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Stress Distribution in Maxillary Alveolar Ridge According to Finite Element Analysis Using Micro-CT

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Abstract

The purpose of the present study was to evaluate stress distribution by finite element analysis in an accurate model simulating trabecular bone using micro-CT. Dentulous and edentulous maxillary jaws of Japanese adult cadavers were used (5 sides each; total, 10 sides). Imaging was performed using a micro-CT, followed by reconstruction with 3-D images. Finite element analysis models were developed using the maxilla with average bone morphometry. A load corresponding to occlusal force was applied in different loading conditions, followed by evaluation of stress distribution. In dentulous maxillas, a load was applied in the dental axis direction to the first molar crown (LD). In edentulous maxillas, a load was applied directly to a circular area 4mm in diameter (LER0) to a cylinder 4mm in diameter and 10mm in height (LER10) corresponding to the first molar area. Stress was concentrated in cortical bone around the first molar, trabecular bone and cortical bone at the maxillary sinus base in LD, cortical bone of the alveolar ridge in LER0, and trabecular bone around the cylinder and cortical bone at the maxillary sinus base in LER10. LER0 showed a stress distribution markedly different from that in LD. Compared with LER0, LER10 showed a stress distribution close to that in LD. A model simulating trabecular bone allows a more accurate evaluation of stress distribution.

Key words: Maxilla—Micro-CT—Finite element analysis—Stress distribution

Introduction

Denture and implant therapies are widely performed as prosthetic methods for tooth missing. In implant therapy, there are many prognostic factors. One patient-associated factor consists of the properties of the jaw bone. Internal changes in the maxillary structure due to tooth loss were measured two-dimensionally by Kitta. The internal structure of the maxilla is usually three-dimensionally evaluated using a micro-focus...
X-ray CT scanner (micro-CT hereafter). The obtained slice data are three-dimensionally reconstructed, and bone morphometry is performed\textsuperscript{18,20,21}. Shibuya et al.\textsuperscript{18} had reported that 3-D reconstruction images obtained by micro-CT had less influence on distortion than raw data. Usami et al.\textsuperscript{20} performed 3-D quantitation of maxillary images using the same method as in that report. These reports\textsuperscript{12,14,16,20} suggest that tooth loss induces alveolar bone resorption and irregularity in the trabecular bone structure.

Finite element analysis is used to evaluate stress distribution in jaw bone. However, there have been no reports on finite element analysis using a jaw model which reproduces the internal structure of the maxillary alveolar ridge. Ito et al.\textsuperscript{11} performed finite element analysis using images of the lumbar spine in rats by micro-CT. The analysis showed a correlation between the results obtained by a non-destructive compression test and the results of actual morphometry, suggesting the potential of the applicability of finite element analysis to a living body. Recent improvements in micro-CTs have allowed more detailed observation and precise measurement.

The purpose of the present study was to evaluate stress distribution by finite element analysis in an accurate model simulating trabecular bone using micro-CT.

### Materials and Methods

#### 1. Materials

Dentulous and edentulous maxillary jaws of Japanese adult cadavers (5 sides each; total, 10 sides) stored in the Autopsy Department of Tokyo Dental College were used (Table 1). In the dentulous maxillary jaws, the molar dental arch remained, and occlusal contact was preserved. In the edentulous maxillary jaws, the entire molar dental arch was absent, and the entire alveolar ridge was covered with cortical bone.

#### 2. Selection of maxilla for production of finite element analysis models

The Frankfort plane (FH) of the maxilla of each jaw was established at right angles to the stage, and imaging was performed using a micro-CT HMX 225-ACTIS+4 (TESCO, Tokyo, Japan) with a minimum slice thickness of 50\,\mu m, at a tube voltage of 110\,kV, tube current of 80\,mA, and an SID/SOD of 170/600\,mm. As a filter, a 0.5-mm copper plate was used.

Maxillary 3-D reconstruction images were produced from slice images using 3-D reconstruction software (VGStudio, Nihon Visual Science, Tokyo, Japan) by the volume rendering method. For these images, arbitrary cross-sections can be set. The internal structure of the region of interest established in trabecular bone was observed (Figs. 1 and 2).

