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Morphological changes in the internal structure of the articular eminence of the temporal bone during growth from deciduous to early mixed dentition

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Abstract

Previously, bio-mechanical studies on the temporomandibular joint have concentrated mainly on the mandibular condyle while the articular eminence has been largely overlooked. Furthermore, research on the mechanical properties of bone using finite element analysis has focused on the cortical bone in preference to cancellous bone. In this study morphorogical changes in the internal structure of the articular eminence as related to child growth were examined using Micro-CT. Morphometric analysis of samples of cancellous bone representing both deciduous and early mixed dentitions showed an increase in the bone volume fraction and trabecular thickness in the early mixed dentition, and finite element analysis indicated directional transmission of stress as well. These results suggest that the morphology of the trabecular bone was altered to adapt to the functional growth progressed from the deciduous to the early mixed dentition.
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Keywords: Cancellous bone; Articular eminence; Deciduous dentition; Mixed dentition; FEA

1. Introduction

The temporomandibular joint is subject to considerable stress produced by the forces of mastication and occlusal contacts. As this stress often causes a variety of painful symptoms, this area has attracted much research from many different aspects (Bodner and Miller, 1998; Yura et al., 2002). Historically, the mechanical effects of stress on bone have been analyzed by finite element analysis of the long bones of the upper and lower extremities, most of which consist of thick cortical bone (Benjamin et al., 2004; Elise et al., 2003; Harun et al., 2003; Taylor et al., 2002; Wirtz et al., 2003). In finite element analysis, the cancellous bone was considered to be no more than bone tissues inside the cortical bone, and assuming that the cancellous bone is a mass, the material constant alone was obtained (Kimura, 1990). However, in the temporomandibular joint with a complicated structure, the cortical bone in the articular eminence is much thinner than that in the limbs bone, and when the cortical bone is stressed, the mechanical properties are markedly affected by the thickness and direction of the cancellous bone. Therefore, to evaluate the mechanical properties of the articular eminence, it is necessary to analyze the stress in the cancellous bone. Many recent studies have used finite element analysis to examine the effects of stress on the mandibular condyle and articular disks (Beek et al., 2000; Chen et al., 1998; Dovocht et al., 2001; Tanaka et al., 2000, 2001; Van Ruijven et al., 2002). To date, the only study on the internal structure of the articular eminence is limited to the changes caused by aging, and it was based on two-dimensional observations made in one direction (Kawashima, 1996). While most studies have examined the distribution of stress on the surface of the cortical bone (Iki, 2001). The effects of stress on the trabecular bone were examined, but the observation

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was performed in the mandibular condyle alone (Otsuka, 2000). The morphology of the articular eminence is markedly changed by growth, and the internal structure is affected by the changes in stress caused by growth. In this study, cancellous bone areas removed from within the articular eminences in two groups of children were three-dimensionally evaluated by micro-CT, and the morphological changes with growth were observed. The mechanical changes in the same samples were then subject to finite element analysis and the relationship between the morphological and mechanical changes as well as the direction of the trabeculae in the samples were assessed.

2. Materials and methods

The materials in this study consisted of twenty temporal bones detached from the dried skulls of Indian juveniles, held in the Department of Anatomy of Tokyo Dental College. The gender of samples were unknown. These skulls were divided into two groups; one group has deciduous dentition (10 samples), and the other has early mixed dentition (10 samples). The criterion for defining the stage of deciduous dentition was that all teeth between deciduous central incisor and deciduous second molar were fully erupted and reached the occlusal plane. Also, the stage of early mixed dentition defined that the first permanent molar and central incisor, or first permanent molar and central, lateral incisor were erupted to the occlusal plane, and all remaining deciduous teeth existed at the occlusal plane. The micro-CT device (KMS-755, Kashimura, Japan) was used in this study. The sample was placed at the center of the material table so that the thickest part of the articular eminence was contained within the imaging range, and imaging was performed at a tube voltage of 44 kV, a tube current of 90 μA, and a magnification of 3.0. From the slice images, three-dimensional images of the articular eminence were reconstructed using three-dimensional reconstruction software (TRI/3D-BON, RATOC SYSTEM ENGINEERING, Japan) by the volume rendering method. Since the bone existed as the image data in this stage, an arbitrary cross-section could be chosen, and the internal structure was observed and measured on the reconstructed images. As the region of interest, a cube, measuring $1.76 \times 1.76 \times 1.76\,\text{mm}^3$ ($80 \times 80 \times 80$ voxel), was established in the cancellous bone of the articular eminence (Fig. 1). In the region of interest, the parameters such as bone volume fraction (BV/TV), trabecular thickness (Tb.Th), trabecular number (Tb.N) and trabecular separation (Tb.Sp) were obtained using the analytic software

