Abstract

"Multiscale Modeling of Bone"

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Bone is a structural material with excellent material properties for its application: high stiffness, strength and fracture toughness, and low weight. These superior properties of bone are due to its complex composite and hierarchical structure. In this paper we conduct the multiscale characterization and modeling of bone to obtain the structure-composition-properties relations. In the analysis, we distinguish the following structural length scales: the nanoscale (few nanometers, apatite crystal and collagen fibril level), the sub-microscale (few microns, single lamella level), the microscale (10-500 microns single trabecula or osteon level), the mesoscale (1–10 cm, involving a random network of struts in trabecular bone, or a random arrangement of osteons in cortical bone), and the macroscale (whole bone). In our experimental study we characterize the bone structure and composition using scanning and transmission electron microscopy, micro-computed tomography, Raman spectroscopy and ash and water contents. We measure mechanical properties of bone using nanoindentation, reference point indentation and tensile, compressive and bending tests. These experimental results are used as inputs for our theoretical models and for their validation. Next, we model bone as a multiscale composite material. We conduct a "bottom-up" approach in which the properties at lower level serve as inputs for modeling at the next structural level. The mechanical properties are determined at each scale either analytically, using micromechanics theories, or numerically, using finite element and beam network approaches. Computational challenges include modeling of the complex irregular structure at each structural level and accounting for a spatial heterogeneity of bone. Theoretical issues include separation of scales and dependence of properties on specimen size and boundary conditions. Elastic constants and strength are calculated at each structural level and are compared with those measured experimentally, and very good agreement is found. Results of this study have a wide range of applications in orthopedics, including a more accurate assessment bone quality and earlier diagnosis of osteoporosis.