Porosity of human mandibular condylar bone
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Abstract
Quantification of porosity and degree of mineralization of bone facilitates a better understanding of the possible effects of adaptive bone remodelling and the possible consequences for its mechanical properties. The present study set out first to give a three-dimensional description of the cortical canalicular network in the human mandibular condyle, in order to obtain more information about the principal directions of stresses and strains during loading. Our second aim was to determine whether the amount of remodelling was larger in the trabecular bone than in cortical bone of the condyle and to establish whether the variation in the amount of remodelling was related to the surface area of the cortical canals and trabeculae. We hypothesized that there were differences in porosity and orientation of cortical canals between various cortical regions. In addition, as greater cortical and trabecular porosities are likely to coincide with a greater surface area of cortical canals and trabeculae available for osteoblastic and osteoclastic activity, we hypothesized that this surface area would be inversely proportional to the degree of mineralization of cortical and trabecular bone, respectively. Micro-computed tomography was used to quantify porosity and mineralization in cortical and trabecular bone of ten human mandibular condyles. The cortical canals in the subchondral cortex of the condyle were orientated in the mediolateral direction, and in the anterior and posterior cortex in the superoinferior direction. Cortical porosity (average 3.5%) did not differ significantly between the cortical regions. It correlated significantly with the diameter and number of cortical canals, but not with cortical degree of mineralization. In trabecular bone (average porosity 79.3%) there was a significant negative correlation between surface area of the trabeculae and degree of mineralization; such a correlation was not found between the surface area of the cortical canals and the degree of mineralization of cortical bone. No relationship between trabecular and cortical porosity, nor between trabecular degree of mineralization and cortical degree of mineralization was found, suggesting that adaptive remodelling is independent and different between trabecular and cortical bone. We conclude (1) that the principal directions of stresses and strains are presumably directed mediolaterally in the subchondral cortex and superoinferiorly in the anterior and posterior cortex, (2) that the amount of remodelling is larger in the trabecular than in the cortical bone of the mandibular condyle; in trabecular bone variation in the amount of remodelling is related to the available surface area of the trabeculae.

Key words cortical bone; cortical canals; mineralization; porosity; quantitative micro-CT; remodelling; trabecular bone.

Introduction
The porosity of bone is the volume fraction of bone which is not occupied by bone tissue. Cortical porosity is due to a complex network of intracortical canals and spaces, while trabecular porosity is due to the intertrabecular marrow spaces. Porosity is considered to be inversely proportional to several mechanical properties, such as bone strength and stiffness (e.g. Carter & Hayes, 1977; Schaffler & Burr, 1988; McCalden et al. 1993; Jordan et al. 2000; Borah et al. 2001; Giesen et al. 2004). Regional variation in porosity has been linked to differences in loading (e.g. Skedros et al. 1997; Bell et al. 1999; Giesen & Van Eijden, 2000; Thomas et al. 2005). Within the human femur, for example, Bell et al. (1999) found a lower porosity in the compression cortex than in the tension cortex.
Apart from porosity, the orientation of the cortical canals may give clues with respect to the loading history of the cortical bone. The orientation of the osteons, and therefore the cortical canals, varies within and among bones. It is believed that this variation reflects the mechanical environment, as osteons are generally preferentially orientated parallel to the main loading direction (Heft et al. 1994; Pettryl et al. 1996).

The degree of mineralization of bone is, like porosity, possibly influenced by loading. In general, more heavily loaded bone is considered to have a higher remodelling rate and is therefore less mineralized and less stiff than bone that is loaded less. Because of regional differences in loading, the degree of mineralization is also likely to vary regionally (Skedros et al. 1997; Lai et al. 2005).

