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Implication of craniofacial morphology for the pneumatization pattern of the human alveolar process*

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This study investigates whether the degree of pneumatization of the alveolar process can be predicted with cranial dimensions. **Materials and methods**. Mixed-sex samples of adult skulls of the prehistoric Jomon population and of the recent population of Japan were CT scanned at the coronal plane through the upper premolars and molars. A perpendicular line from the tangent at the floor of the nasal cavity to the deepest point of the maxillary sinus floor served to measure the depth of the maxillary sinus floor (MSD). Apart from the femur head diameter, several cranial measurements including palatal length and palatal width were taken using a sliding caliper. **Results and discussion**. The deepest point of the maxillary sinus was found in the region of M^1 and M^2. Least-squares regression analysis revealed in both populations a close relationship between the femur head diameter and MSD, suggesting that in humans the maxillary sinus size as well as the pneumatization of the maxillary sinus floor are a function of skull / body size. From cranial measurements, the palatal height showed a very close relationship with MSD. **Conclusion**. The lack of a marked relationship between the form of the hard palate and the maxillary sinus volume in great apes, and the results of this study indicate that the evolutionary changes of the human skull such as the elongation of the facial skeleton beneath the cranial base as well as the reduction in jaw size led to a closer association between maxillary sinus and hard palate.

Key words: maxillary sinus floor, skull pneumatization, hard palate, secondary dentition, Jomon

INTRODUCTION

It is generally accepted that the development and growth of the maxillary sinus are constrained by the developing teeth, especially by the secondary dentition. Even though it is not uncommon that in both humans and great apes the crypts of the developing tooth germs are exposed as bulges in the maxillary sinus floor (MSF), in most macaque species the MSF is well above the roots of the maxillary molars (1). Since the presence or absence of a maxillary sinus is apparently independent of dental morphology (2), it is questioned what factors are responsible for the extent of pneumatization of the alveolar process.

The formation of a secondary palate is one of the features that distinguish the skull of mammals from that of their ancestors. It has been suggested that there is a significant relationship between the morphology of the hard palate and the size of maxillary sinus in humans (3, 4). This relationship, however, has never been tested by statistical methods. While this knowledge is required to explore factors that influence the functional morphology of the paranasal sinuses, it is also of clinical importance. For example, there is still a debate regarding whether clefts of the primary and secondary palate interfere with the normal development of the paranasal sinuses (5, 6). Finally, the shape of the MSF, its relationship to the maxillary posterior teeth as well as the morphology of the alveolar process have become an issue of great importance, especially for the preoperative planning of dental implants (7, 8). Therefore, the aim of this work was to assess the relationship between the morphology of the hard palate and the maxillary sinus under physiological conditions by focusing on the pneumatization of the alveolar process.

MATERIALS AND METHODS

This study is based on a mixed-sex sample of 42 adult skulls of the prehistoric Jomon population

