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Original Article

Study on Internal Structure of Zygomatic Bone Using Micro-Finite Element Analysis Model —Differences between Dentulous and Edentulous Dentition in Japanese Cadavers—

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Abstract

The purpose of this study was to analyze changes in the internal structure of zygomatic bone using a micro-finite element analysis model (μFEA) and compare angular orientation of trabeculae against compressive force in edentulous and dentulous jaws. Twenty zygomatic bones from dentulous jaws and 20 zygomatic bones from edentulous jaws harvested from Japanese male cadavers were used. From 2-dimensional slice images, we reconstructed 3-dimensional (3D) structure by the volume rendering method using micro-computed tomography (micro-CT). To analyze mechanical properties, all voxels were converted to μFEA models. The angle between the strongest direction of trabecular bone and the axial loading direction (angle α) was then determined using the μFEA models. In the 3-D reconstruction images, trabecular density in dentulous jaws was higher than that in edentulous jaws at all loci. Trabeculae in dentulous jaws showed a plate-like structure. The μFEA modeling revealed that the angle of the trabeculae at the Jugale in edentulous jaws was lower than that in dentulous jaws. This suggests that the internal structure of trabeculae is influenced by occlusal force in zygomatic bone from edentulous jaws.

Key words: Zygomatic bone—Micro-CT—Japanese cadavers—
Bone histomorphometry—Finite element analysis

Introduction

In addition to its external form, the internal structure of jaw bone also changes with growth and aging, and biting force influences the morphology of the jaw bone[1,19]. A number of studies have investigated change in trabecular bone with age, with many of them focusing on vertebral trabecular bone. The results revealed enhanced proliferation of holes and

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continuous depletion, and it has been suggested that tabular trabeculae are baculiform and also change[5)]. There have been many studies on the internal structure of the jaw bone. In most of these studies, specimens were embedded, thin sections were prepared, and their soft X-ray images were two-dimensionally observed[13)]. Evaluation of 3-dimensional (3-D) structure is difficult by this method, and information on the margin for cutting can not be obtained. Some studies have 3-dimensionally analyzed bone specimens using a micro-CT system that allowed not only non-destructive serial imaging of specimens, but also 3-dimensional reconstruction[2,9,11,15–17)]. More recently, a micro-CT system that enables high definition 3-D observation of internal trabeculae to facilitate non-destructive preparation and analysis has been developed, allowing more detailed observation of osseous internal structure. It is suggested that trabeculae are formed along the main direction of stress according to Wolff's law[8)]. We were able to observe the directionality of trabeculae via mechanical measurement in 3 dimensions using micro-CT. Kato *et al.*[12)] reported that the internal structure of dentulous jaws was characterized by thicker trabeculae than in edentulous jaws. In this study using micro-CT, we observed the trabeculae of zygomatic bone in Japanese cadavers, evaluated alteration in configuration with tooth loss and performed a 3-D finite element analysis (FEA) of bone density. We then investigated the internal direction of trabeculae in dentulous and edentulous jaws. In addition, we investigated the relationship between change in configuration of internal zygomatic structure and tooth loss.

Materials and Methods

1. Material and specimen preparation

Twenty zygomatic bones from dentulous jaws and 20 zygomatic bones from edentulous jaws harvested from 40 Japanese male cadavers were used. The use of human specimens conformed to the protocol established for such research by the Department of Anatomy, Tokyo Dental College. The dentulous jaws had occlusion from the 1st premolar to the 2nd molar, while the edentulous jaws were without foramens from tooth extraction. Specimens were obtained from the sutura frontozygomatica, posterior to the sutura temporo-zygomatica down to the sutura zygomatico-maxillaris.

2. Micro-CT imaging

To obtain 3-D bone structure, we used micro-CT (HMX225-ACTIS + 3, TESCO). The system has been described in detail by Hara *et al.*[6)]. In this study, imaging was performed at a tube voltage of 90 kV, a tube current of 60 μA, and a magnification of 4.0. Based on the raw data obtained, 2-dimensional slice images were produced by the back projection method.

3. Production of 3-D reconstruction imaging and its observation

From the slice images, 3-D reconstructions were made by the volume rendering method using 3-D reconstruction software (VG Studio1.1, Volume Graphics). We rotated each 3-D reconstruction image and observed internal zygomatic bone structure at specified points. In this study, as anthropological reference points, we used a plane perpendicular to a plane selected to include 3 chosen points[12)]. These were the zygoorbitale point (Zo), as the intersectional point between the infraorbital margin and the zygomaticomaxillary suture; the orbitale point (Or), at the lowermost point of the infraorbital margin; and the zygomaxillare point (Zm), at the lowermost point of the zygomaticomaxillary suture. A plane including 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 Zm was established in the zygomatic bone in jaws with and without teeth, and this was regarded as the reference plane (Fig. 1). To discriminate between different areas within the zygomatic bone, we selected 3 volumes of interest (VOI) in the reference plane of zygomatic bone. The reference plane of the zygomatic bone