For production of the average finite element models of the maxilla, the region of interest was established in the dentulous and edentulous jaws, and 3-D bone morphometry of the trabecular and cortical bones was performed. In the dentulous jaws, a plane crossing the FH plane at right angles to the stage and containing the interalveolar septum between the second premolar and first molar was established (Fig. 3). Next, on this plane, the line connecting the lowest point of the maxillary sinus and the alveolar ridge was divided into 3 portions, and a 2.5-mm cube centering on the upper 1/3 portion was established. In the edentulous jaws, a plane crossing the FH plane at right angles and at the mid-point between the plane containing the infraorbital foramen and the plane containing the subzygomatic crest was established. In this plane, the line connecting the lowest point of the

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<td>Dentulous</td>
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<tr>
<td>No.</td>
<td>Age</td>
</tr>
<tr>
<td>1</td>
<td>48</td>
</tr>
<tr>
<td>2</td>
<td>56</td>
</tr>
<tr>
<td>3</td>
<td>57</td>
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<tr>
<td>4</td>
<td>62</td>
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<td>5</td>
<td>77</td>
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maxillary sinus and the alveolar ridge was divided into 3 portions, and a 2.5-mm cube was established in the upper 1/3 portion. In cortical bone, the measurement region was alveolar cortical bone and cortical bone at the maxillary sinus base contained between the most stenotic site on the maxillary sinus side and the most stenotic site on the palatine process in an area within 2.5 mm from the established plane (Fig. 4).

Subsequently, in the regions of interest in trabecular bone, measurements were performed using trabecular structure measurement software (TRI 3D BON, Ratoc, Tokyo, Japan). The measurement items in trabecular bone were: bone volume (BV) measured by application of the parallel plate model to 3-D structural analysis, tissue volume (TV), bone volume density (BV/TV) obtained based on the bone surface (BS), trabecular thickness (Tb.Th), trabecular separation (Tb.Sp), trabecular bone number (Tb.N), and structural model index (SMI) as a morphological index. In cortical bone, mean cortical bone thickness (Ct) was measured.

Three-dimensional bone morphometry
revealed the following results: bone volume density (BV/TV), 35.3 ± 8.2% in the dentulous jaws and 28.2 ± 5.2% in the edentulous jaws; trabecular bone thickness (Tb.Th), 0.23 ± 0.03 mm in the dentulous jaws and 0.18 ± 0.04 mm in the edentulous jaws (significant difference by t-test \( p<0.05 \)); trabecular bone number (Tb.N), 1.54 ± 0.35/mm in the dentulous jaws and 1.62 ± 0.28/mm in the edentulous jaws; trabecular separation (Tb.Sp), 0.45 ± 0.14 mm in the dentulous jaws and 0.46 ± 0.09 mm in the edentulous jaws; mean Structure Model Index (SMI), 1.58 in the dentulous jaws and 1.91 in the edentulous jaws; mean thickness, 2.28 ± 0.40 mm in the dentulous jaws and 1.33 ± 0.59 mm in the edentulous jaws (significant difference by \( t \)-test \( p<0.05 \)).

3. Evaluation of stress distribution by finite element analysis

Maxillas with a mean bone morphometric value were selected to develop finite element analysis models of the dentulous and edentulous jaws using finite element analysis software (TRI 3D FEM, Ratoc, Tokyo, Japan).

The following loading sites were established in the finite element analysis models. In the dentulous model, load was applied in the tooth axis direction to the first molar crown (Load in corona of dentulous calyx: LD). In the edentulous model, load was applied in an area centering on the alveolar crest in the plane perpendicular to the FH plane, corresponding to the first molar and containing the infrayzomatic crest. In this model, a line was established at 83° to the FH plane in the sagittal direction as the direction corresponding to the tooth axis of the first molar and from the loading site to the lowest point of the maxillary sinus. In the edentulous model, analysis was performed using 2 loading conditions. In one condition, a 4-mm in diameter area was established centering on the alveolar crest, and the load was applied in the direction corresponding to the tooth axis (load in edentulous 0 mm rod: LER0). In the other condition, a cylinder (4 mm in diameter and 10 mm in height) was established so that its base could be positioned at the alveolar crest (load in edentulous 10 mm rod: LER10). The nodes in this superimposition were continuous. Constraint surfaces were established on the anterior,
Table 2 Elastic properties of materials modeled

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<th>Modulus of elasticity (GPa)</th>
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<tr>
<td>Bone</td>
<td>13.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Tooth</td>
<td>41.4</td>
<td>0.3</td>
</tr>
<tr>
<td>Titanium</td>
<td>108.5</td>
<td>0.34</td>
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posterior, bilateral and upper surfaces of the maxillary finite element model. Evaluation was performed using von Mises equivalent stress. The constituents were cortical bone, trabecular bone, teeth, and titanium, and their material constants are shown in Table 2\(^{1–4}\). The load applied to the model was equivalent to occlusal force.

Results

Occlusal, frontal and lateral views of the finite element analysis are shown in Fig. 5.

1. LD

After loading the first molar of the dentulous maxillary bone, stress was concentrated on cortical bone around the cervical area and on the buccal side of the alveolar ridge close to the tooth root, and was also distributed to cortical bone at the maxillary sinus base continuous with the trabecular bone around the tooth root.

