Morphology and mechanical properties of the cancellous bone in the mandibular condyle
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Abstract
The cancellous bone of the mandibular condyle consists of plate-like trabeculae primarily oriented vertically and anteroposteriorly. The objective of the present study was 1) to test the hypothesis that the elastic and failure properties depend on the loading direction, and 2) to relate these properties to bone density parameters. Uniaxial compression tests were performed on cylindrical specimens \((n=47)\) obtained from the mandibular condyles of 24 embalmed cadavers. Two loading directions were examined, i.e., a direction coinciding with the predominant orientation of the plate-like trabeculae (axial loading) and a direction perpendicular to the plate-like trabeculae (transverse loading). Archimedes' principle was applied to determine bone density parameters. The cancellous bone appeared to be highly anisotropic. It was in axial loading 3.4 times stiffer and 2.8 times stronger than in transverse loading. High coefficients of correlation were found among the various mechanical properties and between them and the apparent density and bone volume fraction. For each loading direction about 60% of the variance in the mechanical properties could be explained from apparent density. When the results of both loading directions were combined, only 25% of the variance could be explained. The anisotropic mechanical properties can possibly be considered as a mechanical adaptation of the bone to the loading of the condyle \textit{in vivo.}
Introduction

Mechanical properties of cancellous bone strongly depend on its apparent density (Carter and Hayes, 1977) and structure (Hodgskinson and Currey, 1990; Uchiyama et al., 1999; Ulrich et al., 1999). Over 90% of the variance in the mechanical properties can be explained by these two aspects (Odgaard et al., 1997; Van Rietbergen et al., 1998; Zysset et al., 1998). The stiffness and the strength of the bone are proportional to apparent density. The bone is stiffest and strongest in the direction in which the trabeculae are aligned. Previous studies revealed that in the mandibular condyle the cancellous bone is anisotropic (Hongo et al., 1989b; Giesen and Van Eijden, 2000). It consists of parallel plate-like trabeculae primarily oriented in the vertical direction, perpendicular to the mediolateral condylar axis. In the horizontal direction the plate-like trabeculae are interconnected with rods. From this it can be expected that the bone is stiffer and stronger in vertical and anteroposterior directions compared to the mediolateral direction. In addition, a wide range in bone volume fraction was found between condyles of different individuals (Giesen and Van Eijden, 2000). Hence, a wide range in apparent density, and as a consequence, a wide range in mechanical properties can be expected.

Thus far, to our knowledge no studies are available on mechanical properties of the cancellous bone of the human mandibular condyle. Adequate estimates of the mechanical properties can be used, e.g., in finite element modeling of the mandibular condyle and tissue engineering of mandibular implants. The only study in which the cancellous bone of the mandibular condyle was involved concerned the pig (Teng and Herring, 1996). Previously, determination of mechanical properties of the human mandible was limited to the cortical bone (e.g., Arendts and Sigolotto, 1989; Dechow et al., 1993; Zioupos and Currey, 1998; for review: Van Eijden, 2000), or to the cancellous bone of its body (Misch et al., 1999). The purpose of this study was to determine the mechanical properties of the cancellous bone of the mandibular condyle in different directions and to relate these to the density of the bone. The hypotheses were that, due to the vertical orientation of the plate-like trabeculae in the sagittal plane, the stiffness and strength would be higher for loading in the vertical direction (axial loading) than for loading in the mediolateral direction (transverse loading).
Methods

Specimen preparation

Cylindrical cancellous bone specimens were obtained from the mandibular condyles of 24 embalmed human cadavers (19 female, 5 male, mean age ± SD: 74.8 ± 11.7 yrs). The embalming fluid was a mixture of water, alcohol, glycerin, and formol. The cadavers were selected according to the state of dentition; the mean number of teeth in the upper jaw was 8.5 and in lower jaw 10.7.

