Morphology and mechanical properties of the cancellous bone in the mandibular condyle
Giesen, E.B.W.

Citation for published version (APA):
Chapter 2

The Three-Dimensional Cancellous Bone Architecture of the Human Mandibular Condyle

Abstract

In the present study the hypothesis was tested that the cancellous bone of the mandibular condyle is inhomogeneous and anisotropic. For this purpose, eleven mandibular condyles of embalmed human cadavers were scanned in a micro-CT system. Within each condyle nine volumes of interest were selected from different mediolateral and superoinferior regions. Several bone parameters were calculated to describe the morphology. It appeared that the cancellous bone of the condyle could be approximated by parallel plates. These plates were almost vertically oriented at an angle of 17° relative to the sagittal plane, i.e., perpendicular to the condylar axis. In the superior regions of the condyle the cancellous bone had the largest bone volume fraction (19%), associated with the thickest trabeculae (0.11 mm) and the highest trabecular number (1.72 mm⁻¹). The lowest bone volume fraction (15%) was found more inferiorly. The degree of anisotropy increased from superior to inferior across the condyle. No mediolateral differences in bone morphology were found, but superiorly central regions contained more bone than peripheral regions. The plate-like trabeculae could indicate that the condyle is optimally adapted to sustain loads from all directions in a plane perpendicular to the condylar axis. The high bone mass and lower anisotropy in the superior regions could enable the condyle to sustain multiple load directions. Towards the colhum the trabeculae are more aligned. This could point to stresses acting predominantly in one direction.
Introduction

During masticatory function the mandibular condyle translates and rotates along the saddle-like shaped articular surface of the temporal bone. During these movements the condyle is subject to complex loading patterns. Joint forces are absorbed by the cancellous bone within the condyle and are transferred towards the mandibular collum. As a consequence, stresses and strains are produced. According to Wolff's law (1892), the trabecular bone structure is supposed to be optimally adapted to sustain the loads by aligning the direction of the trabeculae to the direction of the stress trajectories. Joint forces are assumed to act perpendicular to the articular surface of the condyle and therefore the range of joint force directions is primarily determined by the shape of the condyle. While the condyle is more or less ovoid shaped, joint forces may act predominantly towards its mediolaterally directed axis. Hence, a radially oriented stress pattern and thus a concomitant anisotropic cancellous bone architecture can be expected in the condyle. Furthermore, because of the condyle's shape the distribution of condylar loading is probably not homogeneous, which could imply that the distribution of the cancellous bone is inhomogeneous. This anisotropy and inhomogeneity then also apply for the mechanical properties of the cancellous bone, like stiffness and strength, while they are largely determined by its structure. Bone volume fraction and anisotropy are of special interest, as 90% of the variance in mechanical properties can be explained by these parameters (Odgaard et al., 1997; Van Rietbergen et al., 1998; Zysset et al., 1998).

A few studies hint to a relationship between condylar loading and condylar bone structure. In edentulous people the trabecular bone of the condyle was less dense and the trabeculae were thinner than in dentate people (Hongo et al., 1989b; Kawashima et al., 1997). In addition, the direction of the trabeculae was found to be related to the direction of the lateral pterygoid muscle (Hongo et al., 1989b). In the pig mandibular condyle, however, the latter relationship was not confirmed (Teng and Herring, 1995). The results of these studies were based on condylar sections in three perpendicular planes. Therefore, they were limited to the aspects occurring within these planes only and the results are dependent on the choice of sectional planes. This is less adequate for describing cancellous bone architecture because of its anisotropic nature (Müller et al., 1998), therefore, three-dimensional analyses are needed (for review: Odgaard, 1997).

The purpose of the present study was to determine architectural parameters from a three-dimensional analysis of the cancellous bone architecture of the human
mandibular condyle, using micro-computed tomography. The hypothesis was tested that the distribution of cancellous bone of the mandibular condyle is inhomogeneous and anisotropic. The possible inhomogeneity and anisotropy observed might elucidate a possible relationship between cancellous bone structure and mechanical function.

