Observation of the Internal Structure of the Zygomatic Bone by Micro-Computed Tomography

Yorihisa Kato1,2, Yasuhiro Kizu3, Morio Tonogi4, Yoshinobu Ide2 and Gen-yuki Yamane3

1Department of Oral Medicine, Tokyo Dental College
2Department of Anatomy, Tokyo Dental College
35-11-13 Sugano, Ichikawa, Chiba 272-8513, Japan
41-2-2 Masago, Mihama-ku, Chiba 261-8502, Japan

[Received on June 1, 2004; Accepted on July 9, 2004]

Key words: micro-CT/zygomatic/trabecular

Abstract: The purpose of this study was to use micro-computed tomography to investigate the internal structure of the zygomatic bone, and to evaluate the effects of biting force on the zygomatic bone by comparing the internal structure of this bone between dentulous and edentulous maxillae. In this study, 20 zygomatic bones of dentulous maxillae and 28 zygomatic bones of edentulous maxillae were used (mean age: dentulous maxillae, 72.6 years; edentulous maxillae, 79.6 years). Specimens were obtained from the skulls of cadavers, from the sutura frontozygomatica, posterior to the sutura temporozygomatica, down to the sutura zygomatico-maxillaris. From 2-dimensional slice images, we reconstructed the three-dimensional structure by volume rendering methods using micro-computed tomography. We used two anthropological reference points: jugale (Ju) at the most concave point between the lateral margin of the upper zygomatic bone and the upper margin of the zygomatic arch; and zygomaxillare (Zm) at the lowermost point of the zygomaticomaxillary suture. We examined the structure of the zygomatic bone at Ju, Zm and the mid-point between Ju and Zm. The dentulous maxillae had thicker trabeculae at these points than the edentulous maxillae. The thicker trabecular structure in the Ju area was especially pronounced in the dentulous maxillae. These findings indicate that stress from biting force influences the trabecular structure in the zygomatic bone. They also suggest that stress in the zygomatic bone is concentrated in the Ju area, because the masseter muscle and fascia temporalis adhere to the zygomatic bone.

Introduction

Biting force influences the morphology of the jaw bone1. In edentulous jaws, biting force is not applied to the jaw bone due to tooth loss, causing the trabeculae in the jaw bone to become thin, the distance between trabeculae to increase, and the density of the jaw bone to decrease2. Although there have been morphological and mechanical studies of the zygomatic bone, which is in the middle of the face adjacent to the maxillary bone, the inner structure of the zygomatic bone has not been investigated in detail3.

The morphology of bone structure has frequently been studied using soft X-ray images of thin sections of specimens embedded in resin4. However, this method has the following drawbacks: only two-dimensional images can be observed, and informa-
tion about the area between sections is lost during cutting of the sections.

In recent years, micro-focus X-ray (micro-computed tomography [micro-CT]) methods have been developed, allowing nondestructive observation of the three-dimensional structure of trabeculae and the quantification of their structural properties. Several studies of three-dimensional trabecular structure have been conducted using micro-CT.

In the present study, using micro-CT, we investigated the internal structure of the zygomatic bone, and evaluated the effects of biting force on the zygomatic bone by comparing the internal structure of this bone between dentulous and edentulous maxillae.

Materials and Methods

We obtained 20 zygomatic bones of dentulous maxillae and 28 zygomatic bones of edentulous maxillae from the skulls of 48 Japanese male cadavers (mean age : dentulous maxillae, 72.6 years ; edentulous maxillae, 79.6 years) (Fig. 1). The use of these human specimens conforms to a written protocol that was reviewed and approved by the Department of Anatomy, Tokyo Dental College. The dentulous maxillae exhibited occlusion from premolar to molar, and the edentulous maxillae lacked the foramen of tooth extraction.

To visualize the three-dimensional bone structure, we performed micro-CT (KMS-755, Kashimura Inc.) (Fig. 2). The main imaging apparatus consisted of an X-ray generator, specimen stage and detector. The focus size of the X-ray generator was 6 × 8 μA. A tube voltage ranging from 20 to 80 kV could be generated, and the tube current ranged from 0 to 100 μA. X-rays were emitted at 55 kV and 100 μA. The detector was equipped with a 4-inch long image intensifier tube and a 1-inch CCD camera with a scanning line of 1024 × 1024, and was capable of outputting 500 bits of raw data, 16 bits at a time. Based on the raw data obtained, 2-dimensional slice images were produced by the back projection method. Three-dimensional reconstruction was performed using 200 of these 2-dimensional images processed by the volume rendering method using three-dimensional-reconstruction software (AVS, KGT Inc.) (Fig. 3). To determine the threshold, we measured the thickness of the cortical bone of each bone sample and the first specimen by micro-CT.
Fig. 2 Schematic diagram of the present micro-CT system. The system consists of a main imaging apparatus and a computer. This system can be used to analyze the whole mandible. The main imaging apparatus consists of an X-ray generator, specimen stage and detector.

