Morphology and mechanical properties of the cancellous bone in the mandibular condyle

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Chapter 1

Introduction
Introduction

The principal function of the bony skeleton is to provide structural support for the body. It is the basis of posture, opposes muscular contraction resulting in motion, withstands forces, and protects the internal organs. The skeleton also serves as the body's mineral reservoir. Generally, two basic types of bone can be distinguished in the body: cortical bone and cancellous (or trabecular) bone. Cortical bone is compact and forms the shaft of long bones and the shell of, for instance, the vertebral bodies and the bones of the skull. Cancellous bone has an open structure formed by trabeculae with bone marrow to fill the spaces. Cancellous bone is found under articulating surfaces at the end of long bones and within flat and irregular bones. Although the material properties of cortical and cancellous bone tissue have the same order of magnitude (Rho et al., 1993; Rho et al., 1999), due to differences in the amount and spatial distribution of the bone material, the apparent mechanical properties of cortical and cancellous bone are different. For instance, the stiffness of cancellous bone is 10 to 20 times less than that of cortical bone. The differences in mechanical properties presume that the types of bone have different functions. The less stiff cancellous bone is likely to absorb forces and guide and transfer these to the stiffer cortical bone, which supplies the support.

Cancellous bone is built from interconnected trabeculae (Fig. 1). The trabeculae are shaped like plates and rods and together they form a structure that can resist loads. The structure is anisotropic, i.e., the trabeculae are typically oriented,

![Fig. 1 An example of a cancellous bone structure. Plate-like trabeculae are interconnected by rods. The specimen (length ~ 5 mm) was scanned in a micro-computed tomography system. The open spaces were originally filled with marrow, which was virtually removed in processing the three-dimensional reconstruction.](image)
such that it has different mechanical properties in different directions. The bone is also inhomogeneous, i.e., large differences exist in the spatial arrangement of trabeculae for different anatomical sites. Even within an anatomical site, for example a vertebral body, the architecture of the trabecular structure varies locally (Smit et al., 1997). The architecture of the trabecular structure is determinant for the bone's reaction on compression, tension and shear. Its mechanical behavior depends on several architectural characteristics: the mass of the bone, the quality of the trabeculae, and the three-dimensional orientation and structure of the trabeculae. Consequently, this behavior is likely to vary considerably throughout the skeleton.

Since the nineteenth century, a close relationship between the function of bone and its structure has been established (Wolff, 1892). It was found that trabeculae, for instance in the bone of the upper leg, have an orientation that is closely in line with the stress patterns within the bone. Thus, the trabeculae are oriented such that they can optimally withstand the forces during functioning. Bone is also sensitive to the amount of mechanical loading. For instance, patients who have to keep bed rest and astronauts who lack gravity lose bone weight, whereas athletes gain bone weight. This process of adaptation is called adaptive bone remodeling. It is autonomically regulated in the bone itself. Recently, computer models were able to simulate the adaptive remodeling process and to predict the new bone architecture as a result of changed mechanical loading (Mullender et al., 1998; Huiskes, 2000; Adachi et al., 2001).

The adaptation has the consequence that the mechanical properties of the adapted bone fit the forces in the mechanical environment. Adaptation thus links usage, trabecular architecture and mechanical properties. It implies that in a stationary situation bone architecture reflects the mechanical loading of the bone (Odgaard et al., 1997; Herring and Liu, 2001). This enables to estimate the mechanical environment by studying the morphology of the bone. These mechanisms do probably also apply to the human mandible (or lower jaw).

This thesis addresses the structure-function relationships of the cancellous bone in the human mandible. During mastication and biting, the mandible is subjected to forces produced by the muscles of mastication and by reaction forces applied to the jaw joints and the teeth. As a result of this loading, deformations and tensions are produced in the mandible. The range and distribution of these deformations and tensions depend on the nature of the loading and on the material properties and amount and distribution of bone. An understanding of the structure-function
relationships of the mandibular bone is important for several reasons. It may give us insight into the way this structure is optimized to resist loading. In addition, clinical situations, e.g., tooth loss, orthodontic treatment, dental implants, or reconstructive surgery, will alter the loading of the mandible. This, in turn, might affect the architecture of the mandibular bone.

In the mandible, cancellous bone is found in various areas, for instance in the alveolar process to support teeth, in-between the cortical sheets of the ramus and mandibular body, and in the condyle (or mandibular head). This thesis will focus on the cancellous bone in the mandibular condyle (Fig. 2).