Material and Methods

Specimen preparation

Seven left and four right condyles of eleven cadavers were used (three male, eight female, mean age ± SD: 72.6 ± 11.2 years, range: 56 - 89 years). 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. The cadavers were fixed with a mixture of formalin, glycerol, alcohol, and phenol. The mouth was closed in all cadavers. The number of teeth in the upper jaw was 9.6 ± 3.5, in the lower jaw 11.9 ± 2.8.

First, four small reference holes were drilled in the mandible. An electromagnetic tracking device (3space digitizer, Polhemus, Colchester, VT, USA) was used to obtain the three-dimensional position of these reference points relative to a skull-related Cartesian coordinate system (for an extensive description, see Van Eijden et al., 1995). The origin was centered between the two condyles, the x- and y-axes were parallel to the Frankfort Horizontal plane, and the z-axis was perpendicular to that plane. Then, the mandible was removed and four reference points were drilled in the cortex of the condyle. By using the reference points of the mandible, the three-dimensional positions of the reference points of the condyle were determined relative to the skull-related coordinate system. Finally, the condyle was separated from the mandible at the collum by an electric cyclic saw.

Micro-CT

To obtain the three-dimensional bone structure we used a micro-computed tomograph (μCT 20, Scanco Medical AG, Zürich, Switzerland). The micro-CT system is based on an X-ray tube, which produces a fan beam that is detected by a CCD-array. The system has been described in detail by Rüegsegger et al. (1996). The condyles were placed in a cylindrical sample holder with a diameter of 17.4 mm.

Slices were scanned with a size of 512 x 512 pixels. The pixel size was 34 x 34 μm² and the interslice distance was 34 μm, resulting in a voxel size of 34 x 34 x 34...
μm³. The number of slices depended on the size of the condyle and ranged from 526 to 770. The mean scanning time was about 13 hours. By combining the slices the three-dimensional structure was reconstructed. The reference holes of the condyle could be detected relative to the coordinate system of the reconstruction, which enabled the reorientation of the reconstructed condyle to the skull-related coordinate system.

To discriminate between different regions within the condyle, several volumes of interest (VOI) were selected. In most cases the size of the VOIs was 4.35 x 4.35 x 4.35 mm³ (128 x 128 x 128 voxels). The condyle was divided up into three superoinferior zones: a superior zone, directly under the articulating bone, an intermediate zone, and an inferior zone, towards the collum. Each zone was subdivided in mediolateral direction: four VOIs in the superior, three in the intermediate, and two in the inferior zone (Fig. 1).

A uniform threshold for all VOIs of all specimens was used to distinguish bone tissue from bone marrow (Rüegsegger et al., 1996; Müller et al., 1998). To determine this threshold, all VOIs of the first condyle tested were subjected to an adaptive procedure in which the cancellous bone fraction was determined for a range of thresholds. The optimal threshold of each VOI was defined at the minimum change of bone fraction. The average of the optimal thresholds for all VOIs of the

![Diagram](image)

**Fig. 1** The condyle was divided up into three superoinferior zones: a superior zone, directly under the articulating bone, an intermediate zone, and an inferior zone, towards the collum. A schematic representation of the positions of the volumes of interest in the condyle is shown; four volumes of interest in the superior, three in the intermediate, and two in the inferior zone.
first specimen (19.6% of the maximum gray level) was applied to all specimens.