We designated three volumes of interest (VOIs) in each area (Fig. 5). The VOIs did not include cortical bone. The size of each VOI was $80 \times 80 \times 80$ pixels.

We calculated the morphology parameters in each area by counting voxels from the three-dimensional images. The micro-CT unit produced a report of microstructure data in three dimensions. The variables in this analysis were bone volume density (BV/TV), trabecular plate thickness (Tb. Th), trabecular plate number (Tb. N) and trabecular plate separation (Tb. Sp).

Comparisons of variables of VOIs between dentulous and edentulous jaws were performed using Student's $t$-test. Standard deviations of measurement were also calculated.

Results

Visual observation of the reconstructed images clearly showed that, in dentulous maxillae, the trabeculae of the Ju and M.P. areas were arranged in an oriented plate-like structure (Fig. 6). In all VOIs, trabeculae were thicker in the dentulous maxillae than in the edentulous maxillae throughout the entire VOI. In the dentulous maxillae, the trabeculae in the M.P. and Zm VOIs exhibited a rod-like structure. In the Zm area of the dentulous maxillae, the trabeculae were loosely aggregated. In the edentulous maxillae, the M.P. and Zm VOIs contained relatively few and thin trabeculae, and many of the con-
necting rods were missing.

The conclusions of the morphometric analysis are presented in Tables 1 and 2. The trabecular density was higher in the dentulous maxillae than in the edentulous maxillae. The Ju area of both types of maxillae showed higher bone volume density than the other areas, with thicker and more plentiful bone trabeculae in the Ju area. This difference in bone volume density between areas was especially pronounced in the edentulous maxillae.

Fig. 4 We used two anthropological reference points: the jugale (Ju) at the most concave point between the lateral margin of the upper zygomatic bone and the upper margin of the zygomatic arch; and the zygomaxillare (Zm) at the lowermost point of the zygomaticomaxillary suture. a: Frontal process, b: Zygomatico-maxillary suture.

Fig. 5 The zygomatic bone was divided into 3 areas: around Ju, around Zm, and around the midpoint between Ju and Zm. A schematic representation of the positions of the three volumes of interest in the zygomatic bone is shown.
The present morphometric analysis suggests that, in all areas of the zygomatic bone, the bone volume density of dentulous jaws is higher than that of edentulous jaws.

Evaluation of the distribution of stress from biting force in the face has indicated that the biting force applied to the maxillary molars is transmitted through the zygomatic ridge. It has recently been reported that osteocytes in the bone matrix act as pressure sensors, and that there is a pressure sensory network among osteocytes, osteoblasts and osteoclasts, although details of this network have not yet been elucidated.

The present differences in trabecular formation between the dentulous and edentulous maxillae suggest that the difference in mean age between the two types of maxillae was a factor. Also, we speculate that stress from biting force prevents the generation of osteocytes and increases the activation of osteoblasts in zygomatic bones of dentulous maxillae.

The present morphometric analysis suggests that trabecular density is higher in the Ju area than in other areas, in both dentulous and edentulous maxillae. These findings suggest that stress from biting force is concentrated in the Ju area of dentulous and edentulous zygomatic bones, as a result of the adherence of the masseter muscles and fascia temporalis to the zygomatic bone.

In conclusion, the present findings indicate that stress from biting force influences the trabecular structure of the zygomatic bone. We speculate that the particularly thick trabecular structure of the Ju area of both dentulous and edentulous zygomatic bones is due to adherence of the masseter muscle and fascia muscles to the zygomatic bone, and the consequent concentration of stress in the Ju area of the zygomatic bone. The present findings elucidate the distribution of trabeculae in the zygomatic bone and the mid-facial stress distribution. In the future, we plan to perform a detailed examination of mid-facial stress using FE models.

Fig. 6 Three-dimensional reconstruction of the trabecular bone from 3 volumes of interest in the zygomatic bone. Visual observation of the reconstruction clearly showed that the trabeculae were thicker in the Ju area than in other areas.