Cortical bone remodelling occurs by the formation of osteons. As the most recently formed bone is deposited on the surface of the cortical canals, the bone tissue near these canals is younger and thus less mineralized than peripheral osteonal bone and adjacent interstitial bone (e.g. Grynpas, 1993; Paschalis et al. 1996). Trabecular bone remodelling occurs at the trabecular surfaces, and therefore these surfaces are generally less mineralized than the trabecular cores (Paschalis et al. 1997; Mulder et al. 2005; Renders et al. 2006). Cancellous bone is considered to have a higher turnover rate and appears to respond more rapidly to changes in mechanical loading and unloading (Beaupré et al. 1990). This may in part be due to the larger bone surface area available in trabecular bone than in cortical bone for osteoblastic and osteoclastic activity. It might thus be expected that with a higher porosity the surface area of the cortical canals and trabeculae is larger, which in turn might result in a higher remodelling rate and consequently a lower degree of mineralization. For cortical bone an increase in porosity has indeed been found to coincide with a decrease in mineralization (Bousson et al. 2000; Wachter et al. 2002).

The present study concerns the porosity and degree of mineralization of the cortical and trabecular bone of the human mandibular condyle. The subchondral cortex of the condyle is primarily involved in shock absorption and the transmission of joint force from the articular cartilage to the trabecular bone in the condyle (Giesen & Van Eijden, 2000; Van Eijden et al. 2006). The anterior and posterior cortex of the condyle are important in the subsequent transmission of force to the mandibular ramus. In addition, the anterior and posterior cortex are probably loaded differently, i.e. the concave anterior cortex is primarily subjected to compressive strain, whereas the convex posterior cortex is primarily subjected to tensile strain (Van Ruijven et al. 2006).

Thus far, no studies have been published on the three-dimensional structure of the cortical canals in the mandibular condyle. Desktop micro-computed tomography (microCT) has the potential to analyse the cortical canal network in three dimensions (Cooper et al. 2003). Scan resolutions of up to 6 µm are possible, providing a high level of detail without destruction of the bone sample. Recently, desktop microCT has also been applied to evaluate the degree and distribution of mineralization of bone (Mulder et al. 2004, 2006; Renders et al. 2006). The advantage of using desktop microCT is that it considers the three-dimensional structure. Its disadvantage is the polychromatic character of the X-ray beam. However, since the introduction of effective beam hardening correction algorithms this disadvantage no longer has a significant influence on the measurements.

In the present study microCT was used to study porosity in cortical and trabecular bone of the mandibular condyle. We set out, first, to give a three-dimensional description of the cortical canalicular network in the condyle in order to obtain more information about the principal directions of stresses and strains during loading. Our second aim was to determine whether the amount of remodelling was larger in the trabecular bone than in cortical bone of the condyle and to establish whether the variation in amount of remodelling was related to the surface area of the cortical canals and trabeculae. We hypothesized that there would be differences in the amount of porosity and orientation of cortical canals between various cortical regions. In addition, as greater cortical and trabecular porosity is likely to coincide with a greater surface area of cortical canals and trabeculae, we hypothesized that this surface area is related to the degree of mineralization of cortical and trabecular bone, respectively.

Materials and methods

Condyles

Ten right mandibular condyles were obtained from embalmed human male cadavers (mean age ± SD: 69.8 ± 14.4 years, range: 43–92 years). The number of teeth in the upper jaw was 10.2 ± 4.5, in the lower jaw 11.5 ± 2.6. There were no signs of malocclusion or temporomandibular joint disorders. The use of the condyles conforms to a
written protocol that was reviewed and approved by the Department of Anatomy and Embryology of the Academic Medical Centre of the University of Amsterdam. The condyles were separated from the mandible by a hand saw.

**MicroCT**

Three-dimensional reconstructions of the cortical and trabecular bone of the condyles were obtained using a high-resolution microCT system (µCT 40, Scanco Medical AG, Bässersdorf, Switzerland). The condyles were mounted in cylindrical specimen holders (polyetherimide, outer diameter: 20 mm, wall thickness: 0.8 mm), secured with synthetic foam and completely submerged in fixation fluid. The scan resolution was 10 µm, the integration time 1200 ms and the beam intensity 45 kV, which corresponds to an effective energy of approximately 24 keV (Mulder et al. 2004).

The microCT system was equipped with an aluminium filter (0.5 mm) to remove the softest rays. The effect of beam hardening was further reduced by applying a correction algorithm that was developed by the manufacturer. To assess quantitatively the amount of noise and the effect of beam hardening, homogeneous K$_2$HPO$_4$ solutions with different concentrations were scanned (Mulder et al. 2004) using the same settings as described above. Noise level and the effect of beam hardening appeared to be, respectively, maximally 6 and 7%, which was well below natural variations in mineralization.