*** This paper is dedicated to Prof. Dr. Dr. Gert-Horst Schumacher, Rostock, on the occasion of his 80th birthday.**

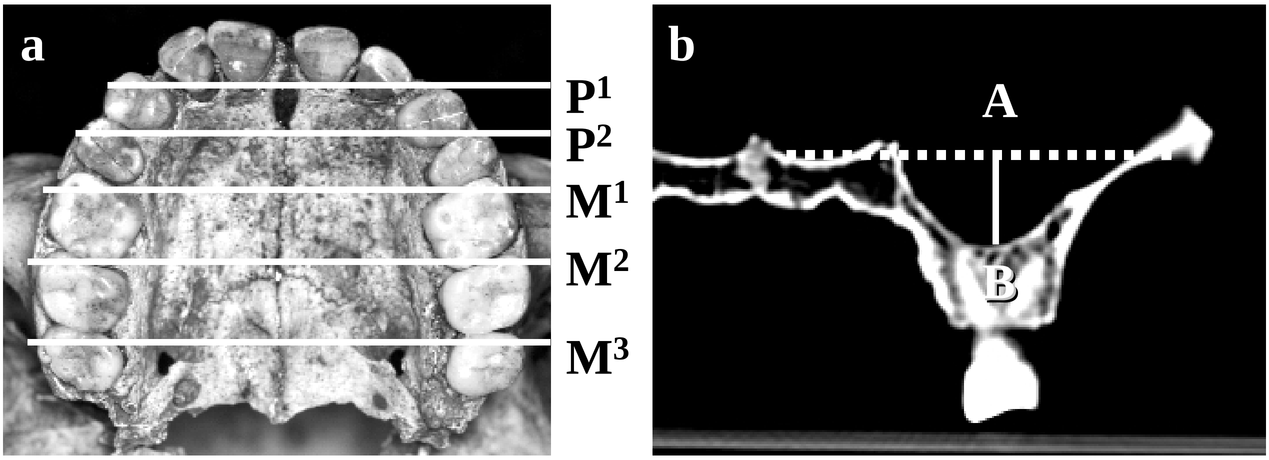

Fig. 1. a: Upper jaw of an adult male Jomon skull showing the regions of CT scanning. Note the missing canines. b: Coronal CT scan through the right M^2 of an adult male Jomon skull showing the measurement of the depth of the maxillary sinus (AB). The dashed line is a tangent at the floor of the nasal cavity. AB is a perpendicular line from the tangent to the deepest point of the maxillary sinus floor

Table 1. **Basic statistics of the cranial variables (cm). Sexes are pooled**

Dimensions	Kyoto population			Jomon population		
	n	Mean	SD	n	Mean	SD
Maxillary sinus volume[a]	20	26.27	10.03	–	–	–
Femur head diamter	20	4.19	0.42	33	4.25	0.32
Basicranial length	20	9.78	0.59	6	10.25	0.42
Upper facial height	20	7.11	0.59	10	6.79	0.51
Facial length	20	9.56	0.37	–	–	–
Bimaxillary width	20	9.54	0.53	11	10.19	0.67
Maxilloalveolar breadth	20	6.36	0.29	31	6.38	0.37
Palatal height	20	1.06	0.21	42	1.09	0.20
Palatal width	20	3.64	0.21	–	–	–
Palatal length	20	4.23	0.34	8	4.34	0.18
Depth of maxillary sinus floor	20	2.49	0.42	38	2.85	0.31

a – volumes in cm^3; n – sample size; SD – standard deviation.

(Inariyama, Yoshiko) of Japan (14 males, 10 females, 18 of unknown sex) and 20 skulls of the recent Japanese population (Kyoto) (10 males, 10 females). Only adult skulls with complete secondary dentition were included in this study. The skulls were CT scanned coronally in 1 mm sections with a Toshiba X-vision CT (scanning parameters: 120 kV, 230 mA) at defined positions: P^1, P^2, M^1, M^2, M^3.

The CT scans served to define the deepest position of the maxillary sinus floor. To obtain the degree of pneumatization of the alveolar process, a tangent was laid at the floor of the nasal cavity (Fig. 1). The distance AB of a perpendicular line from this tangent to the deepest point of the maxillary sinus floor served as a measure for the depth of the maxillary sinus floor (MSD). While negative values indicated a MSF beneath the level of the nasal cavity floor, positive values pointed to a MSF above the nasal cavity floor. Due to the fact that both positive and negative values are present in the sample, the raw MSD were transformed for statistical analysis using the formula: $MSD = |AB - 2|$.

In addition to the femur head diameter (an indicator of body size), the following cranial measurements were taken with a sliding caliper: basicranial length (nasion–basion), facial length (basion–prosthion), upper facial height (nasion–prosthion), bimaxillary width (zygomaxillare–zygomaxillare), maxilloalveolar breadth (ekmolare–ekmolare), palatal length (orale–staphylion), and palatal width (endomolare–endomolare). The palatal height was measured at the coronal CT scans. Because most of the Jomon material consisted mainly of partially preserved material, only the skulls of the Kyoto population were used to calculate the maxillary sinus volume. Pearson's correlation coefficients and least-squares regression analysis were applied to investigate the relationship between the values of MSD, cranial measurements and femur head diameter.