Discussion

In recent studies, the internal structure of bone has been examined in detail using micro-CT. Micro-CT is less time-consuming and less destructive of tissue than conventional methods, and is very useful for observing the three-dimensional internal structure of bone. In the present study, using micro-CT, the internal structure of the zygomatic bone was non-destructively observed within a short time period.

Previous findings indicate that bone formation decreases when force applied to the bone is reduced, and that the trabecular morphology changes from a plate-like to a rod-like structure when mechanical load is decreased, or with age. In the present study of the internal structure of the zygomatic bone of dentulous and edentulous maxillae, we found that the zygomatic bones of the edentulous maxillae had a rod-like trabecular structure.

Table 1 Comparison of bone architecture between dentulous and edentulous maxillae

<table>
<thead>
<tr>
<th></th>
<th>Bone volume density (%)</th>
<th>Trabecular plate thickness (mm)</th>
<th>Trabecular plate number (N/mm)</th>
<th>Trabecular plate separation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentulous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ju</td>
<td>37.4 ± 9.0</td>
<td>0.18 ± 0.06</td>
<td>2.23 ± 0.81</td>
<td>0.32 ± 0.13</td>
</tr>
<tr>
<td>M.P.</td>
<td>24.7 ± 8.8</td>
<td>0.16 ± 0.04</td>
<td>1.51 ± 0.35</td>
<td>0.54 ± 0.18</td>
</tr>
<tr>
<td>Zm</td>
<td>24.6 ± 8.1</td>
<td>0.16 ± 0.05</td>
<td>1.59 ± 0.44</td>
<td>0.52 ± 0.17</td>
</tr>
<tr>
<td>Edentulous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ju</td>
<td>23.2 ± 4.3</td>
<td>0.16 ± 0.05</td>
<td>1.53 ± 0.48</td>
<td>0.56 ± 0.20</td>
</tr>
<tr>
<td>M.P.</td>
<td>19.9 ± 5.4</td>
<td>0.15 ± 0.05</td>
<td>1.38 ± 0.33</td>
<td>0.62 ± 0.18</td>
</tr>
<tr>
<td>Zm</td>
<td>20.5 ± 6.5</td>
<td>0.15 ± 0.06</td>
<td>1.49 ± 0.40</td>
<td>0.58 ± 0.20</td>
</tr>
</tbody>
</table>

*: p < 0.01

The trabecular density was higher in the dentulous maxillae than in the edentulous jaws. The Ju area of both types of maxillae showed relatively high bone volume density, because the bone trabeculae were thicker and more plentiful in that area.

Table 2 Comparison between areas of the maxillae

<table>
<thead>
<tr>
<th></th>
<th>Bone volume density (%)</th>
<th>Trabecular plate thickness (mm)</th>
<th>Trabecular plate number (N/mm)</th>
<th>Trabecular plate separation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dentulous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ju</td>
<td>37.4 ± 9.0</td>
<td>0.18 ± 0.06</td>
<td>2.23 ± 0.81</td>
<td>0.32 ± 0.13</td>
</tr>
<tr>
<td>M.P.</td>
<td>24.7 ± 8.8</td>
<td>0.16 ± 0.04</td>
<td>1.51 ± 0.35</td>
<td>0.54 ± 0.18</td>
</tr>
<tr>
<td>Zm</td>
<td>24.6 ± 8.1</td>
<td>0.16 ± 0.05</td>
<td>1.59 ± 0.44</td>
<td>0.52 ± 0.17</td>
</tr>
<tr>
<td>Edentulous</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ju</td>
<td>23.2 ± 4.3</td>
<td>0.16 ± 0.05</td>
<td>1.53 ± 0.48</td>
<td>0.56 ± 0.20</td>
</tr>
<tr>
<td>M.P.</td>
<td>19.9 ± 5.4</td>
<td>0.15 ± 0.05</td>
<td>1.38 ± 0.33</td>
<td>0.62 ± 0.18</td>
</tr>
<tr>
<td>Zm</td>
<td>20.5 ± 6.5</td>
<td>0.15 ± 0.06</td>
<td>1.49 ± 0.40</td>
<td>0.58 ± 0.20</td>
</tr>
</tbody>
</table>

*: p < 0.01

In both dentulous and edentulous jaws, bone volume density was lowest in the M.P. and Zm areas, because the trabeculae were thinner and more widely separated; this difference was especially pronounced in the edentulous jaws.

Acknowledgements

This research was supported in part by the Department of Anatomy, Tokyo Dental College. The author wishes to thank T. Hara for the use of the micro-CT system and for the technical advice.

References