3 days fluoride	9	13.1 (2.6)[b]	63.8 (9.7)[b]	0.689 (0.032)[a]	73.7 (11.8)[b]	4.64 (1.21)[b]
12 days fluoride	9	9.3 (1.5)[c]	40.9 (7.3)[c]	0.659 (0.041)[a]	65.5 (12.3)[b]	6.39 (1.17)[c]

Different superscripts indicate that the properties are significantly different than other groups ($p = 0.05$).