To produce cylindrical bone specimens a custom-made hollow drill was used. The inner diameter of its shaft was in the middle larger than at the drilling site to prevent the specimens to get jammed. Furthermore, an opening in the shaft of the drill was constructed to remove the specimen easily. Two different groups of specimens were fabricated, drilled in two directions, i.e., superoinferiorly (axial group, n=24) and mediolaterally (transverse group, n=23) (Fig. 1). The resulting specimens had a diameter of 3.57 ± 0.08 (mean ± SD) mm. The position within the condyle for the axial specimen, medial or lateral, was chosen by randomization. Mostly, both specimens originated from one condyle. In a few cases (n=3) the

Fig. 1 The specimens were drilled from the condyle (anterior view) in two directions 1) superoinferior (axial) and 2) mediolateral (transverse). After the axial specimen was drilled out, the condyle was sawed off perpendicular to the direction of the second specimen. Finally, the ends of the core were cut-off perpendicular to the cylindrical axis leaving the actual specimen (lightened).
specimens came from both condyles of the same individual. The specimens were cut perpendicular to their long axes with a Leitz Saw Microtome 1600 (Ernst Leitz Wetzlar Gmbh, Wetzlar, Germany). The exact specimen lengths were measured using a caliper (mean ± SD: 4.88 ± 0.04 mm). The specimens were stored in the embalming fluid prior to testing.

**Mechanical testing**

To measure the elastic and failure properties, the specimens were subjected to uniaxial destructive compressive mechanical tests in a materials testing machine (858 Mini Bionix, MTS Systems Corporation, Minneapolis, MN, USA) using a 1 kN load cell. The specimens were placed between two steel loading rods with low friction using low-viscosity mineral oil as a lubricant. A strain gauge extensometer (model 632.11F-20, MTS) was attached to the loading rods close to the specimen to monitor its deformation and calculate the strain. The specimens were preconditioned with 5 cycles between a pre-load of 3 N (zero strain) and 0.6% bone strain to reach a viscoelastic steady state (Linde et al., 1988). Then a load was applied with a constant strain rate of 0.2% s⁻¹ until a strain of 3% was reached. Four mechanical parameters were calculated from the stress-strain curve, i.e., elastic-(E-)

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**Fig. 2** Diagram of stress-strain curve. Ultimate stress and ultimate strain were determined at the maximum of the curve. The elastic modulus was determined at 0.6% strain as the first derivative of the fitted 5th-order polynomial.
Mechanical properties are anisotropic modulus, ultimate stress, ultimate strain, and failure energy (Fig. 2). The ultimate stress, or strength, 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 between zero and ultimate strain was fitted with a fifth order polynomial (Dalstra et al., 1993). The E-modulus was defined as the tangent of the stress-strain curve at a strain of 0.6% (Linde et al., 1988; Ding et al., 1997). The failure energy was calculated as the area underneath the stress-strain curve between zero strain and ultimate strain.

Bone density

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

Statistical analysis

Paired t-tests were used to test for differences between loading direction (axial vs. transverse), mandibular side (left vs. right), and condylar site (lateral vs. medial). The mechanical parameters and the density parameters were logarithmically transformed and Pearson's coefficients of correlation were calculated (Hodgkinson and Currey, 1990; Kabel et al., 1999). Further, to predict the mechanical properties from density or volume fraction power relationships were determined (Carter and Hayes, 1977; Dalstra et al., 1993), i.e., \(E\)-modulus = \(B \cdot \rho_{\text{app}}^A\), where \(\rho_{\text{app}}\) is the apparent density and \(A\) and \(B\) are constants. SPSS 10.0 software (SPSS Inc.) was used to perform all statistical analyses.
Results

In Table 1 the descriptive statistics of the mechanical and the density parameters are presented. The mechanical properties of the cancellous bone in the mandibular condyle appeared to be highly anisotropic. In axial loading the bone was 3.4 times stiffer and 2.8 times stronger upon failure than in transverse loading. In axial loading the failure energy was about 2 times as high as in transverse loading. The ultimate strain, however, was larger in transverse loading than in axial loading. Obviously, because the specimens of both groups were taken from the same individual, the density parameters did not differ between the two groups. There were no dependencies of mandibular half (left or right condyle) for any of the parameters. However, mechanical properties differed within the condyle, i.e., for the transverse loading group the lateral site of the condyle had a significantly higher E-modulus, ultimate stress and failure energy than the medial site; such a mediolateral difference was not found for the axial loading group.