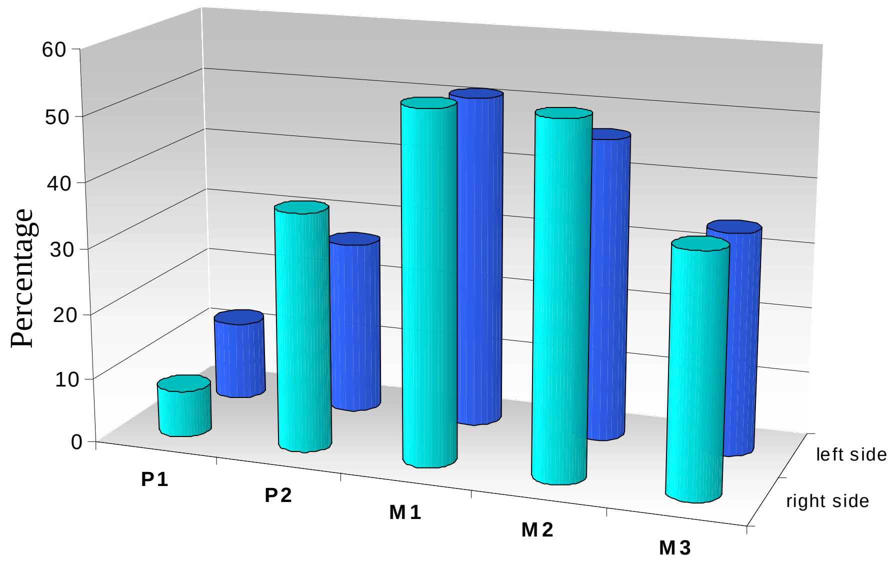

Fig. 2. Frequency of projecting tooth root apices in the right and left maxillary sinus floor of the Jomon human population

extent of pneumatization of the alveolar process in both the prehistoric Jomon human population and the recent Japanese population. This high degree of pneumatization is accompanied by a close proximity of the tooth root apices of all maxillary posterior teeth to the MSF, especially in the Jomon population. Indeed, in more than 50% of the Jomon skulls the tooth root apices of M^1 and M^2 were exposed as bulges in the MSF (Fig. 2).

While the depth of the maxillary sinus floor and the palatal variables showed significant correlations with the maxillary sinus volume, they differed with regard to the other cranial dimensions (Table 2). The results of the regression analysis among the measurement items are listed in Table 3. There was a strong relationship between the MSD, the maxillary sinus volume and the femur head diameter. Furthermore, this study revealed a relatively close association between MSD, palatal height and palatal width (Fig. 4).

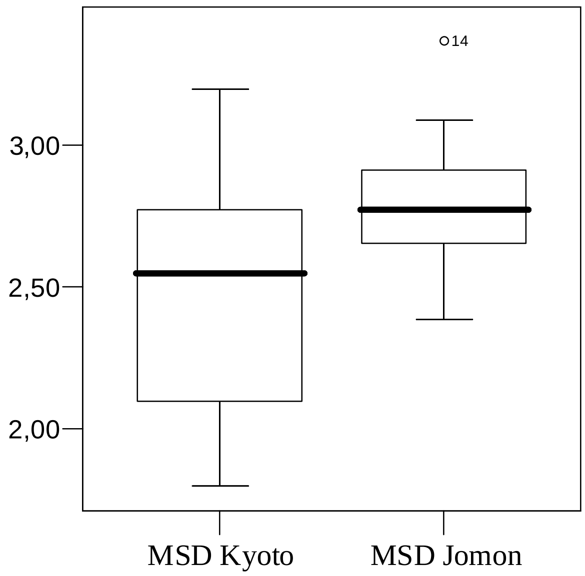

Fig. 3. Box plot showing the variation in the depth of the maxillary sinus floor (MSD) in the Kyoto human population (n = 20) and the Jomon human population (n = 38). Boxes cover the 25th to 75th percentiles of the distribution. Horizontal bold lines represent the median of each MSD distribution. The tail extends to the fifth and 95th percentiles while a small open circle represents an outlier that exceeds the 95th percentile. The difference in the mean of MSD between both populations is not significant

RESULTS

A summary of the cranial variables obtained is given in Table 1. Although the extent of pneumatization of the alveolar process varied greatly among the skulls (Fig. 3), in most of the skulls the maxillary sinus floor (MSF) was well beneath the floor of the nasal cavity, suggesting a comparatively high

DISCUSSION

Morphology of the maxillary sinus floor

This study suggests that the degree of pneumatization of the human maxillary sinus floor depends greatly on both the size of the maxillary sinus and the body size (see below). As a similar association was reported for macaques (1), the variation in the depth of the maxillary sinus floor in the extant anthropoids may be explained by the maxillary sinus size. Even though the validity of this assumption has still to be tested for other primate taxa, the findings of this study are potentially important for both paleoanthropologists and forensic anthropologists, who often have to deal with bone fragments (9). It is tempting to think that the size of the maxillary sinus can be estimated in partially preserved maxillae with exposed MSF.