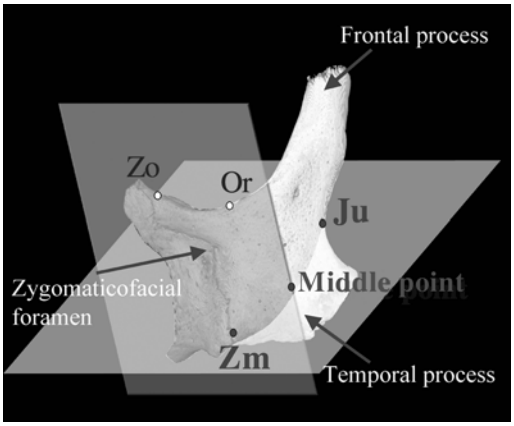

Fig. 1 3-dimensional reconstruction of left zygomatic bone

Jugale (Ju): most concave point between lateral margin of upper zygomatic bone and upper margin of zygomatic arch; zygomaxillare (Zm): lower-most point of zygomaticomaxillary suture; middle point (M.P.): point between Ju and Zm.

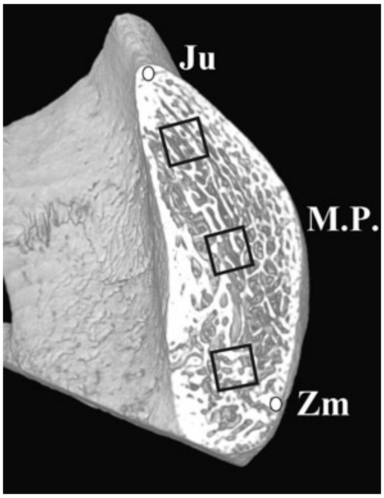

Fig. 2 Volumes of interest sections

Three volumes of interest (VOI) in reference plane of zygomatic bone were selected: Ju, Zm, and the area at the middle-point (M.P.) between Ju and Zm.

was divided into 3 areas. These were the area of Ju, Zm, and the area at the middle-point (M.P.) between Ju and Zm. The VOI were set to exclude cortical bone in each area. The size of each VOI was $2.96 \times 2.96 \times 2.96\,\text{mm}^3$ (Fig. 2). The VOI was segmented using an individual density threshold value. Segmentation was performed visually by comparing the slice before and after segmentation for a range of threshold values. The threshold that resulted in the best fit between the two was used[8)].

4. Mechanical analysis using the FEA

Based on the method of Tanck *et al.*[18)], we used a μFEA model for regional mechanical measurement of the internal structure of the zygomatic bone. To analyze mechanical properties, all voxels were converted to micro-finite element models with an element size of $29 \times 29 \times 29\,\mu\text{m}^3$ for the bone cubes. The elastic modulus and 3-D direction corresponding to the maximal modulus of longitudinal elasticity were determined by compression tests. Compression force was applied to each voxel under conditions where Poisson's ratio was 0.3 and Young's modulus was 5 GPa. Maximal modulus of longitudinal elasticity (E_{max}) and angle α between the 3-D direction and the prefixed axis were then determined. Statistical analysis of the variance of α was performed with the Student's *t*-test.

Results

1. Observation of 3-dimensional reconstruction images

The 3-dimensional reconstructed images revealed dense distribution of thick plate-like trabeculae oriented in a constant direction in the zygomatic bone of dentulous jaws, whereas in edentulous jaws, thin rod-like trabeculae were sparsely distributed in irregular directions. Furthermore, bone density was high at Ju, M.P., and Zm, showing plate-like structures in the zygomatic bone of dentulous jaws, in contrast to that in edentulous jaws. This tendency was marked at Ju (Figs. 3, 4).

2. Mechanical analysis using FEA

Dentulous jaws showed larger maximum values than edentulous jaws at all loci. We determined the direction (α) where the

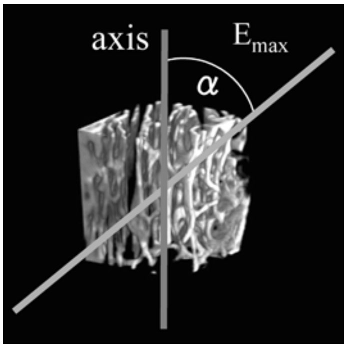

Fig. 3 Measurement items

α: Angle between maximal modulus of longitudinal elasticity (E_{max}) and fixed axis.

Elastic modulus and 3-dimensional direction corresponding to maximal modulus of longitudinal elasticity were determined by compression tests.

