STRUCTURAL EVOLUTION OF BONE TISSUES DURING MINERALIZATION: A GENERAL MATHEMATICAL APPROACH

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Introduction

The fundamental mechanisms that govern bone mineralization have been evidenced experimentally. However, rules for the evolution of the volume and composition of the bone tissue compartments have not been provided yet. The present contribution aims at finding mathematically formulated rules behind the mineralization process within and outside the collagen fibrils. These rules are strictly validated against a variety of physically and statistically independent experimental data collected from the literature on the topic.

Methods

We wish to check whether the structural evolution of bone tissue during mineralization can be explained by means of fluid-solid phase transitions in the fibrils and the extrafibrillar space considered as two thermodynamically closed systems: the mass of lost ionic fluid equals the mass of formed solid mineral in each subvolume, while the collagen mass remains unaltered. The mineralization process is accompanied by an increase in mass density, leading to shrinkage of the compartments, which can be quantified through the change in equatorial diffraction spacing at the fibrillar scale [Morin, 2012]. These propositions are checked through experimental evidences, relating bone mass densities to the equatorial diffraction spacings [Lees, 2003]. Therefore, the mass conservation equations are converted into mass density-diffraction relations in three steps. First, the tissue shrinkage is evaluated based on universal composition rules [Vuong, 2011]. Secondly, this relation is downscaled to the extrafibrillar space using constant mineral concentration in the extracollagenous space [Hellmich, 2003] and hydration swelling rule for unmineralized tissues [Morin, 2012]. Thirdly, the fibrillar shrinkage is analogously derived and related to the change in diffraction spacing.

Results

Our mathematical approach is strictly validated through comparison between experimental and predicted diffraction spacings. Very low prediction errors underline the relevance of computed evolutions of the tissue compartment volumes and volume fractions during the mineralization process in different bone tissues (see Figure 1).

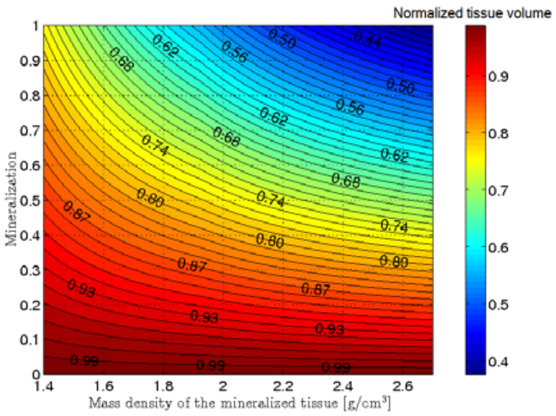

Figure 1: Normalized tissue volume as function of the mineralization degree for different final tissue mass densities.

Discussion

This paper shows that the volume and structure changes in mineralizing bone tissue can be mathematically predicted when considering the tissue as closed thermodynamic system, in which a super-saturated fluid starts to precipitate, while fulfilling the mass conservation law. Resulting shrinkage and composition rules are deemed beneficial for further progress in bone materials science and biomedical engineering.

References

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Acknowledgement

Financial support of the European Research Council (ERC) through the project ERC-2010-StG 257023-MICROBONE "Multiscale poro-micromechanics of bone materials, with links to biology and medicine" is gratefully acknowledged.