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Development of New Formulas for Sex and Age Estimation by Assessing Maxillary Sinus Morphology on CBCT

Kazuma Otsuki,*† Isamu Kodani,† Dawa Zangpo,* Masato Nakatome* and Morio Iino*

**Division of Forensic Medicine, Department of Social Medicine, School of Medicine, Faculty of Medicine, Tottori University, Yonago 683-8503, Japan, †Division of Oral and Maxillofacial Biopathological Surgery, Department of Medicine of Sensory and Motor Organs, School of Medicine, Faculty of Medicine, Tottori University, Yonago 683-8503, Japan*

ABSTRACT

Background The morphology of the maxillary sinus varies between individuals which could be used in the forensic personal identification process.

Methods In the current study, the CBCT images of the maxillary sinus in 453 patients (217 males, 236 females) aged 14 to 95 years were analyzed. In particular, each left, and right maxillary sinus of the subjects was measured for its maximum height, width, and breadth in 2-D, and volume in 3-D perspectives, and their usefulness for age and sex estimation was examined. Regarding age estimation, because the size of the maxillary sinus increases up to 20s and then decreases over time, two separate age estimation formulas were created, one for subjects in their 14–21 years and the other for those over 22 years old. For each age group, multiple regression formulas were generated using the diameters and volume as explanatory variables and the chronological age as a response variable. This study used 150 cases not included in the study as a validation set for age estimation.

Results Generally, all the diameters and volumes in both sinuses tended to increase till the mid-20s, and then gradually decreased over time. The derived formulas were tested for their accuracy on additional 150 subjects. Plausibly, the model could estimate the age between 14–21 years old with an average accuracy of ± 1.8 years for men and ± 3.2 years for women. Whereas for those over 22 years old, it was possible to estimate the age with an accuracy of ± 11.8 years for males and ± 10.3 years for females, respectively. A comparison of estimated age and chronological age did not show a statistically significant difference($P > 0.05$). It was found that the left maxillary sinus had more age groups showing the most significant difference than other measurements between sexes($P < 0.05$). The maxillary sinus height may be significantly affected by gender differences.

Conclusion Overall, this study showed the effectiveness of age and sex estimation using the maxillary sinus morphometric analyses.

Key words Age estimation; CBCT; Forensic sciences; Maxillary sinus; Sex discrimination

The morphometric analyses of human bones have been used in forensic identification since it is the only biological tissue that remains for a longer duration, after the enamel of the teeth postmortem. Similarly, the paranasal sinuses which are an air-filled anatomical cavity in the human skull also survive fire and other taphonomical degradation and have often been used as a personal identification tool. Of particular interest from a forensic perspective is the maxillary sinus.[1–3]

The maxillary sinus develops from about 10 weeks of fetal life, and then its volume expands until the eruption of the wisdom tooth is completed. It attains its maximum growth potential in the mid-20s and then decreases over time. Their growth and development pattern are similar between the sexes, but the final volumes of the maxillary sinus are generally larger in men than in women.[1, 4–8]

The individual variability of the maxillary sinus morphology has the potential to contribute to forensic personal identification. Establishing the identity of the person is important in the context of both the living patients and the skeletonized human remains alike when medicolegal concerns arise. Most social security services, legal proceedings, and ethical judgments require an accurate age determination or confirmation. A young person who does not have proper personal identification documents necessitates a medicolegal resolution. Also, even though most countries consider adult age settings between 14–21 years old, a reliable, and accurate age estimation method remains a priority.

With the widespread use of cone beam computed tomography (CBCT) in dental and maxillofacial clinics,

Corresponding author: Morio Iino, MD, PhD
iino@tottori-u.ac.jp
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Abbreviations: L-MSh, Left maxillary sinus height; L-MSl, Left maxillary sinus length; L-MSw, Left maxillary sinus width; L-MSv, Left maxillary sinus volume; MS, Maxillary sinus; R-MSh, Right maxillary sinus height; R-MSl, Right maxillary sinus length; R-MSw, Right maxillary sinus width; R-MSv, Right maxillary sinus volume; RL-MSh, Right-Left maxillary sinus width; T-MSv, Total maxillary sinus volume

Table 1. Demographic details of the study subjects and the measured items

Samples			
Male	*n* (217/354)	Female	*n* (236/392)
Age		Age	
14	8	14	11
15	11	15	12
16	11	16	6
17	12	17	13
18	10	18	16
19	11	19	15
20	7	20	13
21	14	21	18
22–29	20	22–29	20
30–39	20	30–39	20
40–49	20	40–49	20
50–59	20	50–59	20
60–69	20	60–69	20
70–79	20	70–79	20
80–	13	80–	12