The computed attenuation in each volume element (voxel) was stored in an attenuation map and represented by a grey value in the reconstruction. The attenuation coefficient can be considered to be proportional to the local degree of mineralization (Nuzzo et al. 2002; Mulder et al. 2004). Degree of mineralization values for the bone-positive voxels were derived from the attenuation coefficients using a linear relation, which was calibrated with a phantom containing hydroxyapatite densities of 0, 100, 200, 400 and 800 mg cm$^{-3}$. It is important to recognize the difference between the two mineralization parameters. The first, the degree of mineralization of bone, is the parameter that has been used in the present study. It is determined as the mass (mg) of the mineralized bone tissue relative to the volume of bone (BV; cm$^3$). The second parameter is the so-called mineral density of bone and was not used in this study; it is the mass of the mineralized bone tissue relative to the total volume of the selected volume of interest (BV/TV); this latter parameter is therefore dependent on both the degree of mineralization and the amount of bone present in the volume of interest (VOI).

**Definition of regions**

In the centre of the condyle a cubic (size: 4 × 4 × 4 mm) VOI of trabecular bone was selected (Fig. 1), according to a similar method described previously (Renders et al. 2006; Van Eijden et al. 2006). In the cortical bone three different regions were defined, i.e. subchondral cortex, anterior cortex and posterior cortex. Within each of these cortical regions, six VOIs were chosen from medial to lateral to analyse mediolateral differences. Hence, the total number of cortical VOIs per condyle was 18 (3 cortical regions × 6 mediolateral VOIs). To define the cortical VOIs, first the 15% most medial and 15% most lateral slices of the condyle were excluded; the remaining slices were equally divided into six series of consecutive mediolateral slices ($n = 243 ± 20$).

Once the VOIs were defined, they were segmented. In a segmented image, voxels with a linear attenuation value below a threshold represent soft tissue or background, while voxels above this threshold represent bone. For trabecular bone the threshold separated the bone tissue from the marrow spaces, and for cortical bone it separated the bone tissue from the intracortical canals and spaces. For the trabecular bone an adaptive thresholding procedure (Scanco Medical AG) was used to determine the optimal threshold. For cortical bone, the adaptive thresholding procedure could not be used, because of the relatively large amount of bone

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tissue compared with the small amount of cortical canals and spaces (about 3%). For this reason in cortical bone the threshold was determined by varying it in steps of 1.5% and comparing the outcome of each step with the original CT scan.

After determination of the threshold, small fragments could be seen in the reconstructed cortical canal network; these were remnants of the smallest cortical canals and which we were not able to visualize owing to the applied resolution of 10 µm. These fragments were excluded before the actual determination of morphometric parameters and degree of mineralization.

**Morphometric parameters**

The segmented VOIs of the trabecular bone samples were used to calculate the following bone architectural parameters: bone volume fraction (BV/TV; trabecular porosity = 1 − BV/TV), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), trabecular number (Tb.N), bone surface to volume ratio (BS/BV) and degree of anisotropy, using morphometric software (version 3.2, Scanco Medical AG).

To describe morphometric characteristics of the cortical canal network, various canal parameters were calculated for each VOI. Cortical porosity (Ca.V/TV) is the relative volume of cortical canals, which is determined by dividing the number of canal voxels in the VOI by the total number of voxels in the VOI; thus, porosity is defined by void volume/tissue volume. Canal diameter (Ca.Dm) is the mean diameter of the canals. Canal separation (Ca.Sp) is the mean distance that separates the canals within the canal network. Canal number (Ca.N) is the mean number of canals per millimetre. Canal surface to volume ratio (Ca.S/CaV) is the surface of the cortical canals per unit volume of canals; to relate canal surface area to the amount of cortical bone, in the present study it was expressed per unit volume of cortical bone (Ca.S/BV). Degree of anisotropy is a measure of preference of orientation of the canal network; for this purpose, a mean intercept length tensor was calculated (Harrigan & Mann, 1984). All canal architectural parameters were calculated using the software morphometric package at the microCT system (version 3.2, Scanco Medical AG).