It is worth mentioning, however, that the shape of the maxillary sinus floor is frequently used to classify maxillary sinuses. Based on the shape of the MSF, up to six types of the maxillary sinus have been classified (10–12). With regard to these findings and the results of the present study it is unlikely that the variation in the morphology of the MSF is related to a single factor. The functional matrix hypothesis states that the morphology of the

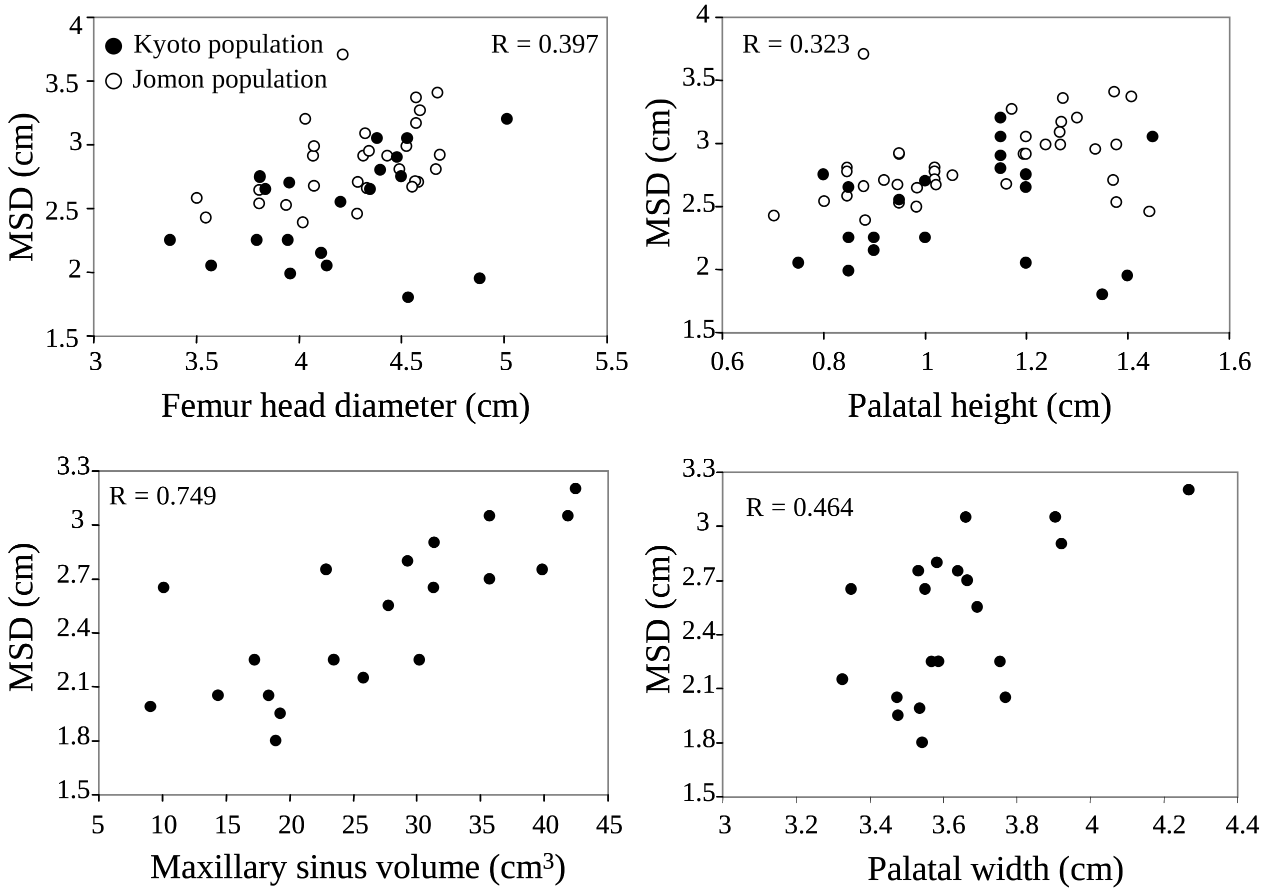

Fig. 4. Scatter diagrams of the depth of the maxillary sinus floor (MSD) in relation to different cranial variables for both the Kyoto and the Jomon human populations. Note that except for the relationship between MSD and palatal height which was significant at $P < 0.05$, all shown relationships were significant at $P < 0.01$.

