Differences in the morphology of the maxillary sinus and roots of teeth between *Macaca fuscata* and *Macaca fuscata yakui* determined using cone beam computed tomography

By

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Summary: The Japanese macaque is an endemic species consisting of two subspecies: *Macaca fuscata fuscata* (MFF) and *Macaca fuscata yakui* (MFY). The MFY is indigenous to Yakushima Island and represents a subspecies of MFF that lives from Honshu to Shikoku and Kyushu, Japan. However, the differences in the skulls of the MFY and MFF are unknown, despite these subspecies having different skull sizes. The maxillary sinus (MS) indicates that the features of the frontal view reflect the transversal growth of the maxilla of the skull. In this study, we show the MS structures of the MFF (n = 9, 18 sides) and MFY (n = 10, 20 sides) using a cone-beam computed tomography instrument. Based on three-dimensional (3D) reconstructed images the MS and nasal cavity were found to present almost no significant differences between MFF and MFY. However, we designated three classifications of the sinus floor based on the 3D MS images of these Japanese macaques: a round-like shape (type a, MFF = 66.7% (12/18), MFY = 45% (9/20)), a flat-like shape (type b, MFF = 22.2% (4/18), MFY = 35% (7/20)), and an irregular shape (type c, MFF = 11.1% (2/18), MFY = 20.0% (4/20)). The sinus floor shapes of the MFF were mostly type a, while those of the MFY were mostly type b. The prevalence of a root contacting the cortical bone is higher in the canine (26.7%, (8/30)) and second premolar (20%, (6/30)) of the MFY at the nasal cavity, moreover, this value is higher in the third molar (42.9%, (9/21)) of the MS in the MFY. These results suggest that the features of the floor of the MS are related to the differences in maxillary root apices teeth between MMF and MMF.

Introduction

The Japanese macaque is an endemic species consisting of two subspecies: *Macaca fuscata fuscata* (MFF) and *Macaca fuscata yakui* (MFY)¹–³. The differentiation between the MFF and the MFY has been suggested to be associated with the craniofacial morphology of these subspecies⁴–⁶. In primates that possess a maxillary sinus, the canine root is placed in the cancellous bone of the maxilla, anterior to the pneumatic space. The root of the canine causes a medial bulge in the inner table of the bone of the maxilla that extends into the nasal cavity⁷. Knowledge of the internal structural configurations may promote a clearer understanding of the development and formation of paranasal pneumatization in primates. All Old World monkeys (excepting the genus *Macaca*) lack the maxillary sinus, except for the primitive bulla of the Chinese golden monkey *Rhinopithecus⁸*. However, it is unknown whether the maxilla sinus in the paranasal cavity of this animal functions in pulmonary respiration through the nasal cavity. There is evidence that the difference in the maxillary sinus size between the Hominoida and Old World monkeys cannot be explained by a single factor, such as body size⁹. The relationships between the sinus floor and the posterior...
maxillary teeth tend to become closer in the large-sized hominoids\(^{10}\), while the root apices of the maxillary molars exposed into the sinus floor can also be found in relatively small-sized macaques, such as *M. Mulatta*\(^9\). The Japanese macaque has larger occlusal loads on their narrow mandibles than other macaques, which significantly influences their mastication\(^{11}\). However, there are few data regarding diets that dissipate greater occlusal loads\(^{12, 13}\).

Therefore, we studied the morphology of the MS and its accompanying structures using cone beam computed tomography (CBCT) to better understand the processes involved in facial development in both the MFF and the MFY, which constitute an endemic species. It is important to attempt to examine the morphology of the MS in relation to the location of the roots of the teeth during the development of the MFF and MFY dry skulls because such an examination facilitates the estimation of the correlation between MS and the nasal cavity, which is related to facial morphology. Macaques were selected as our experimental model to determine the relationship between the MS and nasal cavities of primates. The justification for using the macaque model to test the long-term relationship between MS morphology and nasal cavity is also discussed in this paper.

