Morphology and mechanical properties of the cancellous bone in the mandibular condyle
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Chapter 6

Reduced Mechanical Load Decreases the Density, Stiffness, and Strength of Cancellous Bone of the Mandibular Condyle

Abstract
We investigated the influence of decreased mechanical loading on the density and mechanical properties of the cancellous bone of the human mandibular condyle. For that purpose, we compared cylindrical bone specimens obtained from dentate and edentate embalmed cadavers. With destructive compressive tests mechanical parameters were determined in the axial and in the transverse directions. Subsequently, density parameters were determined according to a method based on Archimedes' principle. The apparent density and volume fraction of the bone were about 18% lower in the edentate group; no age-related effect on density was found. The decrease of bone in the edentate group was associated with a lower stiffness and strength (about 22% and 28%, respectively). The ultimate strain, however, did not differ between the two groups. Both groups had similar mechanical anisotropy; in axial loading the bone was stiffer and stronger than in transverse loading. To conclude, reduced mechanical load had affected the density and herewith the mechanical properties of condylar cancellous bone, but not its anisotropy.
Introduction

In general, as people grow older and lose their teeth, their masticatory function decreases (Boretti et al., 1995). This decrease in function 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, and, as it is known that bone reacts to its mechanical environment (Turner, 1998; Huiskes, 2000), consequently to a change in its mechanical properties.

A number of studies have compared the mandibles of dentate and edentate subjects. All indicate that the density of cancellous bone is lower in edentate than in dentate subjects (mandibular body: Bassi et al., 1999, mandibular condyle: Hongo et al., 1989b; Kawashima et al., 1997). As the mechanical properties of bone are dependent on density (Carter and Hayes, 1977), it can be expected that the cancellous bone in edentate people is less stiff and strong than in dentate people.

The cancellous bone in the mandibular condyle has an anisotropic morphology (Giesen and Van Eijden, 2000). Its principal orientation coincides with the physiologic (superoinferior or axial) loading direction. In accordance with this

Fig. 1 Method of specimen preparation. The specimens were drilled in axial and transverse directions. After the axial specimen was drilled out, the condyle was sawed off perpendicular to the second specimen direction. Finally, the ends of the core were cut-off perpendicular to the cylindrical axis leaving the actual specimen (lightened).
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Anisotropic morphology, anisotropic mechanical properties have also been demonstrated (Giesen et al., 2001). In the axial direction, the bone appears to be more than three times stiffer than in the mediolateral direction. Whether this degree of anisotropy changes according to alterations in mechanical loading of the mandible is unknown.

The objective of the present study was to compare the density and mechanical properties of condylar cancellous bone in dentate and edentate subjects. The loss of teeth in the edentate group was used as a model of reduced mechanical loading, and concomitantly reduced density. We hypothesized that the density, stiffness, and strength of the cancellous bone would be lower in the edentate group than in the dentate group. Furthermore, we investigated the presence of differences in mechanical anisotropy between the two groups.

Materials and Methods

Specimen preparation

Cancellous bone specimens were taken from the mandibular condyles of 49 embalmed human cadavers. Twenty-five of them were edentate (14 female, 11 male, mean age ± SD: 85.2 ± 8.5 yr). It was not known at what age they had lost their teeth. Twenty-four subjects were dentate (19 female, 5 male, mean age ± SD: 74.8 ± 11.7 yr); their mean number of teeth was 8.5 in the upper jaw and 10.7 in the lower jaw. 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.

Using a custom-made hollow drill, cylindrical specimens were produced in the axial direction to coincide with the predominant trabecular orientation (i.e., in a superoinferior direction) and in the transverse direction, perpendicular to this orientation (i.e., mediolaterally) (Fig. 1). In most cases, the axial and transverse specimens were taken from the same condyle. Their position within the condyle, i.e., either medial or lateral, was randomized. The specimens were cut perpendicular to their axis with a Leitz Saw Microtome 1600 (Ernst Leitz Wetzlar GmbH, Wetzlar, Germany). The specimens had a diameter of 3.6 ± 0.14 mm and a length of 4.9 ± 0.06 mm. They were stored in the embalming fluid prior to testing.