**Morphology**

Based on frontal, transversal, and sagittal sections, an inhomogeneous bone distribution has been reported in the human mandibular condyle (Hongo et al., 1989). The density of the bone and the amount of trabeculae are larger in the upper and anterior regions. The trabeculae are oriented in the anteroposterior direction, which has been functionally related to the direction of one of the masticatory

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**Fig. 2** Of a lower jaw the right condyle (or head) is enlarged. The condyle is approximately 2 cm wide. The thin cortical shell is removed that allows us to look at the cancellous bone inside the condyle.
muscles, the lateral pterygoid muscle, which attaches closely to the condyle. In the pig mandibular condyle, however, the latter was not confirmed (Teng and Herring, 1995). Due to the two-dimensional nature of these studies, the findings were limited to the characteristics occurring within the analyzed planes. While the loading of the condyle is not limited to a plane only, this approach is not sufficient to establish the relationship between architecture and loading. In order to assess this relationship adequately, a three-dimensional analysis of the condylar bone architecture is a prerequisite (for review: Odgaard, 1997).

State of the art micro-computed tomography (micro-CT) systems enable us to study the cancellous bone in its three dimensions (Rüegsegger et al., 1996). Micro-CT assesses the complete three-dimensional bone structure at the micro level (resolution: 8 - 50 µm), in a non-destructive fashion. Depending on the system and the required resolution a complete mandibular condyle can be imaged at once. Parameters describing, for instance, the bone volume fraction, the thickness and number of trabeculae, the space between trabeculae and the predominant orientation of the trabeculae can be computed with standard system software (for review: Odgaard, 1997).

In this thesis, the micro-CT technique was applied to determine the three-dimensional architecture of the cancellous bone of the human mandibular condyle (Chapter 2). More specifically, an inhomogeneous and anisotropic distribution of cancellous bone was expected. It was applied to elucidate a possible relationship between the cancellous bone structure of the condyle and its function.

During masticatory functioning the mandibular condyle translates and rotates along the articular surface of the temporal bone of the skull. The shape of the articular surface and that of the condyle do not match, which makes the joint incongruent. During movement the condyle is subjected to complex loading patterns. The temporomandibular joint disc, which is situated between the skull and mandible, plays an important role in the distribution of the loads (Beek, 2001). These loads are localized in an area on the condyle, which is shaped as a mediolaterally oriented band. During function the loaded area moves anteroposteriorly. The joint forces are absorbed by the cancellous bone and are transferred toward the mandibular collum. During loading the condyle, and herewith its cancellous bone, deforms, giving rise to a pattern of internal tensions. The nature of these deformations and tensions, however, is unknown. As they cannot be measured directly, a model approach is required.
To estimate the deformations and tensions in the mandibular condyle a threedimensional finite element model of the mandibular condyle was developed (Chapter 3). Different static anteroposterior load cases were applied and the magnitude and orientation of the local deformations in the condyle were calculated. Furthermore, the deformation of the whole condyle due to the loading was analyzed. By comparing the direction of the deformations with the orientation of the trabecular bone, it could be verified if the architecture of the bone of the condyle reflects its mechanical loading.

**Mechanical properties**

The mechanical properties of cancellous bone are of interest for the bone's load bearing capacities. Different mechanical properties can be distinguished. It is noteworthy to distinguish between the mechanical behavior at the level of the structure of the bone, the apparent properties, and that at the level of the individual trabeculae, the tissue properties. The apparent properties are referred to in this thesis. The following are used: stiffness, strength, failure energy and the ultimate strain. The stiffness is a measure of the ability of bone to resist deformation in the direction of the applied load. The strength or ultimate stress is the amount of stress the bone can maximally sustain. Any surplus of stress will break the bone. The strain at that point is called the ultimate strain. The energy that is needed to break the bone is called the failure energy.

Mechanical properties can be determined by mechanical testing (Carter and Hayes, 1977; for review: Keaveny et al., 2001). Generally, a specimen is deformed at a constant speed in a materials testing machine, and simultaneously the force is recorded. From the force-deformation recordings, the above-described mechanical properties can be determined. This method has the disadvantage that the behavior at the interface between the specimen and the machine may induce substantial errors (Keaveny et al., 1997).

Mechanical properties of cancellous bone strongly depend on the density of the bone (Carter and Hayes, 1977). Different density parameters can be distinguished. Density at the trabecular level is called the tissue density. The density on the structure level is called the bulk density or apparent density.

Only few studies are available on mechanical properties of the bone of the mandible. The only study in which the cancellous bone of the mandibular condyle was involved concerned the pig (Teng and Herring, 1996). In the human mandible, determination of mechanical properties has been limited to the cortical bone (e.g.,
Arendts and Sigolotto, 1989; Dechow et al., 1993; Ziopoulos and Currey, 1998; for review: Van Eijden, 2000), or to the cancellous bone of its body (Misch et al., 1999). The mechanical properties of the cancellous bone of the human mandibular condyle were determined in the study described in Chapter 4. The mechanical properties were related to the density of the bone. As it was expected that due to the anisotropic nature of the bone, the stiffness and strength would differ between different loading directions, these properties were determined in different directions.