Table 2. **Correlation matrix among the measurement items for merged data of Kyoto and Jomon populations**

Dimensions	1	2	3	4	5	6	7	8	9	10	11
Maxillary sinus volume	–										
Femur head diameter	0.391	–									
Basicranial length	0.275	0.498*	–								
Upper facial height	0.020	0.080	–0.211	–							
Facial length	0.117	0.446*	0.673**	–0.079	–						
Bimaxillary width	0.478*	0.319	0.578**	–0.159	0.448*	–					
Maxilloalveolar breadth	0.561*	0.547**	0.387	0.171	0.630**	0.664**	–				
Palatal height	0.290	0.547**	0.326	0.240	0.357	0.396*	0.433**	–			
Palatal width	0.438*	0.478*	0.091	–0.014	0.105	0.273	0.416	0.478*	–		
Palatal length	0.139	0.526**	0.351	0.188	0.647**	0.307	0.246	0.132	0.383	–	
MSD	0.749**	0.397**	0.207	–0.017	0.060	0.346	0.324*	0.316*	0.564**	0.206	–

MSD – depth of maxillary sinus floor; * significant at $P < 0.05$; ** significant at $P < 0.01$.

Table 3. **Results of least squares regression of the depth of the maxillary sinus floor (MSD) against femur head diameter and cranial size variables. Sexes are pooled**

Dimensions	n	Slope	Intercept	95% CI	r
MSD					
Maxillary sinus volume[a]	20	0.031	1.669	(0.017, 0.045)	0.749**
Femur head diamter	53	0.431	0.891	(0.141, 0.719)	0.397**
Basicranial length	26	0.148	1.111	(–0.147, 0.444)	0.207
Upper facial height	30	–0.011	2.649	(–0.270, 0.247)	–0.017
Facial length[a]	20	0.067	1.843	(–0.488, 0.632)	0.060
Bimaxillary width	31	0.211	2.541	(–0.006, 0.428)	0.346
Maxilloalveolar breadth	51	0.387	2.235	(0.058, 0.716)	0.324*
Palatal height	58	0.599	2.077	(0.117, 1.081)	–0.323*
Palatal width[a]	20	1.106	–1.536	(0.304, 1.907)	0.564**
Palatal length	28	0.300	1.326	(–0.274, 0.875)	0.206

a – Kyoto population; n – sample size; CI 95% confidence; r – regression coefficient; * significant at $P < 0.05$; ** significant at $P < 0.01$.

adult skull is the result of complex interactions between its various skeletal units during ontogenesis (13). In addition, the development of each of these skeletal units, such as the pneumatic skeletal unit (13), is influenced by genetic and epigenetic factors. Indeed, it has been shown that the maxillary sinus volume in both the Arctic human populations (14) and in the Japanese macaque (15) is significantly associated with environmental factors. Regarding the great variation in both the craniofacial morphology and the maxillary sinus size among living populations (16), future studies on the role of epigenetic factors in both the growth and evolution of the human maxillary sinus are likely to increase our knowledge about the factors that influence the variation in maxillary sinus morphology.

Maxillary sinus floor and craniofacial morphology

The significant relationship between the depth of the maxillary sinus floor and the femur head diameter suggests that the pneumatization of the MSF is also a function of body size. This association, however, is not as strong as the association between MSD and the maxillary sinus volume (Table 3). This finding may be related to the fact that in primates (including humans) the size of the face is not necessarily linked with body size parameters (17, 18). On the other hand, the regression analysis revealed only a few significant associations between MSD and the cranial measurements (Table 3). Apart from the maxillary sinus volume (see above), only palatal height and palatal width showed significant relationships with MSD. While the relationships between MSD, bimaxillary width and maxilloalveolar width were relatively weak, neither palatal length nor basicranial length nor facial length were significantly associated with MSD.