**Bone architecture**

The bone architecture was described by the morphology and orientation of the trabecular structure. The former was described using the parallel plate model of Parfitt et al. (1983) by determining the bone volume (BV), total volume (TV) and trabecular number (Tb.N). The bone volume and total volume were determined by counting voxels. The trabecular number was determined by the mean intercept length (MIL) method. This method determines the mean distance between two bone-marrow intersections in a linear grid of parallel lines, as a function of the grid's three-dimensional orientation in the VOI (Whitehouse, 1974). The trabecular number was defined by: 

\[ \text{Tb.N} = \text{MIL}^{-1}, \]

the trabecular thickness (Tb.Th) by:

\[ \text{Tb.Th} = (\text{BV}/\text{TV})/\text{Tb.N}, \]

trabecular separation (Tb.Sp) by:

\[ \text{Tb.Sp} = (1-\text{BV}/\text{TV})/\text{Tb.N}, \]

and bone surface density (BS/BV) by:

\[ \frac{\text{BS}}{\text{BV}} = 2\cdot \frac{\text{Tb.N}}{\text{BV}/\text{TV}} \]

(nomenclature according to Parfitt et al., 1987).

The orientation of the trabecular structure was described by the principal direction of the trabeculae and the degree of anisotropy. For this purpose, a mean intercept length tensor was calculated by fitting an ellipsoid to the mean intercept length measurements (Harrigan and Mann, 1984). The eigenvector of the mean intercept length tensor associated with the major axis of the ellipsoid gives the predominant principal direction of the bone material. The eigenvalues of the mean intercept length tensor, H₁, H₂, and H₃, are associated with the length of the axes of the ellipsoid and express the prevalence of the material distribution in the corresponding principal directions. The eigenvalues were sorted such that 

H₁>H₂>H₃. To describe the dominance of trabecular orientation the degree of anisotropy (DA) was used. This was defined by the ratios between the eigenvalues, the first DA = H₁/H₃, the second DA = H₁/H₂. If all three eigenvalues are equal, thus the first DA = 1, the bone architecture is considered to be isotropic. If the second DA = 1 the structure is considered to be oblately transversely isotropic. All bone architectural parameters were calculated using the software package at the micro-CT system (Rüegsegger et al., 1996).

**Statistical analysis**

Univariate analyses for repeated measurements were used to test the regional differences. To analyze differences between the medial and lateral half of the condyle the VOIs in each zone were divided into a medial and lateral group. Using this
method not only zone and mediolateral specific differences could be tested, but also the interaction between these. In the superior zone differences between central and peripheral volumes were also tested. All tests were conducted using the General Linear Model for repeated measures with the SPSS 8.0 software (SPSS Inc.).

Results

Different views of reconstructions of one condyle show the internal trabecular structure (Fig. 2). The nine reconstructed VOIs of this condyle are also visible (Fig. 2e). Due to the thresholding procedure the soft tissues (cartilage and marrow) are not depicted. By visual observation of the reconstructions it appeared that the cancellous bone of the condyle primarily consisted of vertically oriented plate-like structures, running anteroposteriorly at a small angle relative to the sagittal plane. These plates were approximately perpendicular to the mediolateral condylar axis. They were perforated and interconnected by rod-like structures.

For all architectural bone parameters mean and SD values are given in Table 1. Significance levels of different tests are shown in Table 2. The eleven condyles showed a wide variation in the mean bone volume as fraction of the total volume. The bone volume fraction was highest in the superior zone and lowest in the intermediate zone. Within the superior zone, the central regions contained more bone than the peripheral regions. The bone surface density varied in superoinferior direction, with the lowest values in the superior zone and the highest values in the intermediate zone. The mean trabecular thickness was 0.10 mm. The superior zone contained the thickest and the intermediate zone the thinnest trabeculae. The separation of the trabeculae was on average 0.52 mm. The trabecular separation was smallest in the superior zone. Within this zone the central regions showed smaller intertrabecular space compared to the peripheral regions. The mean trabecular number was 1.66 mm\(^{-1}\). The highest trabecular number was seen in the superior zone, with more trabeculae in central regions than in peripheral regions. Hence, the superior zone had a higher bone volume fraction, due to more and thicker trabeculae. In the intermediate zone, thinner and more separated trabeculae resulted in the lowest bone volume fraction. No mediolateral differences were seen in any of the parameters.

