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# Stress distributions in human teeth modeled with a natural graded material distribution

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## ARTICLE INFO

### Article history:

Received 2 July 2013

Received in revised form

22 May 2014

Accepted 8 August 2014

### Keywords:

Finite element analysis

Graded material distribution

Tooth structure

## ABSTRACT

**Objective.** This study aimed to investigate how the structural stress distribution in human teeth could be affected by the presence of a graded material distribution often found in nature using the finite element (FE) method.

**Methods.** Hydroxyapatite (HA) tablets with different densities were scanned using a Micro-CT scanner to obtain a relationship between the attenuation coefficient and the elastic modulus via the mineral density. Two maxillary premolars were scanned to provide the geometries and material distributions for constructing the FE models. Stress analyses were then performed to compare the stress distributions between the models with uniform material properties and those with a graded material layout.

**Results.** The attenuation coefficients and densities of the HA tablets measured ranged from 109.77 to 175.01 cm<sup>-1</sup> and 0.99 to 1.54 g cm<sup>-3</sup>, respectively. A linear relationship was found between them and applied to the premolars to derive the elastic modulus via the mineral density. Stress analysis showed that, with a graded material layout, the peak maximum principal stress in the enamel was reduced by about 50% and the overall stress distribution was more uniform. Along the DEJ, two stress peaks were found near the dentin horns, but again they were much lower in magnitude in the models with a graded material distribution.

**Significance.** The results from this study support the hypothesis that the material layout in human enamel is optimized for distributing the external load evenly. They also point to the importance of taking into account the graded material distribution in nature when performing stress analysis for tooth structures.

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## 1. Introduction

Through evolution, animals have developed various types of mineralized biological tissues with optimal mechanical properties for their survival. For example, the skeletal system of vertebrates was developed to support their body weight,

facilitate muscle movement and protect the many important organs in the body. Invertebrates, on the other hand, have developed different types of exoskeleton to protect themselves. Examples include the shells in mollusks and cuticles in arthropods. Another mineralized biological structure, tooth, with its stiff and wear-resistant nature, plays an important

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<http://dx.doi.org/10.1016/j.dental.2014.08.372>

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role in the daily lives of animals – food intake. The shape and layout of the constituent materials of a tooth have evolved to meet the dietary needs of an animal. For example, carnivores usually own very sharp and strong teeth for hunting, killing and ripping the meat off their prey, while herbivores usually have cusplike teeth for grinding vegetations. Irrespective of the diet, teeth are often subjected to large mechanical forces.

With their constituents organized in highly specific manners, mineralized biological tissues such as nacre [1] usually exhibit far better mechanical properties than their synthetic counterparts made of the same constituent materials. In recent years, there has been increased attention paid to how these unique material layouts in nature are able to maximize and optimize the mechanical performance of natural structures. These specific material layouts, including porous, fibrous and laminate structures, result in tissues with different strengths or anisotropies that meet their functional demands [2]. For example, osseous or bone tissues are mainly composed of hydroxyapatite (HA) crystals. Depending on the density of these minerals, the elastic modulus of bone can vary by a factor of up to ten [3]. High mineral density in the outer cortical bone provides the required strength and bending stiffness for sustaining the body weight. On the other hand, the large porosity in the inner cancellous bone helps reduce the weight of the whole structure and gives it the capacity for shock absorption. Such a structured organization of osseous tissues with different properties in bone makes it an optimized design for accommodating the functional loads.

A similar material layout can be found in teeth or related structures. Although their shapes vary according to their functions, the fundamental structures of fangs, tusks and human teeth share the same material layout [2]. Specifically, they all have a hard outer layer of enamel which provides a strong and wear-resistant surface that gives them the strength for fighting, killing, biting and/or chewing. Underneath, a softer inner layer of dentin contributes to their toughness and resilience to buffer the impact force from these actions. Furthermore, not only is there a difference in the overall mechanical properties between the inner and outer tissues, there is also a graded spatial distribution of these properties within each of them.

Marshall Jr. et al. [4] conducted nanoindentation tests using a modified atomic force microscope (AFM) to obtain profiles of the hardness and elastic modulus of human teeth across the dentinoenamel junction (DEJ). Their results showed that both of these mechanical parameters decreased gradually from enamel to dentin. Fong et al. [5] also reported that the nanohardness across the DEJ gradually decreased from 4.8 GPa to 0.8 GPa, with the elastic modulus following a similar profile. Kishen et al. [6] found a significant correlation among the mineral density, hardness and elastic modulus in human dentin using fluoroscopic X-ray imaging and microindentation. Their results showed that the hardness and elastic modulus of root dentin increased gradually from the central region to the outer surface of the root. Another AFM study further indicated that the nanomechanical properties of dentin varied among its microstructures, including the intertubular dentin, peritubular dentin and peritubular–intertubular dentin junction [7].

In addition to dentin and the DEJ, a graded distribution of mechanical properties has also been found in enamel using indentation [4,5,8–18]. The reported values from these studies

varied with the indenter's size and shape, and the site where the indentation was performed. Nevertheless, the spatial distribution of the mechanical properties followed a similar pattern to that found in dentin, in which the elastic modulus was highest in the outer layer and gradually decreased as one moved toward the DEJ. Moreover, Cuy et al. [10] found that the lingual cusp (the one that is chiefly responsible for breaking down food) of a maxillary molar had a thicker, stiffer layer of enamel. Therefore, researchers have hypothesized that the graded distribution of mechanical property within human teeth was developed to adapt to their particular functional needs [6,10]. The following example further demonstrates that tooth structures are optimized for the mechanical loads that they sustain. A digital photoelastic analysis showed high concentration of bending stresses in the cervical region of a mandibular incisor [6]. It was found that this region of high stress concentration also had higher mineral density, hardness and elastic modulus.

However, in most stress analysis of tooth structures using the finite element (FE) approach, the tissues and materials are usually defined as homogeneous and isotropic. Stress analysis using a graded material distribution for tooth structures has been very limited. Without modeling the material properties properly, the stress distribution obtained from the FE analysis may not be accurate. This study therefore aims to better understand how the graded distribution of the elastic modulus affects the structural stress distribution within a tooth. It is hypothesized that such a material layout would produce a more uniform stress distribution with lower stress concentrations.

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## 2. Materials and methods

### 2.1. Preparation of hydroxyapatite (HA) tablets

As mentioned, it has been found that the degree of mineralization is a major contributor to the mechanical properties of mineralized tissues [19,20]. Therefore, the present study used a micro-CT scanner to provide the spatial distribution of mineral density within teeth to construct the FE models required for the stress analysis. To do so, a relationship between the mineral density of enamel and the corresponding attenuation coefficient in the CT images needed to be established first. This was achieved by using tablets, or phantoms, made of HA, the major constituent in teeth, with different densities.

Approximately 25 mg of HA powder was manually filled each time into a tableting die and compressed with a pre-determined compaction force (0.5–3 kN) using a universal material testing machine (Model 1485, Zwick, Germany). The compression speed and holding time at the maximum compaction force were set at 1 mm/min and 120 s, respectively. The density of the resulting round tablets (flat-faced, 4 mm diameter) were determined by their weights, diameters and thickness. Twelve tablets were successfully constructed in this way and their density ranged from 0.99 to 1.54 g cm<sup>-3</sup>. The dimensions and properties of these tablets are listed in Table 1. Attempts were made to fabricate tablets with higher densities. However, cracks were found inside these high-density HA tablets during the initial CT inspection, probably due to

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