Mechanical testing

Destructive mechanical compression tests were carried out with a materials testing machine (858 Mini Bionix, MTS Systems Corporation, Minneapolis, Minnesota,
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USA) equipped with a 1 kN load cell. For an extensive description of the method we refer to Giesen et al. (2001). Briefly, the specimen was placed between two steel loading rods; with low-viscosity mineral oil as a lubricant it was possible to obtain low friction. An extensometer (model 632.11F-20, MTS) was attached to the loading rods close to the specimen to monitor its deformation. The load cell registered the applied force. The specimen was preconditioned to reach a viscoelastic steady state (Linde et al., 1988). It was then compressed at a constant strain rate of 0.2% s\(^{-1}\) until a strain of 3% was reached. From the stress-strain curve three mechanical parameters were calculated, i.e., elastic modulus (E-modulus), ultimate stress, and ultimate strain. The ultimate stress was defined as the maximal stress during the test and the ultimate strain as the corresponding strain value at that point. The part of the stress-strain curve below the ultimate strain was fitted to a fifth-order polynomial (Dalstra et al., 1993). The E-modulus was defined as the maximum of the slope of the stress-strain curve.

Bone density

After the mechanical testing, Archimedes' principle was applied to determine the density parameters (Ding et al., 1997). In short, the fatty marrow was removed from the bone by an air jet, after which the specimen was soaked in an alcohol/acetone (1/1) mixture for 5 days. The dry mass (\(\mu_d\)) of the defatted specimens and the submerged mass (\(\mu_s\)) were recorded on a balance (Mettler AG204 DeltaRange, Mettler Instruments AG, Greifensee, Switzerland). The apparent density (\(\rho_{\text{app}}\)) was calculated from the dry mass of the specimen divided by its original volume. The tissue density was calculated as: \(\rho_{\text{tissue}} = \mu_d \cdot \rho_t / (\mu_d \cdot \mu_s)\), where \(\rho_t\) is the density of the submersion liquid. The volume fraction was derived from \(\rho_{\text{app}} / \rho_{\text{tissue}}\).

Statistical analysis

One-tailed t-tests were used to detect differences between the dentate and edentate groups. The parameters in the axial and transverse directions were compared with paired t-tests. Significance level was set at \(p < 0.05\). The SPSS 10.0 software (SPSS Inc.) was used to perform all statistical analyses.

Results

An example of a stress-strain recording (axial loading) in a dentate and an edentate subject is depicted in Fig. 2. The cancellous bone of the dentate subject was stiffer.
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and stronger than that of the edentate subject. In Fig. 3 the density and mechanical parameters are given for both groups. As there was no systematic difference in the density parameters between the axial and transverse specimens, their average values were used to compare the dentate and edentate groups. In the edentate group the apparent density and volume fraction, as well as the tissue density were significantly less than in the dentate group (Fig. 3A-C). Thus, not only did the amount of mineralized tissue change with loss of teeth, so, too, did its composition.

In axial loading, the E-modulus and ultimate stress differed significantly between the groups, whereas such a difference was not found in transverse loading (Fig. 3D-F). For both loading directions the ultimate strain did not differ significantly between the dentate and the edentate group. Further, the figure shows that in both groups the cancellous bone in the condyle was highly anisotropic. It was significantly stiffer (dentate: \( p<0.001 \); edentate: \( p<0.01 \)) and stronger (dentate: \( p<0.001 \); edentate: \( p<0.05 \)) in the axial direction than in the transverse direction. Although the absolute difference between the mechanical parameters obtained from the axial and transverse loading experiments was higher in the dentate group than in the edentate group, the ratios of these parameters were the same. This indicates that

![Fig. 2 Stress-strain registrations of axial loading for a specimen from the dentate group (A) and from the edentate group (B) are depicted. The fitted line is a fifth-order polynomial. The elastic modulus was determined at the steepest part of the curve, and is presented by the straight line.](image_url)
the degree of anisotropy did not differ between the two groups.

Figure 4 shows the relationship between E-modulus and apparent density. Regression curves were fitted through the scattered data points using power relationships. Although the mean values for E-modulus and apparent density differed between the dentate and edentate group, both groups depended similarly for stiffness on apparent density, i.e., the fitted lines within one loading direction were comparable.

To exclude a possible confounding effect of age, we also examined the correlations between age and mechanical parameters, and age and density.