Subjects and Methods

Subjects

This study was performed in 19 adult MFF (5 male, 4 female) and MFY (5 male, 5 female); the age of each individual was estimated from the tooth eruption sequence\(^5\). The dry skulls of adult Japanese macaques in osteological collections were supplied for this study by the Department of Neurology, Gross Anatomy Section, Kagoshima University Graduate School of Medical and Dental Sciences (Japan).

Methods

CBCT images

CBCT (PSR 9000N; Asahi Roentgen Industry, Kyoto, Japan) was used in this study. Images of the MS and surrounding structures were acquired from each sample. The CBCT was operated at a tube potential of 80 kV and a tube current of 4 mA, and the scans acquired high-resolution images of 41 × 40 mm cylindrical areas (voxel size = 0.1 mm). From the three-dimensional CBCT images, the diameter of the MS was measured using ASAHI vision software (Asahi Roentgen Industry) and Micro AVS version 11 software (KGT, Tokyo, Japan). After identifying the medial sagittal plane and the palatal plane, which is defined by the anterior and posterior nasal spines and is perpendicular to the median sagittal plane, as reference planes, the measurements described below were performed. The diameter of the skull was measured using ASAHI vision software and MicroAVS Version 11 (KGT, Tokyo, Japan). The 3D images were obtained with INTAGE Realia Professional software (KGT Industry, Tokyo, Japan).

Measurements

The points measured in the CBCT images of the MFF and MFY are shown in Fig. 1. The following seven measurements of the skull: maximum height of the MS (MHMS), maximum width of the MS (MWMS), maximum depth of the MS (MDMS), maximum depth from the anterior nasal cavity to the posterior nasal spine of horizontal plate of the palatine bone (MDANC-PNS), maximum height from the palatine plane to the superior margin of the nasal cavity (MHPP-SMN), maximum width from the midline of the skull to the lateral margin of the nasal (MWMS-LMN) at the center of the second molar position, and the angle between the palatine plane and the nasal plane (APNP) (See Fig. 1). We also classified three types of sinus floor in the 3D MS images: a round-like shape, a flat-like shape, and an irregular shape (see Figs. 2a-c).

Statistical methods

Student’s *t*-test was used to compare the 3D CBCT images of MFF and MFY.

Results

The data from the seven measurements of the skull are shown in Table 1 and 2. No significant correlation was found between MFF and MFY for any measurement. We classified three types of sinus floor from the 3D MS images of the Japanese macaques: a round-like shape (type a, MFF, 66.7%, n = 12; male, 33.3%, n = 6; female, 33.3%, n = 6, MFY , 45.0%, n = 9; male, 25.0%, n = 5; female, 20.0%, n = 4), a flat-like shape (type b, MFF, 22.2%, n = 4; male, 16.7%, n = 3; female, 5.6%, n = 1, MFY , 35%, n = 9; male, 10.0%, n = 2; female, 25.0%, n = 5), and an irregular shape (type c, MFF, 11.1%, n = 2; male, 5.6%, n = 1; female, 5.6%, n = 1, MFY, 20.0%, n = 4; male, 15.0%, n = 3; female, 5.0%, n = 1) (see Fig. 2). The floor sinus shapes of MFF included a high proportion of type A, while those of MFY were mainly type B. The tooth root contacted the cortical bone of the MS and NC at various locations in the MFF and MFY. The roots of the canine tooth, the second premolar, and the first molar were in contact with the NC, and the roots of the second and third molars were also in contact with the MS (See Fig. 3). In the nasal cavity of the MFF, the prevalence of a root contacting the cortical bone...
Fig. 1. Measurement points in the CBCT image of the Japanese macaque. Seven measurements of the skull were made as follows: A: maximum depth of the MS (MDMS), B: maximum height of the MS (MHMS), C: maximum width of the MS (MWMS), D: maximum width from the midline of the skull to the lateral margin of the nasal cavity (MWMS-LMN) at the center of the second molar position, E: maximum height from the palatine plane to the superior margin of the nasal cavity (MHPP-SMN), maximum depth from the anterior nasal cavity to the posterior nasal spine of the horizontal plate of the palatine bone (MDANC-PNS), and the angle between the palatine plane and the nasal plane (APNP). Bar = 20 mm.