2. LER0

After loading the cortical bone within a 4-mm diameter in the dental axis direction to the first molar crown, stress was concentrated on the cortical bone of the alveolar ridge, and was also distributed to internal trabecular bone on the alveolar ridge side. However, no stress distribution was observed in cortical bone at the maxillary sinus base continuous with the trabecular bone.

3. LER10

After loading a cylinder (4 mm in diameter and 10 mm in height) on the edentulous maxillary alveolar ridge corresponding to the first molar, stress distribution to the cortical bone in the alveolar process decreased compared to LER0. Stress was distributed to trabecular bone adjacent to the cylinder and cortical bone at the maxillary sinus base continuous with the trabecular bone.

Discussion

The maxilla shows age- and growth-related changes in not only its external shape but also internal structure. In particular, tooth loss markedly affects the maxilla, inducing alveolar bone resorption and irregularity in the trabecular structure. Grote et al.\(^8\) reported change in plate-like trabecular structure to a rod-like structure due to an increase in spaces and loss of continuity. In their experiment, the preparation of slices caused deformation of various structures such as trabecular bone. In our present study, we used micro-CT to obtain deformation-free measurements. The methods we used allowed us to obtain higher precision images than normally possible with just micro-CT.

There have been many studies on finite element analysis using jaw models with trabecular bone as a uniform mass for data inputting. Although Gabor et al.\(^6\) has performed finite element analysis using a complex maxillary model, this study regarded trabecular bone as a uniform mass. No investigations have been conducted on stress concentration in cortical bone at the maxillary sinus base via trabecular bone. Kitamura et al.\(^13\) reported differences in stress distribution in different morphologies of cortical bone around a cylinder using simplified finite element analysis models. However, each model
showed a constant thickness of cortical bone, and did not simulate trabecular bone. Gurcan et al.\(^9\) has developed a finite element analysis model containing the upper structure of a cylinder and has evaluated stress distribution in cortical and trabecular bones under different loading conditions. This study, however, also regarded trabecular bone as a uniform mass, but no stress concentration in trabecular bone was observed.

In the observation of the frontal section of the maxillary alveolar ridge by 3-D image reconstruction, dentulous maxillary jaws showed interconnection and regular orientation of the trabecular bone. The morphology and direction of trabecular bone are believed
to reflect functional resistance to pressure\textsuperscript{10,20}. Compared with the dentulous jaws, the trabecular bone of the edentulous jaws was irregularly arranged, showing a mixture of thin plate-like trabecular bone and fine rod-like trabecular bone. In the dentulous maxillary alveolar ridges, a radial arrangement of cancellous trabecular bone from the proper alveolar bone around the tooth root to the cortical bone of the adjacent alveolar ridge and cortical bone at the maxillary sinus base was observed. In contrast, the edentulous jaws showed thinner trabecular bone with irregular arrangement indicating a regressive change. Cortical bone was thinner in the edentulous jaw images than in the dentulous jaw images. Geng et al.\textsuperscript{7} reported the necessity of the simulation of trabecular bone as well as cortical bone in finite element analysis models obtained by CT and MRI. In the present study, morphological characteristics of the bone were incorporated into finite element analysis. Finite element analysis of three-dimensionally reconstructed images of the real maxilla allowed simulation of trabecular bone and observation of stress distribution close to that obtainable with \textit{in vivo} conditions.

Nishihara & Nakagiri\textsuperscript{15} investigated stress distribution of occlusal force in periodontal tissue by two dimensional finite element analysis. They found that in dentulous jaws, the trabecular bone was arranged in a radial pattern from the tooth root along the main stress line. Bone formation of the alveolar ridge occurred along the main stress line. Morphological change in the internal trabecular bone may result from changes in functional pressure distribution due to tooth loss. In this study, after loading the first molar in dentulous maxillary bone, marked stress distribution was observed in trabecular bone, which was arranged in a radial pattern from the mesial and distal tooth roots, cortical bone on the buccal side of the alveolar ridge and cortical bone at the maxillary sinus base.

After loading the cortical bone within a 4-mm diameter in the tooth axis direction to the first molar crown, stress was distributed to cortical bone around the loading site and trabecular bone arranged along the loading direction. However, no stress distribution was observed in cortical bone at the maxillary sinus base.

In contrast, after loading a cylinder (4 mm in diameter and 10 mm in height) placed on the edentulous maxillary alveolar ridge corresponding to the first molar, stress was distributed to trabecular bone adjacent to the cylinder, especially in trabecular bone connecting to the cylinder top and cortical bone at the maxillary sinus base. Stress distribution was observed in the cortical bone at the maxillary sinus base. Stress distribution in the model, in which a load was applied on the cylinder, was close to that in the dentulous jaws.

In conclusion, our results suggest that functional stress distributed around the cylinder may inhibit bone morphological alteration regarded as regressive changes in trabecular bone.

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References


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