**Fig. 3** Bar diagrams of density (A-C) and mechanical parameters (D-F) for the dentate and edentate groups. For the density parameters, the values for the axial and transverse directions were averaged and their means for dentate and edentate groups were compared. The probability values of the tests for differences between the dentate and edentate group are indicated by symbols.
Reduced mechanical load decreases density, stiffness, and strength parameters. Although there was a significant age difference between the dentate and the edentate group, age had neither a predictive value for mechanical parameters, nor for density parameters.

Discussion

A number of studies in rats have indicated that the density of the cancellous bone of the mandibular body (Kiliaridis et al., 1996; Bresin et al., 1999) and mandibular condyle (Bouvier, 1988) is affected by a decrease of mechanical loading, i.e., the density of the bone decreased when the animals were fed a soft diet. As a model of reduced mechanical loading in the human masticatory system, we used the edentate mandible. From the literature it is known that with a loss of teeth the cross-sectional area of the masticatory muscles reduces by about 30% (Newton et al., 1993) and that maximal bite force decreases by 4-6 times (Helkimo et al., 1977; Haraldson et al., 1979). Therefore, we hypothesized that the cancellous bone of the mandibular condyle in edentate subjects has a lower density and is less stiff and strong than in dentate subjects. We indeed found that the density of the bone of the edentate group was lower (about 18%) than that of the dentate group. This is in agreement with

![Fig. 4 Scatter plot of E-modulus vs. apparent density. Power relationships were fitted to the data. The r-squared values for the different regression curves are shown. Solid line: dentate axial; dashed-dotted line: edentate axial; dashed line: dentate transverse; dotted line: edentate transverse.](image-url)
other studies in which the amount of cancellous bone of the condyle of edentate and dentate subjects was compared (22% - 25% decrease, Hongo et al., 1989b; Kawashima et al., 1997). It should be noted that not only the volume fraction and apparent density had lower values in the edentate group, but also that the tissue density decreased. Hence both the density and the composition of the cancellous bone changed.

Our edentate group was older than the dentate group. This might have influenced the results, as a decrease of bone mass with aging is well known (e.g., tibial bone: Ding, 2000; vertebral bone: Ebbesen et al., 1999). In the present study, no significant relationships were found between age and any of the density and mechanical parameters. We, therefore, conclude that the difference in density between the dentate and edentate groups cannot be ascribed to a difference in age. This is in agreement with the results of Von Wowern and Stoltze (1978) and Hongo et al. (1989a), but not with those of Yamada et al. (1997).

As far as we know, this is the first study in which the mechanical properties of the cancellous bone of the condyle of dentate and edentate mandibles were compared. We found that the stiffness and strength of the bone of edentate subjects were significantly lower. This was not surprising due to the lower density in the edentate group and the established relationship between apparent density and mechanical parameters (Carter and Hayes, 1977). Although the mean values for E-modulus and apparent density differed between the dentate and edentate group, both groups showed similar relationships between stiffness and apparent density (Fig. 4). This suggests that the mechanical properties of the total bone would have been equal in both groups if the apparent density had been the same.

The mechanical parameters in both groups were anisotropic, i.e., the bone was significantly stiffer and stronger in the axial direction, in which the condyle is normally loaded. The degree of mechanical anisotropy was not increased in the edentate group. This might indicate that the bone loss associated with reduced loading differs from other osteoporotic bone loss, in which an increase in anisotropy has been observed (Ciarelli et al., 2000).

Some points regarding the method should be noted. Firstly, we used relatively small and embalmed specimens. The small dimensions could have led to an underestimation (Linde et al., 1992), while the embalming procedure could have led to an overestimation of the modulus of elasticity (Linde, 1994). The compression tests were performed between parallel plates, which may have generated systematic and random errors (Keaveny et al., 1997). The mechanical properties are therefore indicative. However, the major findings of this study, that is the differences between
Reduced mechanical load decreases density, stiffness, and strength in dentate and edentate subjects, and anisotropy, are not invalidated. Secondly, the method of determining the E-modulus in the present study was different from a previous study (Giesen et al., 2001), where the tangent of the curve at 0.6% strain defined the E-modulus. It appeared that some specimens in the edentate group had already yielded at 0.6% strain. Therefore, we used the maximum slope of the stress-strain curve (Ciarelli et al., 2000). Thirdly, some of the specimens could have been damaged before the actual test was performed, as we preconditioned them to a strain of 0.6%. The edentate group was more susceptible to failure during preconditioning than the dentate group. Therefore, the values for ultimate strain in the edentate group might have been overestimated.

References