CBCT images of maxillary sinuses are easily available. If the maxillary sinus morphometric analyses could be done using CBCT images, the sex and age of the unknown persons and/or skeletonized human remains could not only be reliably achieved but with minimal invasiveness.[8, 9] Indeed, several studies using CBCT images of maxillary sinus have established its forensic applicability, their study samples mostly were limited to 20 years and above.[1–12] Therefore, this study aimed to evaluate the maxillary sinus morphology using CBCT images of subjects between 14–21 years, and over 22 years old, and examine their effectiveness to estimate the age and sex of the person.

MATERIALS AND METHODS

Samples

From April 1, 2013, to November 30, 2018, 746 patients(354 males, 392 females)aged 14 to 95 years have undertaken CBCT images of their heads for dental and oral surgery at Tottori University Hospital, Yonago, Japan. Among them, subjects of known age and Japanese ethnicity were included. Subjects with trauma, surgery, lesions, and toothless jaws in the maxillary sinus were excluded and the final study sample constituted 453 patients (217 males, 236 females) (Table 1). Since there were many study subjects from 22 to 79 years old, random sampling was performed with 20 people in each age group. Although 293 cases were not studied for age estimation, 150 cases, including those with mild disease that did not affect maxillary sinus morphology, were used as a validation set for age estimation.

Measurement of maxillary sinuses

Using the 3-D image analysis system volume analyzer SYNAPSE VINCENT (Fuji diagnostic imaging workstation, Tokyo, Japan), the maxillary sinus was reconstructed from the CBCT image data. Individual left, and right sinus morphology was then assessed by measuring its maximum height (MSh), length (MSl), width (MSw), the distance between the right and left maxillary sinus (RL-MSw) in 2-D planes, and its volume (MSv) and total volume (T-MSv) in a 3-D perspective (Fig. 1).

Age estimation

Because the size of the maxillary sinus increases up to 20s and then decreases over time, two separate age estimation formulas were created, one for subjects in their 14–21 years and the other for those over 22 years old. For each age group, multiple regression formulas were generated using the diameters and volume as explanatory variables and the chronological age as a response variable.

Statistical analysis of measurements

Sex differences in the above-measured items were examined using the t-test. To derive multiple linear regression models, the age of the subjects was used as the response variable while the diameter and volumes of the maxillary sinus were used as explanatory variables. A p-value of < 0.05 was considered significant. All statistical analyses were performed using Microsoft Excel 2019.

Ethical considerations

The study was approved by the Institutional Ethics Committee of Tottori University Hospital (approval number 18A111).

RESULTS

Firstly, each right and left diameter of the maxillary sinus was evaluated for each age group by sex. amongst all, L-MSh had a significant difference between the sexes at 20 and 21 years old, also 30s, 40s, 50s, 60s, 70s, 80s ($P < 0.05$). Other measurements showed significant differences in R-MSh among the 30s, 50s, 60s, 70s, 80s. Similarly, R-MSl had a significant difference in 22–29 years old, 40s, 80s. L-MSl had a significant difference in the 40s, 80s. R-MSw had a significant difference in the 40s, 60s, 80s. L-MSw had a significant difference in