Pearson's correlation coefficients of the log-transformed mechanical and density parameters are presented in Table 2. High correlation coefficients were observed among the mechanical parameters E-modulus, ultimate stress, and failure energy, and between them and the apparent density and volume fraction. Only the ultimate strain in the samples from the transverse group did not correlate to the other parameters. The tissue density showed no correlation with any other

| Table 1 | Average of mechanical and density parameters for the different groups. |
|---------|-----------------|-----------------|-----------------|
|         | Axial           | Transverse      | Paired T-Test   |
|         | Mean (SD) (n=24)* | Mean (SD) (n=19)* | *** |
| E-modulus [Mpa] | 431 (217) | 127 (92) | *** |
| Ultimate stress [Mpa] | 4.5 (1.9) | 1.6 (1.0) | *** |
| Ultimate strain [%] | 1.65 (0.29) | 2.11 (0.46) | ** |
| Failure energy [kJ/m3] | 48.89 (21.64) | 23.95 (16.59) | *** |
|         | (n=17)* | (n=16)* |         |
| Tissue density [g/cm3] | 2.146 (0.054) | 2.127 (0.045) |         |
| Apparent density [g/cm3] | 0.352 (0.063) | 0.336 (0.069) |         |
| Bone volume fraction [%] | 16.4 (3.1) | 15.8 (3.3) |         |

* The number of specimens with valid results is indicated.
** p<0.01
*** p<0.001
Mechanical properties are anisotropic parameter in either the axial or the transverse group.

A scatter plot of the E-modulus and the apparent density is shown in Fig. 3. In both the axial and transverse loading groups, the E-modulus depended on the apparent density. The solid line in the figure represents the power relationship $E\text{-modulus} = B \cdot \rho_{app}^{-A}$, where A and B are constants. The relative difference between the two groups is smaller at higher densities. The power relationships of the mechanical parameters E-modulus, ultimate stress, and failure energy with the apparent density

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Axial loading</th>
<th>Transverse loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus</td>
<td>0.987***</td>
<td>0.915***</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>0.453*</td>
<td>0.031</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td>0.723***</td>
<td>0.760***</td>
</tr>
<tr>
<td>Failure energy</td>
<td>-0.216</td>
<td>0.398</td>
</tr>
<tr>
<td>Tissue density</td>
<td>-0.119</td>
<td>-0.288</td>
</tr>
<tr>
<td>Apparent density</td>
<td>0.795***</td>
<td>0.743***</td>
</tr>
<tr>
<td>Bone volume fraction</td>
<td>0.801***</td>
<td>0.349</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Axial loading</th>
<th>Transverse loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-modulus</td>
<td>0.974***</td>
<td>0.845***</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>-0.017</td>
<td>0.919***</td>
</tr>
<tr>
<td>Ultimate strain</td>
<td>0.366</td>
<td>-0.389</td>
</tr>
<tr>
<td>Failure energy</td>
<td>0.134</td>
<td>0.314</td>
</tr>
<tr>
<td>Tissue density</td>
<td>-0.057</td>
<td>0.304***</td>
</tr>
<tr>
<td>Apparent density</td>
<td>0.724**</td>
<td>0.804***</td>
</tr>
<tr>
<td>Bone volume fraction</td>
<td>0.650***</td>
<td>0.778***</td>
</tr>
</tbody>
</table>

Table 2a Pearson's correlation coefficients and their significance level of log-transformed data of the axial group.

Table 2b Pearson's correlation coefficients and their significance level of log-transformed data of the transverse group.

\* p<0.05
\*\* p<0.01
\*\*\* p<0.001
Table 3 Power relationships of the apparent density and volume fraction with the mechanical parameters.

<table>
<thead>
<tr>
<th></th>
<th>Apparent density</th>
<th>Bone volume fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r^2$</td>
<td>$r^2$</td>
</tr>
<tr>
<td>Axial</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-modulus</td>
<td>$4217 \cdot \rho_{app}^{2.25}$</td>
<td>$19588 \cdot \text{BV/TV}^{1.65}$</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>$31 \cdot \rho_{app}^{1.91}$</td>
<td>$112 \cdot \text{BV/TV}^{1.62}$</td>
</tr>
<tr>
<td>Failure energy</td>
<td>$471 \cdot \rho_{app}^{2.27}$</td>
<td>$2046 \cdot \text{BV/TV}^{1.13}$</td>
</tr>
<tr>
<td>Transverse</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E-modulus</td>
<td>$2786 \cdot \rho_{app}^{3.22}$</td>
<td>$16827 \cdot \text{BV/TV}^{2.87}$</td>
</tr>
<tr>
<td>Ultimate stress</td>
<td>$18 \cdot \rho_{app}^{3.53}$</td>
<td>$77 \cdot \text{BV/TV}^{2.28}$</td>
</tr>
<tr>
<td>Failure energy</td>
<td>$428 \cdot \rho_{app}^{3.02}$</td>
<td>$2735 \cdot \text{BV/TV}^{2.76}$</td>
</tr>
</tbody>
</table>