Although the findings of this study clearly support the previous supposition that a high-vaulted palate may be associated with a large maxillary sinus (4, 19), the relationships between MSD and the palatal measurements are not as straightforward as the formerly mentioned association. Although a high-vaulted palate may be linked with a deep maxillary sinus floor, the lack of a significant association between MSD and palatal length is astonishing. Even though comparable data are not available, it is worth mentioning that a morphometric study on 400 European skulls (4) reported a lack of a significant association between maxillary sinus size and palatal length.

It has been suggested that the relationship between the shape of the hard palate and the size of the maxillary sinus in the great apes is not as close as in human beings (19, 20). Even though it is somewhat problematic to withdraw any conclusion from these results that can be used to explain the variation in the pneumatization of the alveolar process among hominoids, the lack of a marked relationship between these structures in the great apes may be due to the changes in the craniofacial morphology during hominid evolution. In this context, we consider the elongation of the facial skeleton beneath the cranial base, which was accompanied by a reduction in jaw size, as especially important. Because the shapes of both the maxillary sinus floor and the hard palate are essentially three-dimensional, studies under way are going to reevaluate some of the hypotheses concerning the relationship between the morphology of the maxillary sinus floor and the shape of the hard palate in both humans and non-human primates.

CONCLUSIONS

Although it is widely accepted that the formation of the maxillary sinus is influenced by numerous factors such as dentition, masticatory stress, and craniofacial growth, factors that control the pneumatization of the alveolar process are largely unknown. The results of the present study indicate that the variation in the pneumatization of the alveolar process is partially due to differences in maxillary sinus volume, palatal form, and body size. While these findings support a structural role of the paranasal sinuses, it is worth mentioning that the variation in maxillary sinus size among higher primates is not related to a single factor (21). In fact, the relationship is rather complex and obviously not all factors are equally related to skull pneumatization. Since the maxillary sinus size is also associated with geographic factors (14, 15), exploring the pneumatization pattern of the alveolar process in various extant and extinct human populations may shed a new light on the biological role of skull pneumatization, which is still obscure.

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References

1. Koppe T, Rae TC. Factors influencing the pneumatization of the alveolar process in macaques. Brook A, ed. Dental Morphology 2001. Sheffield; Sheffield Academic Press, 2001: 267–76.
2. Swindler DR. The dentition, diet, arch form and maxillary sinuses in some anthropoid primates. Koppe T, Nagai H, Alt KW, eds. The paranasal sinuses of higher primates. Development, function, and evolution. Chicago; Quintessence 1999: 191–206.
3. Eller H. Der Sinus maxillaris und seine Nachbarorgane bei verschiedenen Affen und beim Hunde. Z Anat Entwickl Gesch 1932; 97: 725–56.
4. Paatero YN. Anatomisch-topographische und röntgenologische Untersuchungen über die Oberkieferhöhle. Ann Acad Sci Fennicae. Ser A 1939; 50/3.
5. Nowak R, Mehls G. Untersuchungen zum Verhalten der Pneumatisation des Sinus maxillaris. Anat Anz 1975; 138: 143–51.
6. Robinson HE, Zerlin GK, Passy V. Maxillary sinus development in patients with cleft palates as compared to those with normal palates. Laryngoscope 1982; 92: 183–7.
7. Johansson B, Grepe A, Wannfors K, Åberg P, Hirsch JM. Volumetry of simulated bone grafts in the edentulous maxilla by computed tomography: an experimental study. Dentomaxillofac Radiol 2001; 30: 157–61.
8. Ludwig A, Merten HA, Wiltfang J, Engelke W, Wiese KG. Evaluation der B-scan-Sonographie, 3D-Sonographie, Röntgendiagnostik und Sinuskopie zur Kontrolle der Sinusbodenelevation. Mund Kiefer GesichtsChir 2002; 6: 341–5.
9. Ward S, Pilbeam D. Maxillofacial morphology of Miocene hominoids from Africa and Indo-Pakistan. Ciochion R, Corruccini R, eds. New Interpretations of Ape and Human Ancestry. New York; Plenum Press, 1983: 211–38.
10. Anagnostopoulou S, Venieratos D, Spyropoulos N. Classification of human maxillary sinuses according to their geometric features. Anat Anz 1991; 173: 121–30.
11. Nogi T, Kanazawa E. The relationship between tooth roots and the floor of the maxillary sinus assessed using CT images. Brook A, ed. Dental Morphology 2001. Sheffield; Sheffield Academic Press 2001: 257–65.
12. Kim HJ, Yoon HR, Kim KD, Kang MK, Kwak HH, Park HD, Han SH, Park CS. Personal-computer-based three-dimensional reconstruction and simulation of maxillary sinus. Surg Radiol Anat 2002; 24: 393–9.
13. Moss ML, Greenberg SN. Functional cranial analysis of the human maxillary bone: I, basal bone. Angle Orthodont 1967; 37: 151–64.
14. Shea BT. Eskimo craniofacial morphology, cold stress and the maxillary sinus. Am J Phys Anthropol 1977; 47: 289–300.
15. Rae TC, Hill RA, Hamada Y, Koppe T. Clinal variation in maxillary sinus volume in Japanese macaques (*Macaca fuscata*). Am J Primatol 2003; 59: 153–8.
16. Szilvássy J, Kritscher H, Vlèek E. Die Bedeutung röntgenologischer Methoden für die anthropologische Untersuchung ur- und frühgeschichtlicher Gräberfelder. Ann Naturhist Mus Wien 1987; 89: 313–52.
17. Hylander W. Mandibular function and biomechanical stress and scaling. Am Zool 1985; 25: 315–30.
18. Rae TC, Koppe T. Isometric scaling of maxillary sinus volume in hominoids. J Hum Evol 2000; 38: 411–23.
19. Koppe T, Schumacher KU. Vergleichend-anatomische Untersuchungen zur funktionellen Morphologie der Nasennebenhöhlen des Menschen und der Pongiden. Eine quantitative Studie auf der Grundlage der Computertomographie. Rostock; Thesis B, 1991: 1–184.
20. Koppe T, Röhrer-Ertl O, Hahn D, Reike R, Nagai H. The relationship between the palatal form and the maxillary sinus in orang-utan. Okajimas Folia Anat Jpn 1996; 72: 31–41.
21. Rae TC, Koppe T. Holes in the head: evolutionary interpretations of the paranasal sinuses in catarrhines. Evol Anthropol 2004; 13: 211–3.