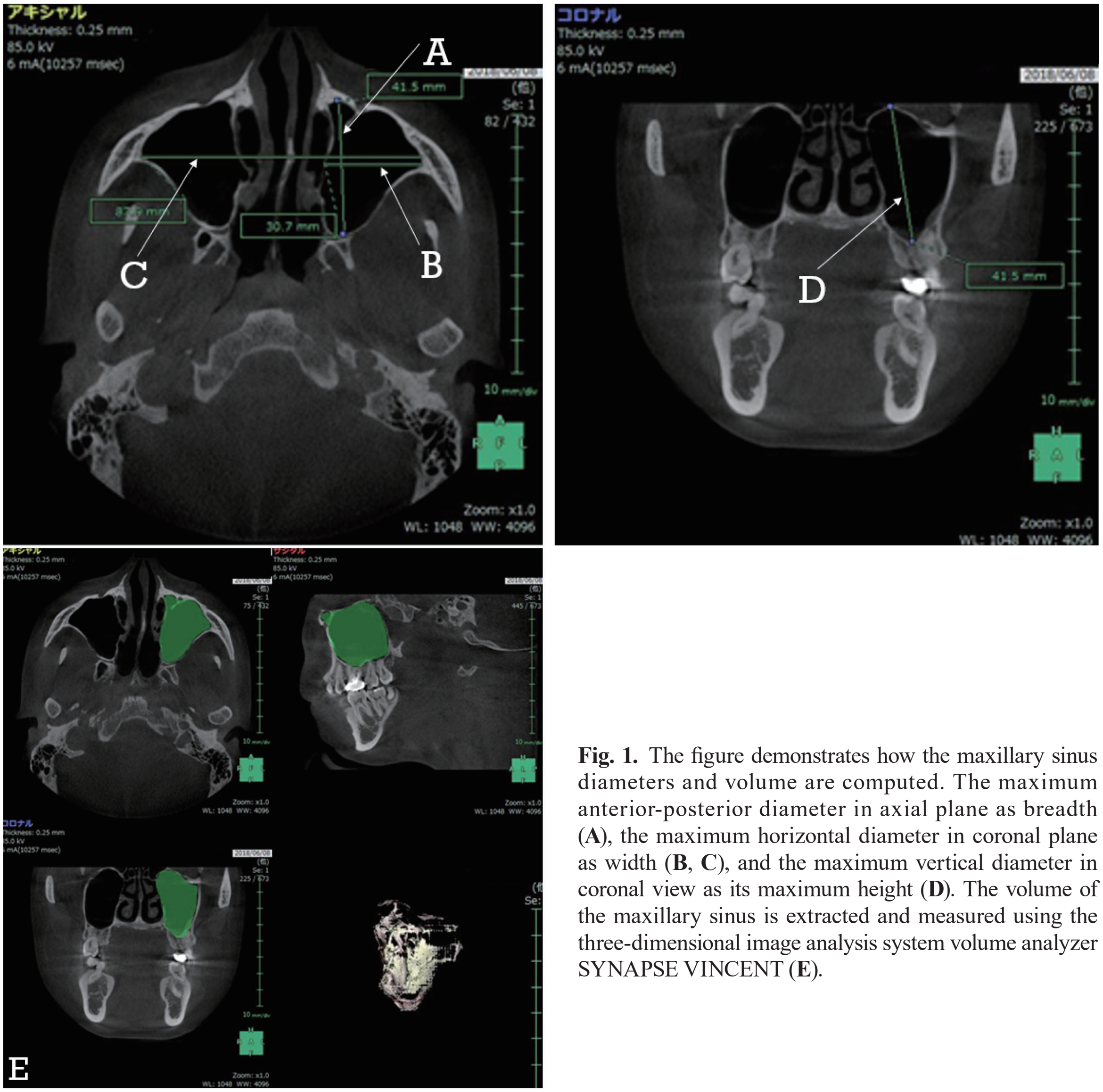

Fig. 1. The figure demonstrates how the maxillary sinus diameters and volume are computed. The maximum anterior-posterior diameter in axial plane as breadth (**A**), the maximum horizontal diameter in coronal plane as width (**B**, **C**), and the maximum vertical diameter in coronal view as its maximum height (**D**). The volume of the maxillary sinus is extracted and measured using the three-dimensional image analysis system volume analyzer SYNAPSE VINCENT (**E**).

the 60s, 70s, 80s. R-L MSw had a significant difference among 14 and 17years old, 40s, 70s, 80s. R-MSv had a significant difference in 20 years old, 30s, 40s, 60s, 70s, 80s. L-MSv had a significant differences among 17 and 20 years old, 50s, 70s, 80s. T-MSv had a significant difference among 20s, 30s, 40s, 50s, 60s, 70s, 80s.

In other words, the maxillary sinus height may be significantly affected by gender differences.

Generally, all the diameters and volumes in both sinuses tended to increase till the mid-20s, and then gradually decreased over time (Figs. 2–6) (Supplementary Figs. S1–5).

The mean measured maxillary sinus volume and the patient's height were used for indexing (mean/h). Ages with significant difference were 60s, 80s in R-MSv (mean/h). L-MSv(mean/h) had a significant difference in the 40s, 70s, 80s. T-MSv(mean/h) had a significant difference in the 30s, 40s, 70s, 80s.

On performing the multiple regression analyses using diameters and volume of both the right and left sinuses as explanatory variables to predict the age (response variable), we obtained the following formulas.