$\rho_{app} = \text{apparent density, BV/TV = bone volume fraction}$

and volume fraction were calculated (Table 3). When the orientation of the specimens was taken into account by specifying by group it appeared that over 60% of the variance in mechanical properties could be explained from the density. In the transverse loading group this percentage was not as high. When the data for both groups were combined only 25% of the variance within the mechanical properties could be explained.

Discussion

Mechanical anisotropy

To our knowledge, this is the first study in which mechanical properties of the cancellous bone in the human mandibular condyle were investigated. A comparison was made between loading in a direction coinciding with an orientation parallel to the plate-like trabeculae (axial loading) and a direction perpendicular to these plate-like trabeculae (transverse loading). It appeared that the mechanical properties of the cancellous bone were highly anisotropic. In axial loading the bone was 3.4 times stiffer and 2.8 times stronger upon failure than in transverse loading. The failure energy was about 2 times higher in transverse loading than in axial loading. The ultimate strain was found to be larger in a direction perpendicular to the plate-like trabeculae, indicating that in the transverse direction the bone can be deformed over a larger distance before it collapses. A direction dependency of ultimate strain was also found by Zysset and Curnier (1996), but not by Chang et al. (1999). For the mandibular condyle of the pig (Teng and Herring, 1996) and for other bones
Mechanical properties are anisotropic. Comparable anisotropy of mechanical properties relative to direction has been demonstrated (e.g., proximal femur: Wirtz et al., 2000; calcaneus, femoral head, iliac crest, lumbar vertebral body: Ulrich et al., 1999; bovine proximal femur: Chang et al., 1999). During normal functioning the mandibular condyle is primarily loaded in a vertical direction (Marks et al., 1997), i.e., along the plate-like trabeculae. That the bone is stiffer and stronger in this direction can possibly be considered as a mechanical adaptation to this external loading.

The values for E-modulus and strength we found were considerably larger than the values reported for cancellous bone of the mandibular body (E-modulus: 56.0 MPa, compressive strength: 3.9 MPa; Misch et al., 1999). The difference can probably be ascribed to differences in structure and function. For example, in contrast to the condyle, a thick layer of cortical bone surrounds the cancellous bone in the body. Our values of the E-modulus for the axial group are in the range found for other bones (proximal tibia: 635 ± 386 MPa (mean ± SD), Ding et al., 1997; proximal femur: 441 ± 271 MPa, Lotz et al., 1990; acetabulum: 60 ± 48 MPa, Dalstra et al., 1993; vertebral body: 316 ± 227 MPa, Hou et al., 1998).

At the lateral site of the condyle we found for the transverse loading a significantly higher E-modulus, ultimate stress and failure energy than at the medial

\[ E_{\text{axial}} = 4217 \cdot \rho^{3.25} \]
\[ E_{\text{transverse}} = 2786 \cdot \rho^{3.22} \]
\[ r^2 = 0.63 \]
\[ r^2 = 0.49 \]

Fig. 3 Scatter plot of E-modulus versus apparent density, filled circles: axial-group, open circles: transverse-group. The fitted line through each group is the power relationship shown in the figure.
site. The lateral site is the site in which in the temporomandibular disc mostly perforations are seen (Werner et al., 1991), which was suggested to be due to the highest friction. Maybe, this high friction might have triggered the bone to increase the mechanical properties in the non-preferential direction at the lateral site of the condyle. Computer simulation studies of the temporomandibular disc show the highest compressive loads at the lateral site (Beek et al., 2000). However, in the vertical direction we did not find any differences in mechanical properties between the lateral and medial half of the condyle.