Fig. 2. Three types of MS structures from three-dimensional CT images of macaques: A: round-like shape; B: flat-like shape; C: irregular shape. Bar = 10 mm.
was determined in the canine tooth (16.7%, 3/18), the first premolar (5.6%, 1/18), the second premolar (11.1%, 2/18), the first molar (44.4%, 8/18), and the second molar (22.2%, 4/18). In contrast, the prevalence of a root contacting the cortical bone was determined in the canine tooth (26.7%, 8/30), the second premolar (20.0%, 6/30), the first molar (33.3%, 10/30), and the second molar (20.0%, 6/30) in the nasal cavity of the MFY. In the MS cavity of the MFF, the prevalence of a root contacting the cortical bone was determined in the first molar (15.0%, 3/20), the second molar (60.0%, 12/20), and the third molar (25.0%, 5/20). In contrast, the prevalence of a root contacting the cortical bone of MFY was determined in the first molar (4.7%, 1/21), the second molar (52.4%, 11/21), and the third molar (42.9%, 9/21) in the MS.

**Discussion**

In general, the rates of shape changes in the neurocranium and neurofacial junction areas are attributed to an expanding fetal macaque brain. Zumpano and Richtsmeier reported that the lower face change rates after inferior zygomatic-maxillary sutures were larger in fetal pigtail macaque at the asterion using 3D CT images. The sexual dimorphism difference with regard to body weight and canine size in primates is related to the polygyny associated with parental investment and various ecological factors. Therefore, various parameters determine the facial region of the craniofacial morphology in the macaque skull. Previous reports have indicated some specific differences in the craniofacial morphology; the MFY generally has a smaller skull with a relatively protruding snout, narrower orbital breadth, more constricted postorbital region, broader zygomatic arch, and higher inion. Our results suggested that the MS morphology is an important component of the defined facial region of the craniofacial morphology. Facial growth is facilitates the development of an adequate nasal cavity for respiratory requirements. Therefore, the MS is an important marker of facial development in macaque. The nasal cavity floor may also constitute an important indicator of the nasal complex because the inspiratory airflow passing through this region requires both temperature modification and humidification. The nasal morphology may affect the paranasal pneumatization in the macaque. In our results, a round-like shape was mainly observed in the MFF, while a flat-like shape was more prevalent in the MFY. The different morphologies of the MS are related to facial formation driven by diet, climate and various living environments. The specific structure of the 3D MS image is affected by the location of the teeth roots in the anterior region of the bony space, with the developed roots of the canine teeth or those of the molars located in the posterior region of the same space. Our results showed that the canine tooth (26.7%) and second premolars (20.0%) of the MFY in the nasal cavity are generally found in different locations than those of the MFF. The third molar (42.9%) of the MFY differs from that of the MFF in the MS to an even greater extent. The locations of these teeth roots are related to the formation of the MS during the tooth eruption. In particular, the location of the canine teeth may influence mastication, as the developed long root of the canine tooth in the MFY is in contact with the cortical bone of the MS. The