For 14–21 years old, Male:

$$\text{Age (years)} = \{0.0755(\text{R-MSh})+0.1394(\text{L-MSh})+0.1377(\text{R-MSl})+0.1725(\text{L-MSl})-0.0704(\text{R-MSw})+0.0381(\text{L-MSw})+0.06(\text{R-MSv})+0.0995(\text{L-MSv})\}/8+14.6155$$

For 22 years old and above, Male:

$$\text{Age (years)} = \{-1.1286(\text{R-MSh})-1.3025(\text{L-MSh})-1.8283(\text{R-MSl})-1.8584(\text{L-MSl})-1.1225(\text{R-MSw})-0.9688(\text{L-MSw})-0.9298(\text{R-MSv})-0.7576(\text{L-MSv})\}/8+94.785$$

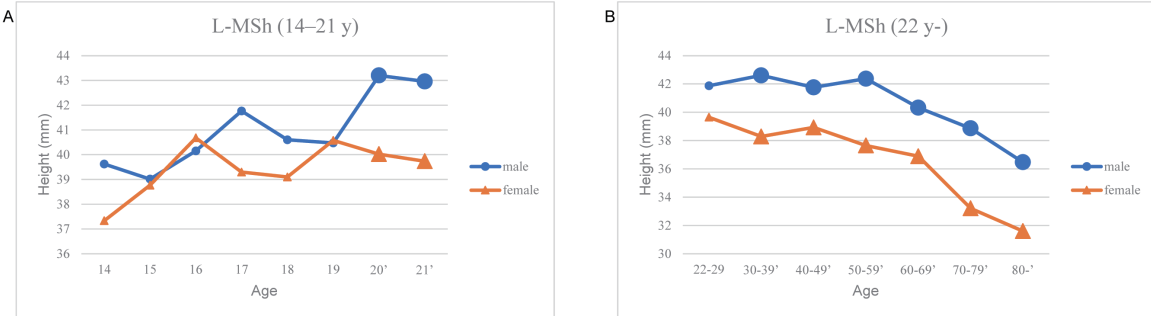

Fig. 2. Significantly different ages are marked with ' in the figure and have larger points. The left maxillary sinus maximum height show a significant difference($P < 0.05$) between the sexes at 20 and 21 years old, but no significant difference is observed between 14–19 years old (**A**). For the above 22 years and older age group, the values start decreasing around the age of 30 in both sexes. However, the rate of decrease is greater for women (**B**).

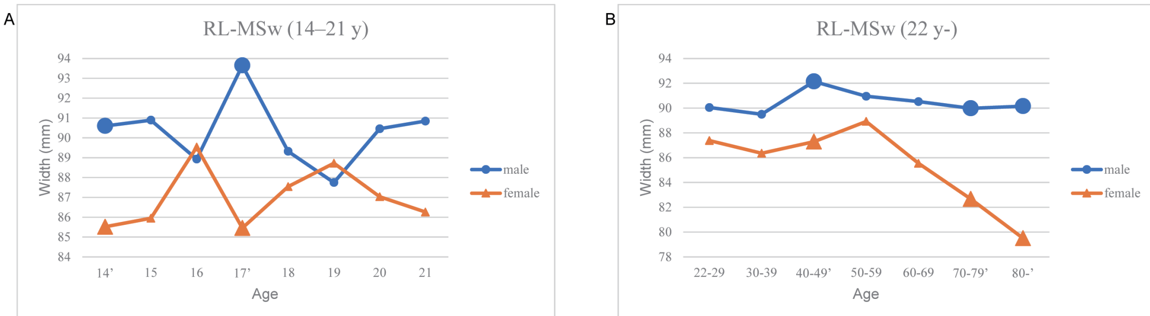

Fig. 3. The total width of the maxillary sinuses (right and left measure together) is significantly different between the ages 14 and 17 years old. Even after the adult age, there is a significant difference in diameters between sexes in the 40s, 70s and 80s ($P < 0.05$). However, the change in width with aging is almost unchanged in men, and no significant difference is observed.