**Degree of mineralization**

The degree of mineralization of trabecular bone was determined for a three-dimensional sample (dimensions: $2 \times 2 \times 2$ mm) extracted from the centre of the trabecular VOI. Similarly, to determine the degree of mineralization of cortical bone a sample (dimensions: $2 \times 0.5$ mm × cortical thickness) was extracted from the centre of each of the 18 cortical VOIs. The previously determined thresholds were applied to these samples to separate bone from background. For this analysis, the voxels exceeding the threshold kept their original grey value. The outermost two layers of the trabecular bone (i.e. transition between bone marrow and trabeculae) and the inner layers of the cortical bone (i.e. transition between cortical canals and bone) were disregarded as these layers were likely to be corrupted by partial volume effects.

**Statistical analysis**

Descriptive statistics included the mean, SD and range of the various morphometric parameters and degree of mineralization. For the trabecular bone samples the values were calculated over the ten condyles. To obtain values for the cortical canal parameters and degree of mineralization of the entire cortical bone of the condyle, the 18 cortical samples were combined. Similarly, these parameters were determined for the three separate condylar regions (subchondral, anterior, posterior) by combining the six regional samples. Finally, grand means were calculated over the ten condyles.

Differences in parameters between the three cortical regions were tested using paired t-tests. Regression analyses were performed to identify relationships (1) among the trabecular bone parameters, (2) among the cortical canal parameters (for the entire cortical bone), (3) between cortical and trabecular porosity, (4) between cortical and trabecular degree of mineralization, (5) between age and porosity, and age and degree of mineralization, and (6) between number of teeth and porosity, and number of teeth and degree of mineralization. In all tests a P-value of less than 0.05 was considered statistically significant. Statistical tests were performed using the SPSS statistical software package (SPSS Inc., Chicago, IL, USA, version 11.5.1).

**Results**

The cortical canal network of the condyle has many longitudinal canals with relatively few perpendicular and oblique connections. The overall orientation of the cortical canals differed between the three cortical
regions. The main direction was mediolateral in the subchondral cortex, whereas it was superoinferior in the anterior and posterior cortex (Fig. 2). Within the anterior and posterior cortex the canals also diverged superomedially and superolaterally in a fan-like manner.

The degree of anisotropy of the canals was significantly higher ($P < 0.05$) in the posterior cortex (2.30) than in the subchondral (1.85) or anterior cortex (2.01).

Cortical canal parameters and degree of mineralization values for the entire cortical bone and for the three separate cortical regions are given in Table 1. The average porosity in cortical bone was 3.5%. No significant differences in porosity were found between the three cortical regions. The diameter of the cortical canals (average: 0.053 mm) was significantly lower in the subchondral cortex (0.048 mm) than in the posterior ($P < 0.01$; 0.058 mm) or anterior cortex ($P < 0.05$;