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KAUKOLËS MORFOLOGIJOS POVEIKIS ÞMOGAUS VIRÐUTINIO ÞANDIKAULIO DANTINËS ATAUGOS PNEUMATIZACIJAI

S a n t r a u k a

Kadangi dantinës ataugos pneumatizacijà nulemiantys veiksniai vis dar neiðaiðkinti, ðiame straipsnyje nagrinëjama, ar dantinës ataugos pneumatizacijai gali turëti átakos kaukolës matmenys. Atliktos abiejø lyèiø suaugusiø asmenø ið prieðistorinës Jomon populiacijos bei ðiuolaikiniø Japonijos gyventojø kompiuterinës tomogramos vainikinëje plokðtumoje, ties virðutiniais kapliais ir krûminiais dantimis. Matuojant virðutinio þandikaulio anèio dugno gylá (MSD), tomogramose buvo iðvedama statmena linija nuo nosies ertmës dugno liestinës iki giliausio virðutinio þandikaulio anèio dugno taðko (MSD). Slankmaèiu buvo matuojamas ðlaunikaulio galvos skersmuo, kai kurie kaukolës matmenys, tarp jø gomurio ilgis ir plotis. Giliausias virðutinio þandikaulio anèio taðkas nustatytas M^1 ir M^2 srityje. Maþiausiø kvadratø regresijos analizë atskleidë, kad abiejose populiacijose esama glaudaus ryðio tarp ðlaunikaulio galvos skersmens ir MSD, o tai liudija, kad virðutinio þandikaulio dydis bei jo dugno pneumatizacija yra kaukolës ir kûno dydþio funkcija. Tarp kaukolës matmenø su MSD labai glaudþiai susijæs gomurio aukðtis. Ryðkesnës sàsajos tarp kietojo gomurio formos bei virðutinio þandikaulio tûrio tarp þmogbeþdþioniø nebuvimas bei ðio tyrimo duomenys liudija, kad þmogaus kaukolës evoliuciniai pokyèiai, tokie kaip pailgëjæs veido griauèiø þemiau kaukolës pamatas bei sumaþëjæs þandikauliø dydis, nulëmë glaudesná ryðá tarp virðutinio þandikaulio ir kietojo gomurio.