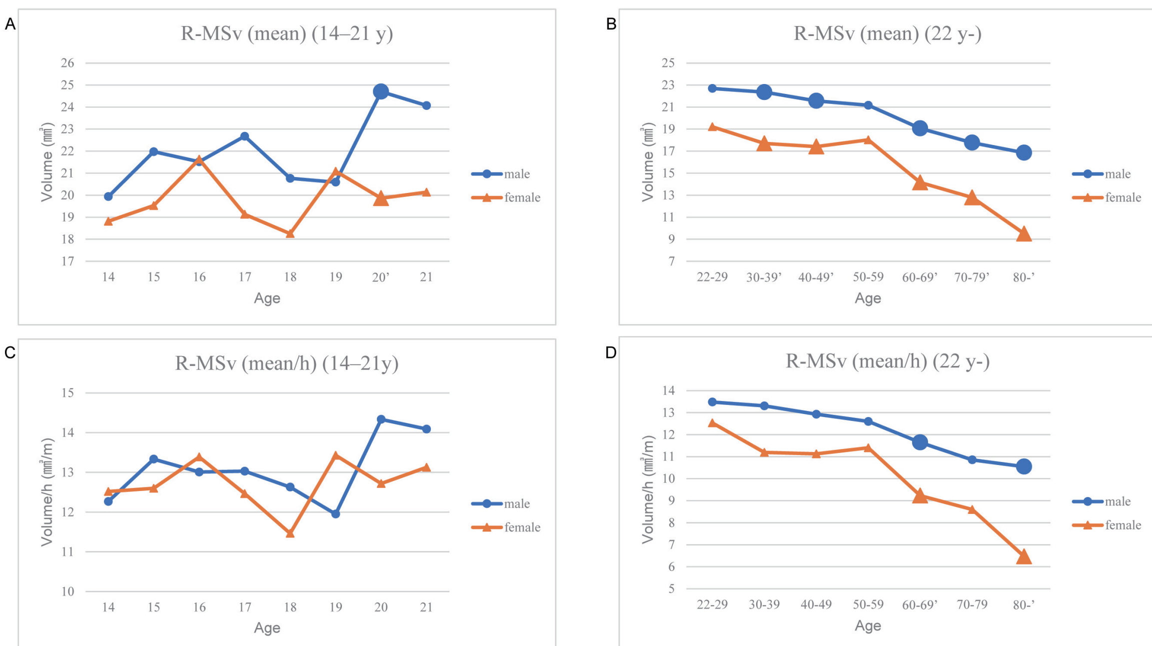

Fig. 4. In the case of the volume of the right maxillary sinus, there is a significant difference between sexes only at the age of 20. In addition, in the 30s and above age group, a significant difference is observed except for those in their 50s ($P < 0.05$). In addition, for the purpose of correcting the physical disparity, the measured average value and the average value of the height at each age are used to index (mean/h) and compare between sexes, but the effectiveness as an index is not recognized.

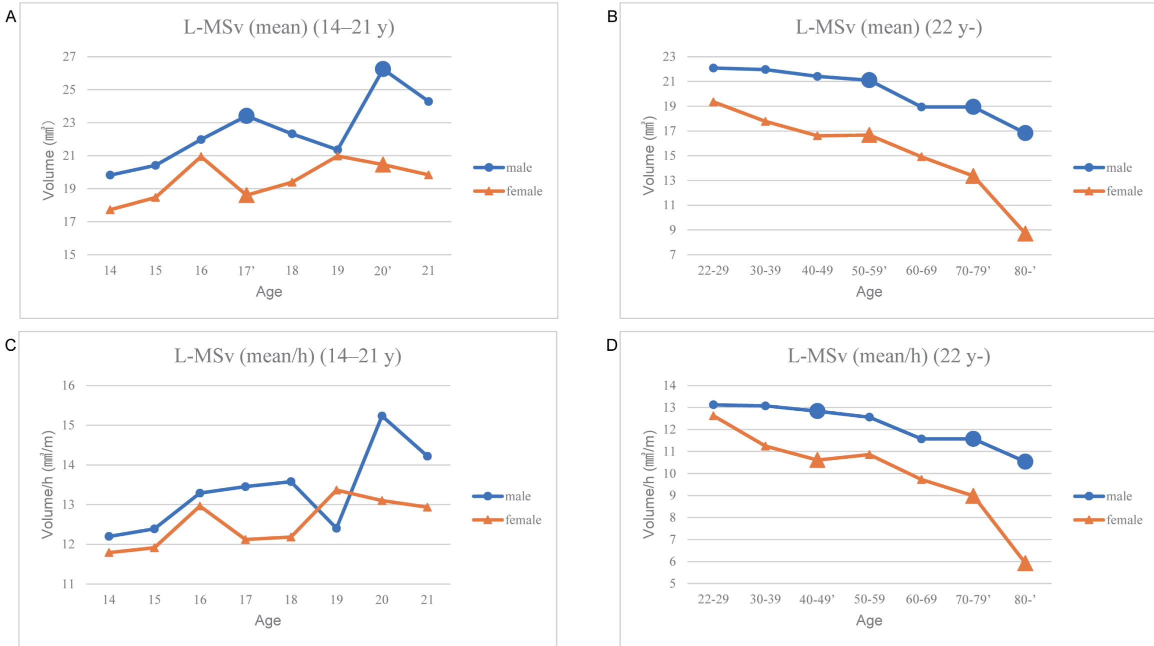

Fig. 5. Regarding the volume of the left maxillary sinus, there is a significant difference between the sexes at 17 and 20 years old. In the adult age group, there is a significant difference between the 50s and older except for the 60s ($P < 0.05$). Even in the case of the left maxillary sinus, the effectiveness as an index (mean/h) is not recognized.