In Fig. 3 the orientations of the trabecular structure of one condyle are shown. In each VOI an ellipsoid is plotted. The axes of each ellipsoid express the three principal directions of the local trabecular structure. The main orientation of the trabeculae, expressed by the first principal direction, was in the vertical direction. In
Fig. 2  a) Three-dimensional reconstruction of a left mandibular condyle. One of the four condyle related reference points can be clearly seen in the anterior rim of the collum. Of this condyle the b) superior, c) anterior, and d) lateral half is removed to show the internal trabecular structure. e) Reconstruction of nine volumes of interest of the same condyle. The size of the VOIs was $4.35 \times 4.35 \times 4.35 \text{ mm}^3$ and had small overlap. For visualization purposes the VOIs are separated. The vertically oriented plate-like structure is visible.
Table 1 Mean (SD) of all parameters for different superoinferior and mediolateral regions.

<table>
<thead>
<tr>
<th></th>
<th>Bone volume fraction (%)</th>
<th>Bone surface density [mm$^{-1}$]</th>
<th>Trabecular thickness [mm]</th>
<th>Trabecular separation [mm]</th>
<th>Trabecular number [mm$^{-1}$]</th>
<th>First degree of anisotropy [-]</th>
<th>Second degree of anisotropy [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superior</td>
<td>19.4 (5.6)</td>
<td>18.7 (3.3)</td>
<td>0.11 (0.02)</td>
<td>0.49 (0.11)</td>
<td>1.72 (0.26)</td>
<td>1.47 (0.09)</td>
<td>1.12 (0.05)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>15.1 (5.7)</td>
<td>23.0 (4.9)</td>
<td>0.09 (0.02)</td>
<td>0.56 (0.17)</td>
<td>1.61 (0.33)</td>
<td>1.50 (0.11)</td>
<td>1.09 (0.04)</td>
</tr>
<tr>
<td>Inferior</td>
<td>16.9 (6.1)</td>
<td>20.4 (4.5)</td>
<td>0.10 (0.02)</td>
<td>0.54 (0.14)</td>
<td>1.60 (0.28)</td>
<td>1.57 (0.15)</td>
<td>1.09 (0.04)</td>
</tr>
<tr>
<td>Superior peripheral</td>
<td>18.1 (5.7)</td>
<td>19.1 (3.7)</td>
<td>0.11 (0.02)</td>
<td>0.52 (0.12)</td>
<td>1.63 (0.25)</td>
<td>1.47 (0.10)</td>
<td>1.12 (0.04)</td>
</tr>
<tr>
<td>Superior central</td>
<td>20.6 (5.4)</td>
<td>18.3 (2.8)</td>
<td>0.11 (0.02)</td>
<td>0.45 (0.09)</td>
<td>1.81 (0.24)</td>
<td>1.47 (0.09)</td>
<td>1.13 (0.05)</td>
</tr>
<tr>
<td>Lateral</td>
<td>18.0 (6.1)</td>
<td>20.0 (4.8)</td>
<td>0.11 (0.02)</td>
<td>0.52 (0.16)</td>
<td>1.66 (0.31)</td>
<td>1.50 (0.13)</td>
<td>1.24 (0.05)</td>
</tr>
<tr>
<td>Medial</td>
<td>17.4 (6.0)</td>
<td>20.5 (4.2)</td>
<td>0.10 (0.02)</td>
<td>0.52 (0.13)</td>
<td>1.66 (0.26)</td>
<td>1.51 (0.11)</td>
<td>1.11 (0.04)</td>
</tr>
<tr>
<td>Average of condyles</td>
<td>17.5 (5.1)</td>
<td>20.5 (3.4)</td>
<td>0.10 (0.02)</td>
<td>0.52 (0.13)</td>
<td>1.66 (0.26)</td>
<td>1.51 (0.10)</td>
<td>1.11 (0.02)</td>
</tr>
</tbody>
</table>