| Table 1. Measurements data of right and left sides of CBCT images in MFF and MFY |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------------|
|                                | MWMS (mm)| MHMS (mm)| MDMS (mm)| MWMS-LMN (mm)| MHPP-SMM (mm)| MDANC-PNS (mm)| Volume of MS (mm³) |
| MFF (total)                    | 6.35±1.63 | 10.05±2.06 | 10.81±2.15 | 12.29±1.13 | 31.93±2.41 | 45.00±5.78 | 0.50±0.29       |
| MFF-Right                      | 6.24±1.70 | 10.02±1.87 | 10.72±1.98 | 12.31±1.14 | 31.93±2.48 | 45±5.96    | 0.51±0.35       |
| MFF-Left                       | 6.46±1.66 | 10.08±2.34 | 10.91±2.43 | 12.27±1.19 | 31.93±2.48 | 45±5.96    | 0.48±0.24       |
| MFY (total)                    | 7.56±4.08 | 10.61±2.64 | 12.15±2.86 | 11.93±1.36 | 30.88±2.78 | 43.56±2.78 | 0.68±0.38       |
| MFY-Right                      | 7.79±3.95 | 10.72±3.12 | 12.4±2.95  | 12±1.72    | 30.88±3.02 | 43.56±3.23 | 0.69±0.47       |
| MFY-Left                       | 7.32±4.11 | 10.5±3.58  | 11.89±3.53 | 11.85±1.64 | 30.88±3.01 | 43.56±3.23 | 0.67±0.67       |

| Table 2. Measurements data of gender of CBCT images in MFF and MFY |
|---------------------------------|-----------|-----------|-----------|-----------|-----------|-----------|-----------------|
|                                | MWMS (mm)| MHMS (mm)| MDMS (mm)| MWMS-LMN (mm)| MHPP-SMM (mm)| MDANC-PNS (mm)| Volume of MS (mm³) |
| MFF (total)                    | 6.35±1.63 | 10.05±2.06 | 10.81±2.15 | 12.29±1.13 | 31.93±2.41 | 45.00±5.78 | 0.50±0.29       |
| MFF-Right                      | 6.24±1.70 | 10.02±1.87 | 10.72±1.98 | 12.31±1.14 | 31.93±2.48 | 45±5.96    | 0.51±0.35       |
| MFF-Left                       | 6.46±1.66 | 10.08±2.34 | 10.91±2.43 | 12.27±1.19 | 31.93±2.48 | 45±5.96    | 0.48±0.24       |
| MFY (total)                    | 7.56±4.08 | 10.61±2.64 | 12.15±2.86 | 11.93±1.36 | 30.88±2.78 | 43.56±2.78 | 0.68±0.38       |
| MFY-Right                      | 7.79±3.95 | 10.72±3.12 | 12.4±2.95  | 12±1.72    | 30.88±3.02 | 43.56±3.23 | 0.69±0.47       |
| MFY-Left                       | 7.32±4.11 | 10.5±3.58  | 11.89±3.53 | 11.85±1.64 | 30.88±3.01 | 43.56±3.23 | 0.67±0.67       |
Fig. 3. Various types of correlation between tooth roots and MS or NC in the sagittal section of CBCT images of the MFF and the MFY. A, The roots of the second and third molars in contact with the cortical bone of the MS floor. B, The roots of the premolars and molars in contact with the cortical bone of the NC floor (palatine). C, The roots of the canine tooth and the first and second molars in contact with the cortical bone of the NC floor (palatine). D, The roots of the canine tooth and second molar in contact with the cortical bone of the NC floor (palatine). E, The root of the second molar in contact with the cortical bone of the MS floor. F, The roots of the canine tooth and second molar in contact with the cortical bone of the NC floor, as well as that of the third molar in contact with the cortical bone of the MS floor. 3; canine, 4; first premolar, 5; second premolar, 6; first molar, 7; second molar, 8; third molar, MS; maxillary sinus, NC; nasal cavity. Bar = 20 mm
Mastication required to eat a hard food in a specific environment may have produced this difference in the development of the upper and lower face. Antón\textsuperscript{11}) also suggested that the shorter face of the Japanese macaque was better suited to processing a hard diet compared to that of the other macaque. Macaques are weaned early compared to humans to prepare them for masticating adult diets\textsuperscript{19, 20}). Macaque teeth are ready to erupt soon after birth\textsuperscript{21, 22}). In this context, we have refined the hypothesis that this feature of MS is needed by MYF because this subspecies consumes a harder diet than that consumed by the MFF. Thus, these different characteristics are due to the distinct food preferences of the MFF and the MYF.

\textbf{Reference}