Some points should be noted. Firstly, in studying mechanical properties of cylindrical bone specimens a diameter of 7.5 mm and length of 6.5 mm is recommended, resulting in the testing of a structure and not of a few trabeculae (Linde et al., 1992). However, we had to limit the diameter to 3.6 mm because of the relatively small size and curved shape of the human condyle. Larger specimens would have included cortical bone within the specimen. The small specimen size could have influenced the measurements, e.g., underestimation of the modulus of elasticity (Linde et al., 1992). To prevent buckling during the mechanical tests the length of the specimen was predetermined to approximately 5 mm. Due to the specimens size the continuum assumption (Harrigan et al., 1988) is not valid, but at this point no alternative testing methods are available. Further, the compression tests between parallel plates generate systematical and random errors (Keaveny et al., 1997). The mechanical properties are therefore indicative, but the major findings of this study in terms of anisotropy are not invalidated. Secondly, the elastic modulus was determined at 0.6% strain. The elastic modulus might be underestimated as in some specimens the bone already begins to yield at that strain level. However, in literature often 0.6% strain is used to calculate the elastic modulus (Linde et al., 1988; Ding et al., 1997), but it remains arbitrary. Thirdly, the embalming procedure could have changed the mechanical properties, i.e., a slight increase in stiffness (Linde, 1994). Fourthly, the specimens were taken from relatively old cadavers. Age-related decrease of density and E-modulus (Ding et al., 1997) could be expected. In the present study (data not shown) and that of Hongo et al. (1989a), both examining the human mandibular condyle, no correlation between these parameters and age were found.

Mechanical properties and density

The bone volume fraction appeared to be in the same range as found in a previous study (Giesen and Van Eijden, 2000). The apparent density, 0.35 g/cm³, was in the range found for other bone (acetabular bone: 0.20-0.35 g/cm³, Dalstra et al., 1993;
Mechanical properties are anisotropic proximal tibia: $0.46 \pm 0.12 \text{ g/cm}^3$, Ding et al., 1997; $0.24 \pm 0.09 \text{ g/cm}^3$, Carter and Hayes, 1977).

Not only high coefficients of correlation among mechanical properties were found, but also between mechanical properties and the apparent density and bone volume fraction. The power relationships of mechanical and density parameters could explain over 60% of the variance in the mechanical parameters within each group. When the results of both loading directions were combined, only 25% of its variance could be explained. Thus, it is of great importance to take the orientation of the trabecular structure into account when using density parameters to model bone mechanical parameters. The explained variance in mechanical properties would have been higher if we had no variation in trabecular orientation at all. We fabricated our specimens approximately in directions relatively parallel or perpendicular to the predominant trabecular orientation of the bone, as found in Giesen and Van Eijden (2000). However, as already mentioned in that study, the plate-like trabeculae are not truly parallel throughout the whole condyle. In the upper regions of the condyle the trabeculae are directed outwards and converge to the mandibular neck. This means that the trabeculae in the cylindrical specimen are not perfectly parallel or perpendicular to its axis. Comparable r-squared values to explain the variance in mechanical properties for different kinds of bones (calcaneus, femoral head, iliac crest, and lumbar spine) from density parameters alone were found (36%, Uchiyama et al., 1999; 37-67%, Ulrich et al., 1999). Other authors reported the explanation of the variance in mechanical properties solely from bone volume fractions up to 94%. In those studies mostly homogenous bone is analyzed (Van Rietbergen et al., 1998), or comparison is made relative to a calculated primary principal direction or mean elastic properties of the bone of the specimen (Kabel et al., 1999).

Ultimate strain does not correlate with apparent density (Kopperdahl and Keaveny, 1998). This was confirmed in the present study. It implicates that independently of the amount of tissue the bone can deform to a predetermined strain before it collapses. If the bone is subject to larger loads it will adapt and increase the apparent density, allowing the same amount of strain. Ultimate strain did not correlate to any of the other parameters investigated.

In conclusion, despite the small dimensions of the human mandibular condyle we were able to perform mechanical tests to its cancellous bone. We showed that the cancellous bone has anisotropic mechanical properties. The present data can provide input for future finite element modeling of the temporomandibular joint.
References


Mechanical properties are anisotropic