Table 2. Case: 1 Measured value

Sex: Male	Age: 18
R-MSh: 43.6 mm	R-MSw: 33.6 mm
L-MSh: 43.1 mm	L-MSw: 31.6 mm
R-MSl: 45.2 mm	R-MSv: 31.8 mm^3
L-MSl: 47.1 mm	L-MSv: 34.4 mm^3

Table 3. Case: 2 Measured value

Sex: Female	Age: 53
R-MSh: 41.3 mm	R-MSw: 33.6 mm
L-MSh: 39.7 mm	L-MSw: 28.8 mm
R-MSl: 39.5 mm	R-MSv: 18.4 mm^3
L-MSl: 40.8 mm	L-MSv: 21.1 mm^3

For 14–21 years old, Female:

Age (years) = {0.0509(R-MSh)+0.0887(L-MSh)+0.0655(R-MSl)+0.1358(L-MSl)+0.0506(R-MSw)+0.0719(L-MSw)+0.0287(R-MSv)+0.0637(L-MSv)}/8+11.8481

For 22 years old and above, Female:

Age (years) = {−1.5225(R-MSh)−1.5526(L-MSh)−2.0794(R-MSl)−2.4282(L-MSl)−1.6536(R-MSw)−1.5975(L-MSw)−1.5272(R-MSv)−1.3671(L-MSv)}/8+104.4141

The following cases will illustrate the age estimation method using the multiple regression equations derived from our study.

Case 1: 18 years old man's maxillary sinuses were measured (Table 2).

Estimated Age (years) = {0.0755* (43.6)+0.1394* (43.1)+0.1377* (45.2)+0.1725* (47.1)−0.0704* (33.6)+0.0381* (31.6)+0.06* (31.8)+0.0995* (34.4)}/8+14.6155 = **16.87** (difference from actual age, 1.13 years).

Case 2: 53 years old woman's maxillary sinuses were measured (Table 3).

Estimated Age (years) = {−1.5225*(41.3)−1.5526*(39.7)−2.0794* (39.5)−2.4282* (40.8)−1.6536* (33.6)−1.5975* (28.8)−1.5272* (18.4)−1.3671* (21.1)}/8+104.4141= **46.39** (difference from actual age, 6.61 years).

By using the above age estimation formula, it was possible to estimate the age in Case 1 with an error of 1.13 years from the actual age. In Case 2, it was possible to estimate the age with an error of 6.61 years from the actual age.

Furthermore, to validate the accuracy of the derived regression equations, the model was tested on 150 additional subjects (75 males, and 75 females). In them, the average error between the actual age and the

Table 4. Comparison between the average actual ages and the average estimated ages in years

Age: 14–21	Mean	SD	*P*	Age: 22	Mean	SD	*P*
Male (*n* = 35)				Male (*n* = 40)			
Actual age	17.5	2.29	0.3142	Actual age	54.57	19.71	0.1321
Estimated age	17.66	1.32		Estimated age	51.77	7.24	
Female (*n* = 35)				Female (*n* = 40)			
Actual age	17.5	2.29	0.3994	Actual age	54.37	19.95	0.1482
Estimated age	14.35	1.21		Estimated age	52.14	10.1	

To validate the derived age estimation formulas, the models were tested on additional 150 subjects who were not included in the training data set.