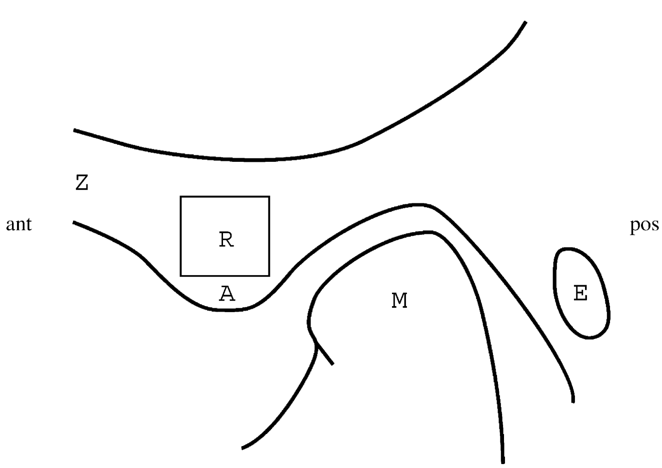

Fig. 1. Schema of the temporomandibular joint of left side at lateral view. A: articular eminence. E: external auditory meatus. M: mandibular condyle. Z: zygomatic process. R: region of interest (ant = anterior, pos = posterior).

(TRI/3D-BON, RATOC SYSTEM ENGINEERING, Japan). In addition, structure model index (SMI), degree of anisotropy (DA), trabecular bone pattern factor (TBPf) and fractal dimension (FD) were determined to observe the detailed structure of the trabecular bone. A significant difference examination between two groups based on each parameter was performed by Student's *t*-test.

Mechanical measurement in the region of interest of the samples was conducted by the finite element method. The condition used in this examination was a Poisson's ratio of 0.3 and a Young's modulus of 5 GPa, which was reported by Tanck (2001). Image data, measuring $1.76 \times 1.76 \times 1.76\,\text{mm}^3$, were transformed into a μ finite element analysis (FEA) model with element sizes of $17.6 \times 17.6 \times 17.6\,\mu\text{m}^3$ for bone cubes. This model was made for each sample. The elastic modulus and the three-dimensional direction corresponding to the maximal modulus of longitudinal elasticity were determined by compression tests (Fig. 2). Then the maximal modulus of longitudinal elasticity ($E_{\max}$) and the angle α between the three-dimensional direction and prefixed axis were determined. The prefixed axis was in the antero-posterior direction of the articular eminence and vertical to the anterior and posterior faces of the cube. The orientation of this specimen was based on skull orientation. Statistical analysis of $E_{\max}$ and the variance of α were performed by Student's *t*-test.

Analysis of stress of the reconstructed micro-CT images was performed using the software of the finite element method for stress analysis (TRI/3D-FEM, RATOC SYSTEM ENGINEERING, Japan). The maximum stress value displayed on the screen was used for the evaluation, and the distribution patterns of stress indicated by colors were observed. Finite element models were constructed directly from the micro-CT data. Following the labeling process, finite element models were produced by mapping with eight-noded cube brick elements. Finite element analysis under loading conditions was performed with fixed boundaries, so that no displacement was generated along the directions other than the direction of loading. Positive loads were applied to the upper front region corresponding to the region in contact with the mandibular condyle via the articular disk in the direction vertical to the posterior slanting surface of the articular eminence. The magnitude of the load was 110 N for the deciduous dentition and 140 N for the early mixed dentition (Karibe et al., 1997; Ogata et al., 2001; Tanaka, 1993). The material constants of the bone were a Young's modulus of 10 GPa and a Poisson's ratio of 0.3 (Kimura, 1990; Tanaka, 1993).

3. Results

The lateral observation of the reconstructed images indicated that the height of the articular eminence and the depth of the mandibular fossa increased from the deciduous dentition to the early mixed dentition (Table 1, Fig. 3). In the 3-D images of the deciduous dentition group extracted for bone morphometry and finite element analysis, the trabecular bone was narrow and stick-shaped at all sites. While in the early mixed dentition group, the trabeculae in the anterior-posterior direction showed a wide board-like appearance, and those were connecting tightly (Fig. 4).

Bone volume fraction (BV/TV) and Trabecular thickness (Tb.Th) increased with growth. Trabecular number (Tb.N) decreased with growth. SMI indicated a change in the shape of the trabecular bone from stick-like to board-like with growth. TBPf indicated an increase in the connectivity of the trabecular bone with growth (Table 2).

$E_{\max}$ had larger average values in the early mixed dentition group than in the deciduous dentiton group, but there was no significant difference between the 2 groups (Table 3).

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