Table 2 P-values of different univariate tests for different regions

<table>
<thead>
<tr>
<th></th>
<th>Bone volume fraction</th>
<th>Bone surface density</th>
<th>Trabecular thickness</th>
<th>Trabecular separation</th>
<th>Trabecular number</th>
<th>First degree of anisotropy</th>
<th>Second degree of anisotropy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Superoinferior</td>
<td>0.0003</td>
<td>0.0001</td>
<td>0.0004</td>
<td>0.0040</td>
<td>0.0080</td>
<td>0.0002</td>
<td>0.0040</td>
</tr>
<tr>
<td>Peripheral/central</td>
<td>0.0110</td>
<td>0.1490</td>
<td>0.2560</td>
<td>0.0008</td>
<td>0.0002</td>
<td>0.9130</td>
<td>0.4310</td>
</tr>
<tr>
<td>Mediolateral</td>
<td>0.7700</td>
<td>0.4700</td>
<td>0.5090</td>
<td>0.8040</td>
<td>0.9030</td>
<td>0.5480</td>
<td>0.4850</td>
</tr>
<tr>
<td>Total condyle</td>
<td>0.0001</td>
<td>0.0000</td>
<td>0.0001</td>
<td>0.0011</td>
<td>0.0001</td>
<td>0.0070</td>
<td>0.1670</td>
</tr>
</tbody>
</table>
In Fig. 4 the orientations of all principal directions of all VOIs of all specimens are plotted on the surface of a sphere. The variation in orientation of the first and second principal directions was large within the condyles. The third principal orientation had a smaller variation. The narrow band formed by the two main orientations represents the plane of the trabecular plates and indicates that the plates of different VOIs run more or less parallel. The plane through the band was almost vertical and had an angle of 17° with respect to the sagittal plane. Within a zone or site the variation of the first two principal directions was smaller, i.e., the band became smaller and data points were more grouped. The directions of the principal axes in the peripheral regions in the superior zone deviated from the vertical axis. They were pointing upwards to the periphery of the condyle. In the center of the condyle and more inferiorly the principal directions were more vertical and parallel. In superoinferior direction the first principal direction followed the curve of the condyle (Fig. 5).

The first degree of anisotropy had a mean value of 1.51 (Tables 1 and 2). The highest first degree of anisotropy was found in the inferior zone. The superior and intermediate zones had an equal first degree of anisotropy. No peripheral/central or mediolateral differences were found. The second degree of anisotropy had a mean

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**Fig. 3** The nine ellipsoids express the orientation of trabecular structure of different VOIs in one mandibular condyle (the same as in Fig. 2). The main orientation of the trabecular structure, first principal direction, is primarily in the vertical direction.
value of 1.11. It was smallest in the intermediate and inferior zones.

**Discussion**

The micro-CT system enables the reconstruction of the cancellous bone architecture of the mandibular condyle in three dimensions. Major advances of this technique are: the full three-dimensional information of the whole condyle, independence of planes of section, non-destructive evaluation, fast scanning time and standard software for determining the bone morphology parameters. The technique has proven to be reliable while the estimated bone parameters resemble those obtained by traditional histomorphometry (Kuhn et al., 1990; Uchiyama et al., 1997; Müller et al., 1998).

The micro-CT system produced images with a gray level that depends on the mineral content of the tissue. An adaptive threshold procedure was used to distinguish bone tissue from bone marrow. The mean threshold of all regions of one condyle was used as uniform threshold for all specimens. This makes the different condyles more comparable. Ding et al. (1999) compared the bone volume fraction determined by the adaptive threshold procedure and by a method based on Archimedes' principle. For low-density specimens (bone volume fraction < 20%) the adaptive threshold procedure resulted in a bone volume fraction underestimation.

![Fig. 4](image)

**Fig. 4** The orientations of the first (o), second (x) and third (+) principal directions of all VOIs of all specimens are plotted. A large variation in the orientation of the first and second principal directions was seen, whereas variation of the third principal orientation was smaller.
of 12%. The choice of the threshold influences the detected bone volume and thus it also influences secondary determined bone parameters. Rüegsegger et al. (1996) found a change in bone volume fraction of 5% with a 10% change of threshold. In the present study an analysis of changes in threshold in all condyles revealed a bone volume fraction change of 7.9% by variation of the threshold by 5% (data not shown). The lower contrast might be the result of the embalming procedure and the presence of marrow in the condyles.