**Table 1** Descriptive statistics of cortical canal parameters of the human mandibular condyle

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
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<tbody>
<tr>
<td><strong>Cortical porosity (%)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>3.53 ± 1.19</td>
<td>2.26–5.52</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>3.35 ± 1.77</td>
<td>1.11–6.27</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>3.27 ± 1.13</td>
<td>1.41–4.80</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>3.98 ± 1.68</td>
<td>2.06–7.01</td>
</tr>
<tr>
<td><strong>Canal diameter (mm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>0.053 ± 0.005</td>
<td>0.044–0.062</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>0.048 ± 0.007</td>
<td>0.040–0.060</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>0.053 ± 0.004</td>
<td>0.045–0.059</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>0.058 ± 0.008</td>
<td>0.043–0.074</td>
</tr>
<tr>
<td><strong>Canal separation (mm)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>0.52 ± 0.08</td>
<td>0.43–0.66</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>0.50 ± 0.12</td>
<td>0.39–0.73</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>0.56 ± 0.10</td>
<td>0.49–0.83</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>0.51 ± 0.10</td>
<td>0.34–0.68</td>
</tr>
<tr>
<td><strong>Canal surface area (mm$^2$)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>1.88 ± 0.56</td>
<td>1.22–2.69</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>1.84 ± 0.87</td>
<td>0.67–3.26</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>1.79 ± 0.56</td>
<td>0.81–2.57</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>2.03 ± 0.72</td>
<td>1.17–3.32</td>
</tr>
<tr>
<td><strong>Canal degree of anisotropy</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>2.05 ± 0.17</td>
<td>1.77–2.34</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>1.85 ± 0.20</td>
<td>1.57–2.24</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>2.01 ± 0.21</td>
<td>1.65–2.21</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>2.30 ± 0.23</td>
<td>1.96–2.63</td>
</tr>
<tr>
<td><strong>Mineralization bone (mg HA cm$^{-3}$)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>cortical total</td>
<td>1045 ± 57</td>
<td>922–1110</td>
</tr>
<tr>
<td>subchondral cortex</td>
<td>1120 ± 52</td>
<td>1026–1201</td>
</tr>
<tr>
<td>anterior cortex</td>
<td>987 ± 66</td>
<td>884–1077</td>
</tr>
<tr>
<td>posterior cortex</td>
<td>1028 ± 68</td>
<td>857–1082</td>
</tr>
</tbody>
</table>

Cortical total: values of all 18 VOIs of the three subregions combined; SD values are a measure for inter-individual variation ($n = 10$); HA: hydroxyapatite.
0.053 mm). The canal separation (average: 0.52 mm), canal number (average: 2.05 mm\(^{-1}\)) and canal surface to volume ratio (average: 1.88 mm\(^{-1}\)) did not differ significantly between the three cortical regions. The degree of mineralization of cortical bone [average: 1045 mg hydroxyapatite (HA) cm\(^{-3}\)] was highest in the subchondral cortex (1120 mg HA cm\(^{-3}\)), and lowest in the anterior cortex; the differences in degree of mineralization between the cortical regions were significant (subchondral vs. anterior: \(P < 0.001\), subchondral vs. posterior: \(P < 0.01\), anterior vs. posterior: \(P < 0.05\)). No significant mediolateral differences in canal parameters and degree of mineralization were found within each of the three cortical regions (data not shown).

A large number of significant correlations were found among the canal parameters (Table 2). For example, porosity was positively correlated with the diameter and number of canals, and negatively correlated with the separation of the canals. None of the canal parameters, including canal surface to volume ratio, correlated significantly with the degree of mineralization of cortical bone.

Morphometric parameters of the trabecular bone are summarized in Table 3; correlation coefficients among the parameters are given in Table 4. The average porosity of trabecular bone was 79.3% and its average degree of mineralization was 857 mg HA cm\(^{-3}\). Note that trabecular porosity correlated positively with, for example, the bone surface to bone volume ratio of the trabeculae and negatively with their thickness and number (Table 4). There was a significant negative correlation between the trabecular bone surface to volume ratio and the degree of mineralization of trabecular bone. Thus, a larger trabecular surface coincided with a lower degree of mineralization.

The degree of mineralization of trabecular bone was significantly \((P < 0.001)\) lower than that of cortical bone. There was no significant correlation between trabecular and cortical porosity, nor between trabecular and cortical degree of mineralization. Porosity and degree of mineralization were not affected significantly by age or number of teeth in either trabecular or cortical bone.

### Table 2 Correlation coefficients between all canal parameters and mineralization

<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Ca.V/TV</td>
<td>0.77***</td>
<td>-0.91****</td>
<td>0.95****</td>
<td>0.99****</td>
<td>-0.27</td>
<td>0.03</td>
</tr>
<tr>
<td>Ca.Dm</td>
<td>-0.52</td>
<td>0.55*</td>
<td>-0.93****</td>
<td>0.96****</td>
<td>-0.30</td>
<td>0.16</td>
</tr>
<tr>
<td>Ca.Sp</td>
<td>-0.38****</td>
<td>-0.52</td>
<td>-0.31</td>
<td>0.08</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ca.N</td>
<td></td>
<td>-0.12</td>
<td>-0.01</td>
<td>-0.01</td>
<td></td>
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</tr>
<tr>
<td>Ca.S/BV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.35</td>
</tr>
<tr>
<td>DA</td>
<td></td>
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</tbody>
</table>