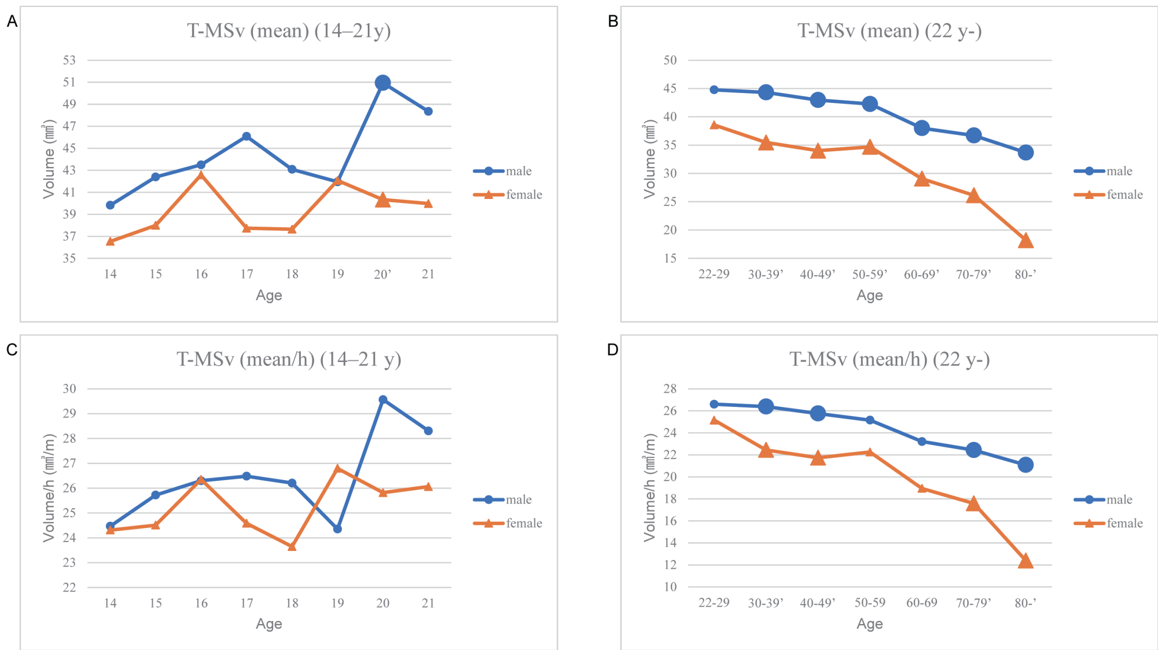

Fig. 6. A comparison using the total volume of the maxillary sinuses on both sides reveale a significant difference between sexes at 20 years of age. In the 22 years and above, a significant difference is observed after the age of 30 ($P < 0.05$). No index (mean/h) effectiveness is found.

estimated age was ± 1.8 years for men aged 14 to 21, ± 11.8 years for men aged 22 years and above, ± 3.2 years for women aged 14 to 21, and ± 10.3 years for women aged 22 and above, respectively (Table 4). There was no statistically significant difference between the estimated age and the actual age($P > 0.05$), indicating that the age estimation formula can be used effectively.

DISCUSSION

In forensic anthropology, dental age estimation is considered highly accurate, and to this end, several population-based dental age estimation methods exist. Most dental age evaluations are based on the person's dental development and conditions of tooth wear. Unlike in adults, where enamel attrition due to aging becomes easily recognizable, young people aged between 14–21 years rarely have complete wisdom tooth germs on radiographs and evidence of tooth attrition on their enamel, demanding additional age estimation methods in them. In addition, after adulthood, the degree of tooth attrition is greatly influenced by dietary habits.It is generally known that tooth enamel is worn away and dentin is exposed after the age of 30 or 40. However, people who have a habit of eating hard foods wear their enamel more quickly, which is an obstacle to age estimation using teeth.

Since maxillary sinus morphology changes in volume over time, it is superior to teeth as a sample for age estimation.

In the past, there have been few reports of creating an age estimation formula using the maxillary sinus. In particular, we searched a wide range of past literature, but there were no reports that created an estimation formula that can estimate the age of young people in their teens. Our study is the first to develop an age estimation formula using the maxillary sinuses of young people in their teens.

In this study, we explored the morphometrics of the maxillary sinus and evaluated its usefulness to estimate age and sex in the Japanese population. Considering the fact that the maxillary sinus size begins to increase from birth, reaches its maximum in the mid-20s, and then decreases over time,[4] two separate age estimation formulas corresponding to each changing phase were created. Overall, in young people aged 14–21 years, all maxillary sinus diameters and volume tended to expand, even though the growth of maxillary sinus height gets affected depending on the condition of maxillary permanent teeth. For example, in the event of the impaction of maxillary premolars, maxillary sinus growth is not uniform, with its particular effect on its floor. We expected that there would be wider individual variability of maxillary sinus diameters due to the non-uniformity of the sinus floor anatomy and present challenges to estimating age. Interestingly, when the age was estimated using the derived age estimation formula, it was possible to estimate the age with an average accuracy of ± 1.8 years for men and ± 3.2 years for women, respectively, irrespective of the conditions of the maxillary permanent tooth and sinus floor present in our study subjects.