The specimens used were relatively old. In the process of aging a change of trabecular structure from plate-like to more or less rod-like is seen and in advanced cases the remaining bone may consist entirely of rods (Feldkamp et al., 1989). The parallel plate model of Parfitt et al. (1983) may then become less reliable. We found that the cancellous bone in the human mandibular condyle consisted of plates rather than rods, which validated the use of the plate model. As in trabecular bone apparent density loss is correlated with aging (e.g., Ding et al., 1997), we would expect to find a low bone volume fraction. However, in the human mandibular condyle, this age related change was not found (Hongo et al., 1989a).

The size of the volumes of interest (sides of 4.35 mm) prevented us from comparing anteroposterior regions. Smaller VOIs, however, could have introduced edge artifacts influencing the measurements. Therefore, we could not confirm the results of histological studies, in which the anterior regions showed higher bone density (Hongo et al., 1989a) and thicker trabeculae (Teng and Herring, 1995) than

![Diagram](image)

**Fig. 5** Means of the principal directions for all regions of all condyles in lateral view. The first principal direction follows the curve of the condyle.


Chapter 2

posterior regions.

The mean values for bone volume fraction (17%) and trabecular thickness (0.10 mm) of the present study were relatively low compared to the ranges reported in other studies involving the human mandibular condyle (bone volume fraction: 18-30%, trabecular thickness: 0.27-0.34 mm; Hongo et al., 1989a; Kawashima et al., 1997) and pig mandibular condyle (trabecular thickness: 0.23-0.27 mm; Teng and Herring, 1995), but correspond well with the ranges reported for various trunk and limb bones (bone volume fraction: 16-21%; Ding et al., 1997; Zysset et al., 1998; Hou et al., 1998, trabecular thickness: 0.10-0.14 mm; Goulet et al., 1994; Müller et al., 1998; Kinney and Ladd, 1998). The relatively high values of Hongo et al. (1989a) and Kawashima et al. (1997) may be explained by their technique, i.e., soft X-ray images of 400-500 μm sections. Using this technique, these authors also found relative high bone volume fractions for the vertebral body, compared to the values reported elsewhere (Kinney and Ladd, 1998; Hou et al., 1998).

The trabecular separation in the human mandibular condyle (0.52 mm) was relatively large compared to that in the pig mandibular condyle (0.23-0.27 mm; Teng and Herring, 1995), but relatively small compared to the human vertebral body (1.47 mm; Kinney and Ladd, 1998) and various limb bones (0.64-0.77 mm; Goulet et al., 1994; Müller et al., 1998; Kinney and Ladd, 1998). We also found that the trabecular number (1.66 mm⁻¹) was relative small compared to the pig mandibular condyle (2.4-2.9 mm⁻¹; Teng and Herring, 1995), but relatively large compared to the vertebral body (1.18 mm⁻¹; Hou et al., 1998) and limb bones (1.39 mm⁻¹; Goulet et al., 1994). Because of the relative thick trabeculae in the pig mandibular condyle it was concluded that the condyle is a highly stressed structure (Teng and Herring, 1995). We found the trabecular structure comparable to that of other anatomical sites. The relatively high values in the pig mandibular condyle might be explained by a species effect.

The results of the present study confirm our hypothesis that the distribution of cancellous bone in the human mandibular condyle is inhomogeneous and anisotropic. We found highest the bone volume fraction in the central superior regions, associated with the thickest, the least separated and the most numerous trabeculae. Higher bone volume fraction and thicker trabeculae in these regions were also found by Hongo et al. (1989b). In the pig mandibular condyle trabeculae were less separated and more numerous in the superior regions, but thinner trabeculae were found compared to the inferior regions (Teng and Herring, 1995).