Ca.V/TV, cortical porosity; Ca.Dm, canal diameter; Ca.Sp, canal separation; Ca.N, canal number; Ca.S/BV, canal surface area per unit volume of cortical bone; DA, degree of anisotropy; DMB, degree of mineralization of cortical bone. Significance of correlation: *\(P < 0.1\), **\(P < 0.05\), ***\(P < 0.01\), ****\(P < 0.001\).

### Table 3 Descriptive statistics of trabecular bone parameters of the human mandibular condyle

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trabecular porosity (%)</td>
<td>79.3 ± 5.1</td>
<td>72.6–87.4</td>
</tr>
<tr>
<td>Trabecular thickness (mm)</td>
<td>0.15 ± 0.03</td>
<td>0.11–0.22</td>
</tr>
<tr>
<td>Trabecular separation (mm)</td>
<td>0.70 ± 0.10</td>
<td>0.56–0.85</td>
</tr>
<tr>
<td>Trabecular number (mm(^{-1}))</td>
<td>1.44 ± 0.15</td>
<td>1.16–1.67</td>
</tr>
<tr>
<td>Trabecular bone surface area (mm(^{-1}))</td>
<td>16.44 ± 3.28</td>
<td>12.05–22.46</td>
</tr>
<tr>
<td>Degree of anisotropy</td>
<td>1.94 ± 0.21</td>
<td>1.71–2.23</td>
</tr>
<tr>
<td>Mineralization bone (mg HA cm(^{-3}))</td>
<td>857 ± 41</td>
<td>790–906</td>
</tr>
</tbody>
</table>

SD values are a measure for inter-individual variation (\(n = 10\)); HA, hydroxyapatite.

### Table 4 Correlation coefficients between all trabecular bone parameters and mineralization

<table>
<thead>
<tr>
<th></th>
<th>Tb.Th</th>
<th>Tb.Sp</th>
<th>Tb.N</th>
<th>BS/BV</th>
<th>DA</th>
<th>DMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Porosity</td>
<td>-0.79***</td>
<td>0.49</td>
<td>-0.63**</td>
<td>0.88****</td>
<td>0.47</td>
<td>-0.54</td>
</tr>
<tr>
<td>Tb.Th</td>
<td></td>
<td>-0.16</td>
<td></td>
<td>-0.86***</td>
<td>-0.46</td>
<td>0.60*</td>
</tr>
<tr>
<td>Tb.Sp</td>
<td></td>
<td></td>
<td>-0.85***</td>
<td>0.32</td>
<td>0.08</td>
<td>-0.09</td>
</tr>
<tr>
<td>Tb.N</td>
<td></td>
<td></td>
<td></td>
<td>-0.57*</td>
<td>-0.12</td>
<td>0.21</td>
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<tr>
<td>BS/BV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.49</td>
<td>-0.67**</td>
</tr>
<tr>
<td>DA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>-0.29</td>
</tr>
</tbody>
</table>

 Porosity, 1 – BV/TV; Tb.Th, trabecular thickness; Tb.Sp, trabecular separation; Tb.N, trabecular number; BS/BV, bone surface area; DA, degree of anisotropy; DMB, degree of mineralization of trabecular bone. Significance of correlation: *\(P < 0.1\), **\(P < 0.05\), ***\(P < 0.01\), ****\(P < 0.001\).
Discussion

Recently, microCT has been applied in a few studies to quantify non-destructively the three-dimensional cortical canal network (desktop microCT: Cooper et al. 2003; synchrotron radiation microCT: Martin-Badosa et al. 2003; Bousson et al. 2004; Matsumoto et al. 2006). We provide here for the first time quantitative information on topographical variation in orientation of the cortical canals in the human mandibular condyle using a microCT system. In addition, we have been able to examine porosity in relation to the degree of mineralization of the condyle. Together with porosity, the degree of mineralization is crucial for bone quality (Currey, 1988).