Concerning the age group 22 years and above, it was possible to estimate the age using the age estimation formula with an average accuracy of ± 11.8 years for men and ± 10.3 years for women. Also, as shown in Table 1, the standard deviations between the actual age and the estimated age are different for both men and women after the age of 22, indicating individual variability in changes of maxillary diameters and volume in that population group highly vary by sex as well. This was evident when some diameters of the maxillary sinus exceeded the average values in a handful of the cases in older age groups. In addition, in a few subjects who were above 80 years old, the diameter of the maxillary sinus was excessively reduced due to degenerative changes and consequent sinus cavity remodeling even though there was no history of maxillary sinus disease. On the contrary, in the younger age group, even as the maxillary sinus height depended on the maxillary permanent teeth, only in a few cases of an impacted tooth, the maxillary sinus height was below the average value. Therefore, accurate age estimation was possible by evaluating multiple measurement items of the maxillary sinus.

In personal identification in the forensic field, it is a challenging task to discriminate sex when skeletonized human remains are collected in fragments. Generally, if both the skull and pelvis are recovered, it is possible to determine sex from its morphological features with 98% accuracy, whereas if only the skull is used, it can only be discriminated with an accuracy of about 90%.[3, 7, 11] To determine sex using the skull, morphological features such as the degree of development of the eyebrow arch, the thickness of the supraorbital margin, the degree of mastoid process development, and the degree of protrusion of the chin are commonly used. However, if the skull is severely damaged, it may be difficult to distinguish these characteristics. Therefore, an alternative anatomical site, the maxillary sinus was explored to use it as a sex discrimination tool in the current study. Moreover, the maxillary sinus remains relatively intact from many destructive forces like fire and animal predation.

In the current study, several morphometric and volume analyses were performed based on individual maxillary sinuses and compared between sexes. Remarkably, L-MSh had the most significant age differences in gender. Our study clarified the left maximum sinus height as the most distinguishing biological parameter between the sexes. This result was important for gender discrimination, consistent with the study of Teke et al. We used left sinus height to test for sexual dimorphism and achieved a rate of 68%.[12] In this study, indexing by MSv and height was performed, and the effectiveness in gender discrimination was evaluated. However, since no clear significant difference was observed in each age group, indexation is not effective. Sugaya et al. measured the positional relationship of the occlusal plane based on the FH plane, and showed that the occlusal plane is lower in males than in females.[13] In other words, MSh may be significantly affected by gender differences. One of the reasons for the left-right difference in height may be that the eruption timing of the permanent teeth differs between the left and right sides. There has been no previous study that the eruption period of permanent teeth affects the maxillary sinus morphology, and this is a topic for future research.

On the other hand, RL-MSw in men showed little change with age in this study. As a factor, we consider the possibility that the lateral growth of the skull ends with the completion of the maxillary dental arch of the permanent teeth and does not expand further.

Despite no change over time in RL-MSw, the reason why MSw decreased over time on one side may be that bone was added to the inner wall of the maxillary sinus instead of the outer wall. Fernandes performed sex discrimination analysis using maxillary sinus diameters with additional anatomical landmarks using nasal cavity width, the total distance across the sinuses, head circumference, head width, bizygomatic width at the zygon, glabellar/ nasion,/ nasal bone angle, and left and right lateral canthal angle.[10] Although our study clarified the left maximum sinus height as the most distinguishing biological parameter between the sexes, we feel it is necessary to evaluate the skull from a more multifaceted perspective rather than depending only on the maxillary sinus.

One limitation of this study is that the sex of the subject must be established prior to applying the proposed age estimation formula. While it would be easy to apply our methods to living subjects, it would be difficult in the case of skeletonized remains with unknown sex. This is because it is impossible to apply the age estimation formula if the sex is unknown. This problem can be solved if it becomes possible to distinguish between the sexes only by the morphology of the maxillary sinuses. Our future research will focus on sex discrimination accuracy using sinus morphometrics, and we hope it will address the current limitations.

In conclusion, in this study, we evaluated the morphology of the maxillary sinus using CBCT images, and an age estimation formula was developed. Irrespective of the nature of maxillary permanent tooth and sinus floor anatomy, sinus diameters and volume measurements can accurately describe the age of the person.

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The authors declare no conflict of interest.

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