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Biomechanical effect of mineral heterogeneity in trabecular bone

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ABSTRACT

Due to daily loading, trabecular bone is subjected to deformations (i.e., strain), which lead to stress in the bone tissue. When stress and/or strain deviate from the normal range, the remodeling process leads to adaptation of the bone architecture and its degree of mineralization to effectively withstand the sustained altered loading. As the apparent mechanical properties of bone are assumed to depend on the degree and distribution of mineralization, the goal of the present study was examine the influences of mineral heterogeneity on the biomechanical properties of trabecular bone in the human mandibular condyle. For this purpose nine right condyles from human dentate mandibles were scanned and evaluated with a microCT system. Cubic regional volumes of interest were defined, and each was transformed into two different types of finite element (FE) models, one homogeneous and one heterogeneous. In the heterogeneous models the element tissue moduli were scaled to the local degree of mineralization, which was determined using microCT. Compression and shear tests were simulated to determine the apparent elastic moduli in both model types. The incorporation of mineralization variation decreased the apparent Young's and shear moduli by maximally 21% in comparison to the homogeneous models. The heterogeneous model apparent moduli correlated significantly with bone volume fraction and degree of mineralization. It was concluded that disregarding mineral heterogeneity may lead to considerable overestimation of apparent elastic moduli in FE models.

1. Introduction

The mandibular condyle plays an important role in the function of the masticatory system, serving as a fulcrum between the mandible and the cranium. It is subjected to a wide range of mechanical loads both in direction and in amplitude. As a consequence it endures various deformations (i.e., strain), which in turn lead to stress patterns in the bone tissue (Currey, 2003). The relationship between bone loading (stress) and deformation (strain) depends mainly on bone properties like degree of mineralization and architecture (Currey, 1988). As the condyle consists of a trabecular bone core with a relatively thin cortex, the properties of the former can be considered dominant.

Variations in the degree of mineralization of bone (DMB) are the product of the remodeling process, which occurs at the trabecular surfaces. Remodeling is also responsible for adaptation of the bone structure to make it effectively withstand the variety of applied forces during normal function (Turner, 1998; van Eijden, 2000; Giesen et al., 2004; van Ruijven et al., 2005). DMB is low in newly formed bone, and increases with the maturation of the bone tissue. Consequently, the DMB increases from the outer layers of trabeculae towards their centers (Paschalis et al., 1997; Mulder et al., 2005; Renders et al., 2006).

Bone tissue with a high DMB is relatively stiff and brittle (Ciarelli et al., 2003) whereas bone with a relatively low DMB is more compliant, leading to relatively low stress (van Ruijven et al., 2007; Mulder et al., 2008). Therefore, mineral heterogeneity implicates heterogeneity of tissue stiffness, which may influence the apparent mechanical properties of the complete trabecular structure (Kopperdahl and Keaveny, 1998; van der Linden et al., 2001; van Eijden et al., 2004; van Ruijven et al., 2005; Mulder et al., 2006, 2007). Since mineral heterogeneity is a product of bone remodeling, which is caused by the loading history of the bone, it may contribute to the bone's capability to effectively withstand habitual loading.

The consequences of variation in microarchitecture for the apparent bone stiffness have been predicted by finite element (FE) analysis of trabecular bone (van Rietbergen et al., 1995; Van Rietbergen, 2001; Ulrich et al., 1995) and cortical bone (Muller et al., 2007). In addition, they have increased our understanding of

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the mechanical properties of the trabecular bone in the human mandibular condyle (van Ruijven et al., 2002; van Eijden et al., 2006). However, the effect of mineral distribution has so far not been taken into account. Recently, it has been demonstrated that in developing bone the estimation of apparent mechanical behavior using FE modeling is considerably influenced when the effects of mineral heterogeneity are ignored (Mulder et al., 2008). When these variations are incorporated, FE methods may be used to predict the mechanical properties of bone with more accuracy (Bourne and Van der Meulen, 2004). Therefore, the purpose of the present study was to investigate to what extent the distribution of mineralization affects bone stiffness (i.e., apparent Young's and shear moduli of the trabecular structure). Using FE analyses, we compared the apparent Young's and shear moduli in simulated compression and shear tests of models where heterogeneity of mineral distribution was incorporated or disregarded.

2. Materials and methods

2.1. Condylar specimens

The study was performed on the right condyles of nine dentate mandibles recently used in two other studies (Renders et al., 2006, 2007), which were obtained from embalmed male human cadavers. Mean age was 68.1 years ($\pm$14.2), range: 43–92 years, the number of teeth in the upper jaw 10.0 ($\pm$4.7) and in the lower jaw 11.9 ($\pm$2.4). The cause of death of the subjects was unknown. There were no signs of temporomandibular disorders. The cadavers were embalmed with a mixture of formalin, glycerol, alcohol, and phenol. The use of human specimens conforms to a written protocol that was reviewed and approved by the Department of Anatomy and Embryology of the Academic Medical Center of the University of Amsterdam.