**Relation between 3-D morphology and mechanical properties**

The mechanical properties of cancellous bone depend not only on bone density, but also on the three-dimensional morphology of bone tissue (Hodgskinson and Currey, 1990; Uchiyama et al., 1999; Ulrich et al., 1999; Nafei et al., 2000a,b; Borah et al., 2000; Ikeda et al., 2001). By establishing the relationship between morphology and mechanical properties, predictions can be made of the mechanical quality of the bone from its architecture. This may relate to healthy bone, but possibly also to situations like osteoporosis and other pathologic circumstances like the edentulous jaw.

Generally, the aim in relating mechanical properties and morphology is to ascribe the variation in mechanical properties to the variation in morphology. In order to assess the relationship between morphological parameters and mechanical properties, mostly these parameters are entered into regression analyses one by one. One of the problems is that various morphological variables are mutually dependent. For example, an increase in bone mass can be achieved by an increase of the amount of the trabeculae, a thickening of the trabeculae or, alternatively, by a transition from rod-like trabeculae to more plate-like trabeculae, or a combination of these. Thus if some parameters represent the same kind of property it is likely they can explain the same amount of variance in mechanical properties individually, but together they will not add more. Therefore, it can be expected that the additional explanatory value of a large number of variables is rather limited.

One of the objectives of the study described in Chapter 5 was to determine which of the morphological variables of cancellous bone could be considered as covariates. For this purpose, a principal components analysis was used. The other objective of this chapter was to investigate the predictive value of the microstructural parameters for the mechanical properties of the bone in the mandibular condyle. The effect of trabecular orientation on the mechanical properties was emphasized. Usually, in the determination of mechanical properties of cancellous
bone, specimens are taken relative to an anatomical axis or a presumed physiological loading direction. It is then assumed that the main trabecular orientation coincides that direction. The orientation itself, however, is seldom measured. If the principal trabecular orientation misaligns the loading direction with for example 10 degrees, errors of 9.5% in the estimation of the elastic modulus can be expected (Turner and Cowin, 1988).

**Adaptation**

The continuous adaptation of bone to its mechanical environment has consequences when the loading on the bone changes. In the masticatory system the amount of mechanical load is changed as people grow older or lose their teeth. The masticatory function decreases (Boretti et al., 1995), which coincides with an atrophy of the masticatory muscles (Newton et al., 1993) and a reduction in bite force (Helkimo et al., 1977). This leads to a reduction in the forces acting on the mandible. It can, therefore, be expected that the structure and mechanical properties of the mandibular bone change with a decreased masticatory function.

In Chapter 6 the density and mechanical properties of condylar cancellous bone of dentate and edentate subjects were compared. The loss of teeth in the edentate group was used as a model of reduced mechanical loading. It was hypothesized that the density, stiffness, and strength of the cancellous bone would be lower in the edentate group than in the dentate group. Furthermore, it was investigated whether the mechanical anisotropy differed between the two groups.

For the mandibular condyle, it is not known by which structural changes a decrease in bone density is accompanied. In the human tibia, for example, such a decrease is accompanied by a change of the bone structure type toward more rod-like trabeculae (Ding and Hvid, 2000) and by an increase in the anisotropy (Ding et al., 2002). Also in patients with hip fractures, a lower bone density is accompanied by a higher degree of anisotropy (Ciarelli et al., 2000). In Chapter 7 it was, therefore, questioned if the morphology of the cancellous bone of the mandibular condyle of edentate subjects changes in a similar fashion. Further, it was investigated if a difference exists in the relationship between the morphology and mechanical properties of the bone of dentate and edentate subjects.
Summary of objectives for the thesis

- Describe the three-dimensional architecture of the cancellous bone of the mandibular condyle (Chapter 2).
- Determine the deformations occurring in the mandibular condyle due to static loads and compare the direction of these deformations with the orientation of the trabecular bone (Chapter 3).
- Determine the mechanical properties of the cancellous bone of the mandibular condyle and relate these to the density of the bone (Chapter 4).
- Determine morphological covariates of condylar bone and determine the relationship between groups of morphological measures and the mechanical properties (Chapter 5).
- Determine the effect of reduced mechanical load on the cancellous bone of the mandibular condyle on both mechanical properties and morphology (Chapter 6 and 7).

References


