

38th International Sun Valley Workshop
August 3-6, 2008
Nanomechanics of Bone (Session Summary)

Nanomechanics and bone tissue quality

X.E. Guo

Departments of Biomedical Engineering, Columbia University, New York, NY, USA

Keywords: Nanomechanics, Bone Quality, Ultrastructure

Bone tissue is a multiscale and hierarchical material with mineral crystals and organic components (such as collagen fibers) having inherent nanostructure. There is no question that the nanoscale ultrastructure of bone tissue and its alteration in metabolic and genetic bone diseases are important in governing bone tissue and material properties. Genetic mutations in either biomineralization (such as phosphate-regulating gene with homologies to endopeptidases on the X chromosome, PHEX) or organic phase (such as type I collagen point mutation in osteogenesis imperfecta) can result in changes at the nanoscale in bone tissue, which translate into clinical manifestation of bone disorder or bone fragility. The Nanomechanics Session focused on the recent developments in both theoretical and experimental aspects of nanomechanics, mechanotransduction experiments and theoretical modeling at the sub-cellular and nanoscale, and the implication of nanomechanics in bone quality and metabolic bone diseases.

Dr. X. Edward Guo gave an overall introduction of nanomechanics of bone tissue. He discussed the recent development in experimental measures of bone tissue properties at the nanoscale. Experimental techniques are available to study bone tissue properties at nanoscale, which include: nanomechanics testing of single collagen fibers or fibrils, deformations of collagen fibrils and minerals using small angle X-ray scattering and wide angle X-ray diffraction, observing bone tissue fracture at nanoscale using electron microscopy, nanoindentation to measure intrinsic bone tissue properties. In addition, non-invasive imaging techniques have been pushing to the nanoscale with NanoCT.

The author has no conflict of interest.

Corresponding author: X. Edward Guo, Ph.D., Professor of Biomedical Engineering, Department of Biomedical Engineering, Columbia University, 351 Engineering Terrace MC 8904, 1210 Amsterdam Avenue, New York, NY 10027, USA

E-mail: ed.guo@columbia.edu

Accepted 11 August 2008

From a theoretical perspective, models for bone tissue have been developed from molecular dynamics simulation, or hybrid reactive mesoscopic models to predict single collagen molecule, collagen fiber, or mineralized collagen fiber deformation. Conceptual models can also be constructed to examine the interactions between microdamage and the collagen/mineral interface. An interesting model, named the virtual internal bond (VIB), was introduced in modeling human trabecular bone and discussed by Dr. Guo. The advantage of this model is its inherent ability to bridge across multi-scales while incorporating realistic constitutive physical law. Dr. Guo presented results using this approach to link the yield strength of trabecular bone to the microdamage accumulation in trabecular bone tissue. The perspectives of using advanced nano imaging techniques, nanoscale modeling, and nanoscale experimental methods to explore bone tissue quality at the nanoscale are quite promising.

Dr. Xiaodu Wang presented both experimental and analytic analyses of the role of mineral and collagen interfaces on bone strength. An eloquent model of mineral and collagen debonding with probability distribution predicts that diffuse microdamage only occurs when there exists mineral collagen debonding while linear microcracks occur without mineral and collagen debonding. Although the model is simple, it clearly demonstrates that the nanoscale behavior of bone tissue is critical to tissue quality. Dr. Wang also presented experimental data on the role of water on bone tissue toughness. The results are not surprising, as it is well known that water affects bone tissue properties especially fracture toughness, i.e., dehydration makes bone stiffer while more brittle. However, the mechanisms of water in bone tissue toughness are not well characterized. Dr. Wang presented experimental data to clearly demonstrate that water influences the mineral and collagen interface and therefore bone tissue toughness.

The important role of osteocytes has been recognized in the past ten years. Dr. Daniel Nicolella presented atomic force microscopy maps of bone tissue elastic modulus in trabecular bone tissue from ovariectomized rats. The prelimi-

nary data indicate that there are measurable changes in local, nanoscale mechanical properties due to estrogen deficiency. These data suggest that osteocytes may be able to regulate local bone tissue properties. This work related nicely to the presentation by Dr. Shelly Weinbaum who presented elaborate analytic nano models of osteocyte mechanotransduction. Dr. Weinbaum also presented new experimental evidence suggested by his theoretical model that osteocytic processes with stiff actin bundles are more sensitive to mechanical stimuli.

There is no question that nanoscale bone mechanics and nanoscale bone tissue properties are important and central to bone quality. There are significant advances in experimental, theoretical, and computational methods for nanoscale bone mechanics. However, the field of nanomechanics and bone quality needs to bring nanomechanics into the biological and clinical arena. It should not just be basic science. One has to

demonstrate how nanomechanics and bone quality can improve our general understanding of physiological or pathological processes in bone tissue metabolism and maintenance of bone function. One has to envisage and sketch out the pathway where knowledge in nanomechanics and bone tissue quality can be used to improve people's skeletal health. This is critical to the emerging field of nanomechanics of bone and even more crucial for the field of bone quality. It is important that we bring physicists and mechanists working side-by-side with bioengineers, biologists, and endocrinologists. Physicists and mechanists have to work with human diseased bone tissues or bone tissues from transgenic animals. Modelers of nanomechanics have to think how to link nano scale models to practical or clinical applications. In order to do that, a dedicated nanomechanics and bone quality workshop will be necessary to bring multidisciplinary experts together and to work on physiologically and clinically relevant issues in nanomechanics of bone tissue.