Underneath the articulating surface the cortical shell is very thin. It is generally believed that the cortical shells of most cancellous bone regions contribute
little to the stiffness and strength of the structure (Odgaard, 1997). The cancellous bone beneath the cortical shell will deform easily during loading, and, therefore, peak forces that could destroy the cartilage layer can be absorbed. The stresses are distributed and transferred to the thicker distal cortex. In the present study the highest bone volume fraction was found in the superior regions, adjacent to the articular surface. This is comparable to the vertebral body, where the highest bone volume fraction was found under the endplate and near the cortex. It has been suggested that local higher trabecular bone densities are related to multiple load conditions, rather than to higher stresses (Smit et al., 1997). Photo-elastic stress studies also indicated that the condyle is designed to receive less heavy but varied forces rather than heavy, cyclical unidirectional forces (Standlee et al., 1981). We also found a higher trabecular number in the superior regions. This indicates a finer bone structure that may be in favor for a multiple loading situation (Smit et al., 1997).

The distribution of bone in different orthogonal directions was expressed by the degree of anisotropy. The first degree of anisotropy was 1.51. This implies that the trabecular structure has a pronounced orientation and that the trabeculae are not randomly distributed. For the pig mandibular condyle values of 1.43 to 2.60 were found for three orthogonal planes (Teng and Herring, 1995). In three-dimensional analyses values of the first degree of anisotropy were 1.61 for various limb bones (Goulet et al., 1994) and 1.59 for the vertebral body (Hou et al., 1998). The second degree of anisotropy was 1.11; this means that the trabecular structure of the condyle tends to be oblately transversely isotropic. If it were equal to unity the structure would consist of perfect parallel plates. The slightly larger number could indicate that the plates have oval shaped perforations and are not truly parallel. The degree of anisotropy was highest in the inferior regions and smallest in the superior regions. This suggests that the trabeculae in the inferior regions are more oriented into one direction, in contrast to the superior regions where the trabecular plates were more densely interconnected.

The plane of the two main orientations (Fig. 4) represents the plane of the parallel plates. It was almost vertical and had an angle of 17° relative to the anteroposterior axis. Hongo et al. (1989b) related the orientation of the trabeculae to the direction of the lateral pterygoid muscle, which was 30.4° to 42° in the transversal plane relative to the anteroposterior axis. However, in another study corresponding angles of 41.7° for the superior head and of 47.4° for the inferior head were found (Van Eijden et al., 1995). Teng and Herring (1995) found the trabeculae to be in the growth direction of the condyle in immature pigs. We
suggest, however, that the plate orientation is likely to coincide with the plane perpendicular to the condylar axis. Such a trabecular structure would be optimally adapted to sustain loads in directions that presumably coincide with the majority of joint forces applied to the condyle. The trabeculae in the peripheral superior regions were directed from the periphery towards the center of the condyle. In the central regions the trabeculae were more vertically oriented. Thus the ovoid shaped articular surface is supported by trabeculae oriented perpendicular to this surface.

Because the cancellous bone of the condyle is anisotropic there is an obvious dependence of the material properties. From several studies it is known that the anisotropy of the trabecular structure and the anisotropy of mechanical properties are closely related (Van Rietbergen et al., 1998; Odgaard et al., 1997; Goulet et al., 1994; Turner et al., 1990; Zysset et al., 1998). The three-dimensional condylar reconstructions of the present study can be used to construct large-scale finite element models, which allow for calculation of mechanical properties and for simulation of different loading conditions. Furthermore, these models offer the possibility to simulate the effects of adaptational and remodeling processes on the mechanical properties (Van Rietbergen et al., 1996; Mullender et al., 1998).

In conclusion, the plate-like trabeculae could indicate that the condylar structure is optimally adapted to sustain the range of joint loads that act on the articular surface. The high bone mass and lower anisotropy in the superior regions could enable the condyle to sustain loads acting in diverse directions. Towards the collum the trabeculae are more aligned. This could point to stresses acting in primarily one direction.

References


3D cancellous bone architecture


Chapter 2