The orientation of the cortical canals was clearly anisotropic, i.e. the main direction was mediolateral in the subchondral cortex whereas it was superoinferior in both the anterior and the posterior cortex. It is generally assumed that the osteons, and hence the cortical canals, are preferentially orientated along the main direction of loading (Cohen & Harris, 1958; Heft et al. 1994; Petryl et al. 1996). Thus, the direction of cortical canals in the condyle might provide information about the loading history of the condyle.

Thus far, no information is available on the magnitudes and principal directions of stresses and strains in the cortical bone during loading of the condyle. The direction of the cortical canals suggests that the principal directions of stresses and strains are orientated mediolaterally in the subchondral cortex and superoinferiorly in the anterior and posterior cortex. The anisotropic orientation of cortical canals also suggests that the stiffness of the cortical bone is anisotropic, i.e. the subchondral cortex is probably stiffer mediolaterally than anteroposteriorly, whereas the anterior and posterior cortex are stiffer superoinferiorly than mediolaterally. This anisotropy implies that the subchondral bone is more capable of sustaining loads in the mediolateral direction, whereas the anterior and posterior cortex are more capable of sustaining loads in the superoinferior direction. A possible explanation for the anisotropy within the subchondral cortex is the direction of loading forces occurring during movement of the mandible. Koolstra & Van Eijden (2005) reported a mediolateral shift of stress along the articular surfaces of the temporomandibular joint during open–close movements of the jaw. A similar mediolateral shift of stress is likely to occur within the subchondral cortex.

The mediolateral orientation of the osteons within the subchondral cortex might be considered as an adaptation to this loading. Another possible explanation is related to mediolateral and anteroposterior differences in bending during loading (Van Eijden, 2000). Owing to the shape of the subchondral cortex, i.e. its convexity is less in the frontal than in the sagittal plane, the amount of bending is probably larger mediolaterally than anteroposteriorly. Mediolaterally orientated osteons might be more capable of resisting these larger bending forces. Comparably, the superoinferior orientation of the osteons in the anterior and posterior cortex might be optimal to resist the superoinferiorly directed forces that are transmitted from the subchondral cortex and trabecular bone to the mandibular ramus.

The cortical porosity in the mandibular condyle (3.5%) reported in the present study is consistent with values reported for other sites of the human mandible (Hara et al. 1998; Verna et al. 1999). Cortical porosity in the human mandible seems relatively low compared with other human bones (e.g. femoral shaft: > 5%, Stein et al. 1999; femoral neck: > 10%, Bell et al. 1999). The average diameter of the cortical canals (0.053 mm) in the condyle is also consistent with other sites of the mandible (Dempster & Enlow, 1959; Verna et al. 1999). Canal diameter and number have been reported to vary considerably across age, sex and sampling site (Stein et al. 1999; Bousson et al. 2001). We found that both these parameters correlated positively with cortical porosity.

Cortical porosity of the condyle did not change with age. By contrast, a positive correlation between cortical porosity and age has frequently been reported (human femur: Bousson et al. 2001; Thomas et al. 2005; human mandible: Verna et al. 1999). The lack of influence of age in the present study may have been due to the relatively small number of condyles (n = 10) in comparison with the study of Verna et al. (n = 50). In the latter study both male and female samples were examined, without taking into account the possible effect of post-menopausal osteoporosis on cortical porosity (Feik et al. 1997; Seeman, 2002). In the present study only samples from male subjects were examined to eliminate any additional phenomena that might have resulted from post-menopausal osteoporosis in females.

No significant differences in porosity between the three cortical regions of the condyle were found. This is in contrast with other studies; for example, within the human femoral neck, differences were found between
The inferior and superior cortex (Bell et al. 1999). The anterior cortex of the mandibular condyle had a significantly lower degree of mineralization than the subchondral and posterior cortex, indicating that the proportion of less mineralized bone is higher in the anterior cortex. These differences are probably due to differences in the tensile/compressive stresses involved (Skedros et al. 1997; Bell et al. 1999).

