Characteristics of Human Mandibular Condyle Bone Tissue

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Introduction: Temporomandibular joint disorder (TMJD) is the second most commonly occurring musculoskeletal symptom, affecting up to 25% of Americans [1]. More than 10% of TMJD patients have osteoarthritis, characterized by a degenerative joint which results from erosion of articular cartilage and degeneration of the bony mandibular condyle under daily loading by static occlusion and dynamic mastication [2]. Thus, mechanical characteristics of mandibular condylar bone tissue are important in determining the ability of TMJ to resist its degeneration under loading. The mechanical properties of bone have been determined mainly by its elastic modulus and fracture strength using static fracture testing. On the other hand, bone is a viscoelastic material in which mechanical properties change over the duration of static and dynamic loading [3,4]. However, few studies have been performed to investigate the viscoelastic response of mandibular bone to dynamic masticatory loading. Recently, a regional variation of correlations between elastic and viscoelastic properties of bone tissue was found at different anatomical sites under various types of loading [5]. It was also found that significant heterogeneity of bone tissue mineralization exists between local regions at the human mandibular condyle, which plays an important role in controlling its mechanical properties [6]. In this study, we hypothesized that the viscoelastic properties, as well as elastic and plastic properties, of mandibular condylar bone vary in association with tissue mineral distribution reflecting its local functional demands to bear loading at the TMJ. Thus, the objective of this study was to examine distributions of the tissue mineralization, elastic, plastic, and viscoelastic properties of bone tissue at local regions of human mandibular condyle bone.

Methods: Nine fresh human male cadaveric mandibles (75±15 years) were obtained and condyles were dissected parallel to the occlusal plane using a low speed saw under water irrigation. The mandibular condyle specimens were subjected to scanning by a micro-computed tomography (micro-CT) scanner with voxel sizes at 27×27×27 µm³. The 3D micro-CT image was used to digitally isolate upper and lower cortical bone (CB) and trabecular bone (TB) regions of the mandibular condyle (Fig.1a). Gray value histograms were identified for each region (Fig.1b). Mean, Low and High gray values (Low₅ and High₅) were determined at the mean, the lower and upper 5th percentile values, respectively. After scanning, specimens were longitudinally dissected and three bone regions (Upper and Lower CBs, and TB) were identified for nanoindentation sites (Fig. 2a). A pyramidal Berkovich tip for the nanoindenter was used to probe the specimen up to 500 nm deep with a displacement rate of 10 nm/sec in hydration (Fig. 2b). The plastic hardness (H) was the ratio of a peak indenting load (Pₘₐₓ) and contact area. The viscosity (η) and normalized creep (Creep/Pₘₐₓ) were assessed during a 30-second hold period under peak load by fitting the creep curve using a traditional viscoelastic Voigt equation [3]. Tan δ was assessed by continuous stiffness measurement (CSM) that uses the harmonic oscillatory response during the 30-second holding period. Oscillatory force was applied at 45 Hz corresponding to 2 nm of
displacement, which is a common operating condition of CSM [7]. Potential errors in measuring the initial phase angle were recently indicated, so a correction procedure was employed following suggestions in a previous study [7]. Finally, the elastic modulus (E) was measured during the unloading period of nanoindentation. As results, the five parameters (E, H, n, Creep/P_{max} and tan δ) of elastic, plastic, and viscoelastic mechanical properties could be assessed at the same site of fresh human mandibular condylar bone tissue using a cycle of nanoindentation. A total of 523 nanoindentation measures (179 from Upper, 225 from Lower, and 119 from Trabecular bone regions) were obtained. Repeated measures analysis of variance (ANOVA) was utilized to compare the regional variations of the tissue mineralization and nanoindentation parameters (E, H, n, Creep/P_{max}, and tan δ). Significance was p<0.05.

**Results:** Mean values of Mean and Low_{5} gray values were not significantly different between the upper and lower cortex bone regions (upper and lower CBs) of the mandibular condyle (p>0.091) while those of the trabecular bone region (TB) were significantly less than both CBs (p<0.034)(Table). Mean values of High_{5} gray values of the lower CB were significantly greater than the upper CB and TB (p<0.007) while no significant difference between the upper CB and TB (p=0.647). The upper CB had significantly greater mean values of elastic modulus (E), plastic hardness (H), and viscosity (η) than the TB (p<0.047) while those values were not significantly different between the lower CB and TB (p=0.093). A marginally higher value of Creep/P_{max} was found for the TB than the upper CB (p<0.065). However, the TB had a significantly higher mean value of tan δ than both CBs (p=0.04).

**Discussion:** The cortical bone region (CB) of human mandibular condyles had higher gray values, and therefore mineralization, than the trabecular bone region (TB) consistent with findings of a previous study that examined bone mineral distribution in human mandibular condyles [6]. Nanoindentation parameters including modulus (E), hardness (H), and viscosity (η) were measured higher at the more mineralized upper CB than at the less mineralized TB. On the other hand, the TB had a greater mean value of dynamic viscoelastic creep (Creep/P_{max}) and tan δ than the upper CB. The E, H and η account for the ability of bone tissue to resist elastic, plastic, and viscous deformations, respectively. The Creep/P_{max} represents the capacity of static constant energy absorption and the tan δ indicates an ability to dissipate dynamic energy. As such, the current findings indicate that tissue properties of the upper CB are better able to resist static deformation and those of the TB have a better time-dependent static and dynamic energy absorption and dissipating efficiency. This regional variation within mandibular condyle bone tissue properties likely helps maintain a balance of its mechanical stability under a combination of static and dynamic functional loading during occlusion and mastication.

A limitation of the current study was that material composition of bone tissue at the nanoindentation site was not investigated. Thus, further studies are recommended to examine the mechanism of how the interaction of bone tissue components, mainly mineral and collagen, can characterize its mechanical properties.

**Significance:** The current results provide mechanical properties of the human mandibular condyle, which can be used to develop standard criteria for appropriate clinical treatments and optimal design of implantable devices reflecting its functional demand.
Nanoindentation parameters (mean±SD)

<table>
<thead>
<tr>
<th></th>
<th>E (GPa)</th>
<th>H (GPa)</th>
<th>η (GPa·s)</th>
<th>Creep/P_{max} (nm/N)</th>
<th>tan δ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper Cortical Bone</td>
<td>7.63±1.31</td>
<td>0.311±0.057</td>
<td>19347.58±4323.46</td>
<td>42.19±35.04</td>
<td>0.069±0.010</td>
</tr>
<tr>
<td>Lower Cortical Bone</td>
<td>7.48±3.09</td>
<td>0.204±0.102</td>
<td>12710.59±8158.26</td>
<td>65.57±35.29</td>
<td>0.088±0.020</td>
</tr>
<tr>
<td>Trabecular Bone</td>
<td>5.11±2.82</td>
<td>0.138±0.069</td>
<td>8213.70±5056.48</td>
<td>111.85±56.02</td>
<td>0.114±0.033</td>
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</tbody>
</table>

Fig. 1 (a) Separation of upper and lower CBs, and TB images from a complete mandibular condyle and detailed voxel gray value distribution (red box) of the micro-CT image. A darker color represents a lower gray value and (b) the regional variation of gray value histogram.

Fig. 2 (a) Human mandibular condyle dissected in the anteroposterior direction and regions of interest for nanoindentation, and (b) Five nanoindentation parameters assessed using a cycle of indentation force-displacement curve at the same site.

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