MODELING THE MINERAL PHASE OF BONE: AN EMPIRICAL APPROACH

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Bone is a composite material that has been conceptualized as a continuous, compliant collagen matrix with a stiff, mineral reinforcing phase [1]. However, bones remain intact even after selective removal of the organic phase. Recent bone models consider a continuous [2] or partially-continuous mineral phase [3]. The current study uses site-matched elastic modulus and mineral density values at a volume scale of a few hundred cubic micrometers, the length-scale of the bone microstructure, to examine a range of bone samples and to examine the evidence for mineral phase continuity in bone.

Bone specimens were selected to explore a range of compositions, from poorly- to highly-mineralized. Briefly, osteomalacic and normal human bone samples were embedded in PMMA, micromilled to an optically flat finish, and carbon-coated for using quantitative backscattered electron (qBSE) imaging as in Ferguson et al, 2003 [4]. Site-matched measurements were made for elastic modulus, obtained via nanoindentation, and mineral density, via qBSE measurements (with a calibrated conversion to mineral volume fraction). Modulus was plotted as a function of mineral volume fraction values were compared with the Hashin-Shtrikman composite bounds.

Normal bone from human subjects varied in mineral volume fraction from ~23 to 58% with little change in modulus. Osteomalacic bone, characterized by a mineralization defect, formed the lower end of the spectrum where modulus values changed relatively little for a wide range of mineral volume fraction (0 to 19%). The upper end of the mineral range was supplemented by measurements from hypermineralized whale bone, the rostrum of the Mesoplodon densirostris [5], where the modulus varied greatly over a small range of mineral volume fraction (~73 to 77%). The bone response differs from that of most engineering composites such that modulus trends with mineral fraction demonstrate large ranges of behavior and large differences in the trends are observed for hypo- and hyper-mineralized bone. The evidence supports a model for bone with a partially-continuous mineral phase network.

References:

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