The reported values for the trabecular morphometric parameters were consistent with values reported by Giesen & Van Eijden (2000). We found no relationship between trabecular and cortical porosity, nor between the trabecular degree of mineralization and the cortical degree of mineralization. This suggests that adaptive remodelling is independent and different between trabecular and cortical bone. The lower degree of mineralization of trabecular bone points to a higher remodelling rate, which is consistent with the higher surface to volume ratio available for remodelling in trabecular bone (16.44 mm⁻¹) compared with that in cortical bone (1.88 mm⁻¹). Mineral maturation in the condyle is less advanced in trabecular bone than in cortical bone and consequently the trabecular bone has an increased proportion of less mineralized bone and a decreased proportion of more mineralized bone compared with cortical bone. The present results indicate that a higher trabecular porosity, and thus a larger trabecular surface area, coincides with a larger surface for remodelling and thus a lower degree of mineralization. Such a correlation was not found between the surface area of cortical bone and cortical degree of mineralization. Although bone formation occurs at the surfaces of the cortical canals, the absence of a significant correlation is presumably due to the relatively small remodelling surface compared with the large cortical bone volume. In trabecular bone the remodelling surface is much larger.

The higher degree of mineralization in the cortical bone compared with that in the trabecular bone indicates that the tissue stiffness is higher in the cortical bone than in the trabecular bone, as the degree of mineralization is related to tissue stiffness (Currey, 1999). From a mechanical point of view it should be noted that bone mineral provides rigidity to the bone. Bone tissue with a high degree of mineralization can be expected to be relatively stiff and brittle, which is likely to have reduced fracture toughness (Ciarelli et al. 2003). The relatively low degree of mineralization of the trabecular bone makes the trabecular bone of the condyle more compliant to bending than its cortical bone. Moreover, due to the relatively low degree of mineralization, the accompanying stresses remain relatively low. The higher degree of mineralization in the cortex results in higher stresses.

Some remarks about the methods used in the present study need to be made. First, microCT is superior in non-invasively visualizing and quantifying cortical canals in three dimensions. In the present study we did not compare our microCT data with those obtained from histological or microradiographic bone sections. Such comparisons have been reported for porosity measurements from microCT and histological sections (Wachter et al. 2001; Cooper et al. 2004). These studies showed strong correlations between the techniques. Secondly, the resolution used in the present study (10 µm) was relatively high compared with the mean diameter of cortical canals (53 µm). Therefore, we expected to be able to visualize the majority of cortical canals in the bone of the mandibular condyle, and subsequently to quantify their orientation and the cortical porosity. However, with the resolution we used, the smallest cortical canals could not be visualized. According to Dempster & Enlow (1959) about 7% of the canals in the mandible are 15 µm or less in diameter. Thus, the resolution used in the present study will inevitably result in an underestimate of the porosity and number of canals. This was also evident from the three-dimensional reconstructions, where the smallest canals had been broken up as the resolution was insufficient to resolve them. Cooper et al. (2004) found that microCT underestimated porosity by about 0.5% and the number of pores (canals viewed in cross-section) by about 14%. The use of a higher resolution might decrease the amount of underestimate. A disadvantage of using higher resolution is the decrease of the field of view and consequently the requirement of relatively small bone samples; for the highest resolution possible with our scanner (6 µm), the maximum width of the samples would be 12 mm. Finally, the choice of the threshold influences the values of the morphometric and mineralization parameters. For example, if the chosen threshold was too low, it may be expected that this results in an underestimate of the cortical porosity. In a separate sensitivity analysis we found that an increase or decrease of the threshold of 1.5% relative to the optimal threshold resulted in, respectively, an increase and decrease of about 7% of cortical porosity and of about 3.5% in diameter and number of canals (unpublished
results). The error in the visually checked threshold was much smaller than the 1.5% variation that was used in this sensitivity analysis.

We conclude (1) that the principal directions of stresses and strains are presumably directed mediolaterally in the subchondral cortex and superoinferiorly in the anterior and posterior cortex, and (2) that the amount of remodelling is larger in the trabecular than in the cortical bone of the mandibular condyle; in trabecular bone variation in the amount of remodelling is related to the available surface area of the trabeculae.

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