2.2. MicroCT

Three-dimensional reconstructions of trabecular bone cubes were obtained by using a high-resolution microCT system (μCT 40, Scanco Medical AG, Brüttisellen, Switzerland). The condyles were mounted with their lateral pole facing down in cylindrical specimen holders (polyetherimide, 20.0 mm outer diameter, 1.5 mm wall thickness) and secured with synthetic foam. The specimens were completely submerged in fixation fluid to avoid dehydration and scanned at 10 μm resolution. A 45 kV peak voltage was used, which corresponds to an effective energy of approximately 24 keV. An integration time of 1200 ms was applied to reduce noise substantially and to facilitate the discrimination between bone and background. The microCT was equipped with an aluminum filter and a correction algorithm that reduces the effects of beam hardening (Mulder et al., 2004). The scan time was 51.7$\pm$4.0 h for each specimen. The number of slices was 2090$\pm$182. The computed linear attenuation coefficient of the X-ray beam in each volume element (voxel) was stored in an attenuation map and represented by a gray value in the reconstruction.

Cubic volumes of interest ($300\times300\times300\,\mu m^3$) were selected in four quadrants of each condyle: superolateral, superomedial, inferolateral, and inferomedial (respectively: SL, SM, IL, and IM; Fig. 1). To discriminate between bone and background, the reconstructions were segmented using an adaptive threshold determination procedure supplied by the manufacturer. In order to facilitate segmentation, this procedure pursues a clear distinction between two peaks in the gray values histogram, one representing bone and another background. Thus, in segmented images every voxel with a linear attenuation below the threshold (assumingly representing soft tissue or background) was made transparent and voxels above this threshold (representing bone) kept their original gray value. Gray values were considered proportional to the local degree of mineralization (DMB). This is equivalent to the concentration of hydroxyapatite (HA; Nuzzo et al., 2002; Mulder et al., 2004) and quantified by comparing the attenuation coefficient with reference measures of a phantom containing HA of 0, 200, 400, 600, and 800 mg/cm^3. The obtained threshold was 39.7% of the maximum gray value (i.e., 477 mg HA/cm^3; Ding et al., 1999), which was visually checked. To determine the radial distribution of DMB in the trabeculae a peeling algorithm was used. For description of this algorithm see Mulder et al. (2005) and Renders et al. (2006). Relevant bone architectural parameters (BV/TV: bone volume fraction, Tb.N: trabecular number, Tb.Th: trabecular thickness, Tb.Sp: trabecular separation, SMI: structure model index,

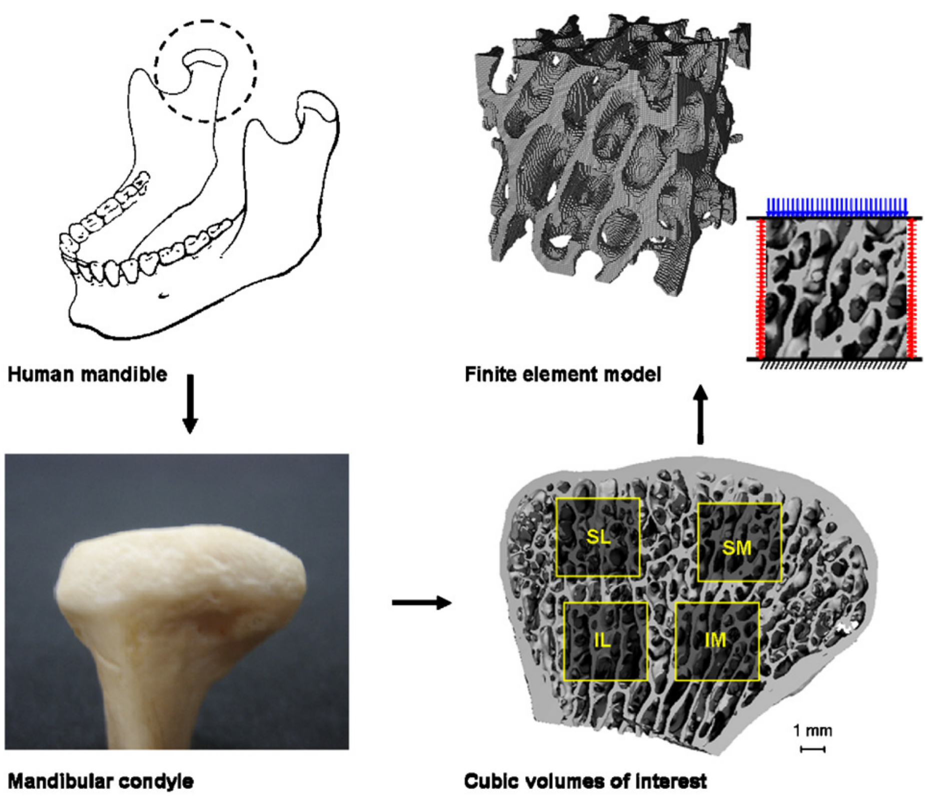

Fig. 1. A schematic overview of the different steps in sample preparation. After the right condyle was separated from the mandible, it was scanned (resolution: 10 μm) in a microCT system. Within each condyle, four cubic volumes of interest (i.e., SL, SM, IL, and IM) were selected and used for the construction of finite element (FE) models. The FE model and boundary conditions are shown in the top right panel (blue arrows: prescribed displacement on the top surface; red arrows: the displacements of nodes at the vertical surfaces were suppressed in the direction normal to the face; black hatching: the bottom surface was fixed).