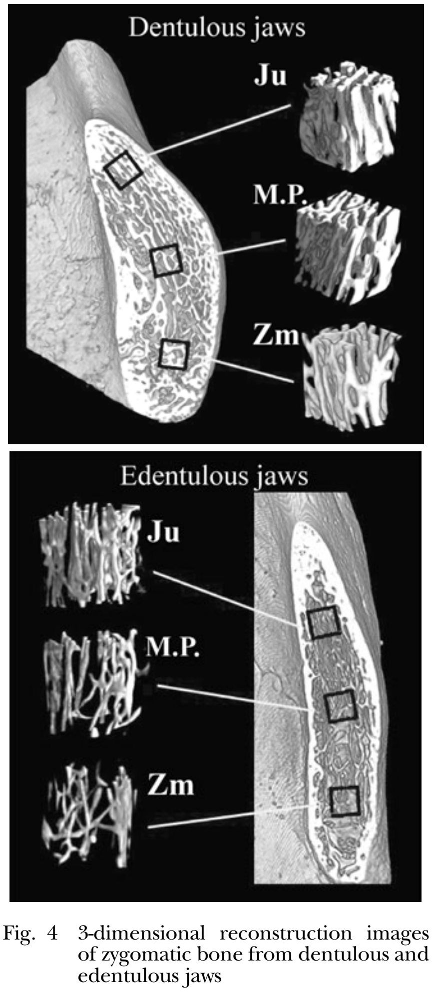

Fig. 4 3-dimensional reconstruction images of zygomatic bone from dentulous and edentulous jaws

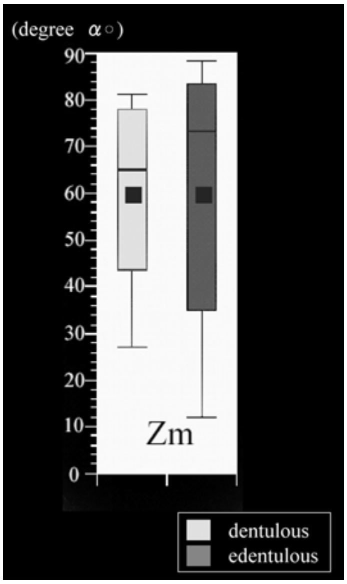

Fig. 5 Angle between strongest trabecular direction and axial loading direction (α) at Zm

No constant directionality was recognized at Zm in both dentulous and edentulous jaws, and no significant differences were recognized between the two.

elastic modulus showed a maximum value. There was a significant difference between the dentulous jaws and edentulous jaws at Ju. Although polarity was recognized at M.P. in both dentulous jaws and edentulous jaws, no significant differences were found between the two. No constant directionality was found at Zm in both dentulous and edentulous jaws (Fig. 5).

Discussion

Mechanical measurement has been performed in lumbar spine using micro-CT[7,8,10], but not in zygomatic bone, except for in a study by Kato *et al.*[12]. They reported that the internal structure of dentulous jaws revealed thicker trabeculae than that of edentulous jaws. In this study, we performed detailed observation of change in the internal structure of zygomatic bone by means of mechanical measurement.

1. Observation of 3-D reconstruction images

We observed internal zygomatic bone structure using 3-D reconstitution images, and observed the polarity of thick trabeculae in dentulous jaws. It has been suggested that the configuration of trabeculae alters depending on the pressure acting upon it on[8,14], and, in this study, thin trabeculae running in various directions were noted in zygomatic bone from edentulous jaws. This suggests that biting force is transmitted into zygomatic bone. Previous findings indicated that bone formation decreases when force applied to the bone is reduced, and that trabecular morphology changes from a plate-like to a rod-like structure when mechanical load is decreased[12]. Inside zygomatic bone, the process whereby trabeculae change from a plate-like structure to a rod-like structure was observed by pressure change due to tooth loss[12].

2. Mechanical analysis using FEA

In this study, morphometry revealed that the trabeculae had a coarser structure in edentulous jaws than in dentulous jaws. They were also larger, and 3-dimensional measurement using FEA revealed that the elastic modulus of cancellous bone had undergone protracted pressure due to the polarity of the trabeculae. This resulted in the trabeculae running parallel to functional pressure, thus resisting it. It has been suggested that intersection is configured so as to allow pressure dispersion[8]. It was thought that the difference in directionality in zygomatic bone from dentulous and edentulous jaws was due to change in the transmission of mechanical pressure acting on the inside of the zygomatic bone[12]. Three-dimensional FEA of the facial skeleton with simulated occlusal loading has indicated that occlusal loading of the maxillary molar is transmitted through the zygomatic ridge[4]. In recent years, studies at the cellular level on the influence of mechanical loading on bone tissue have drawn much attention and have revealed that osteocytes function as receptors of mechanical loading[17]. 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 decrease[3]. The results of comparing Ju, representing the zygomatic margin, in edentulous jaws and dentulous jaws, showed diversification of trabecular orientation. We believe that this may have been due to loss of transmission of biting force through tooth loss. In conclusion, it is suggested that the internal structure of trabeculae in zygomatic bone in edentulous jaws may be influenced by odontogenic presence.

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