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Novel method of constructing a stable reference frame for 3-dimensional cephalometric analysis

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Introduction: Three-dimensional (3D) cephalometric analysis has provided the ability to overcome the limitations of 2-dimensional cephalometrics. However, there is no international standard method for 3D cephalometric analysis yet. Determining the position of the midsagittal plane (MSP) practically is the most important step when constructing a 3D cephalometric reference frame. Recent studies have used several approaches to construct the MSP. In this study, we aimed to determine the true MSP of the skull to establish a stable reference frame for 3D cephalometric analysis. **Methods:** Cone-beam computed tomography data of 12 adult patients were divided into 2 groups: symmetry (n = 6) and asymmetry (n = 6). The anterior cranial base region model and its mirror model were registered and used to determine the MSP to prevent any influence of the degree of symmetry on the registration of other parts of the skull, particularly for subjects with severe facial or cranial asymmetry. Intraclass correlation coefficients were used to assess intraexaminer and interexaminer reliabilities of the x, y, and z coordinates of all landmarks measured by 2 investigators. **Results:** The intraclass correlation coefficient values were greater than 0.9, indicating almost perfect agreement. **Conclusions:** The candidate reference planes constructed using this novel method were thought to be reliable for 3D cephalometric analysis and may expand its clinical applicability in patients with cranial asymmetry. (Am J Orthod Dentofacial Orthop 2018;154:397-404)

Two-dimensional (2D) cephalometric analysis has played a crucial role in clinical measurements in orthodontics and craniofacial surgery since its introduction in 1931.[1] However, there are many disadvantages of 2D cephalometric analyses[2,3]: (1) blurred images by overlapped anatomic structures, (2) image distortion by rotation of the head and regional magnification, (3) limited parameters that can be measured, and (4) distortiaon of most measurements with facial asymmetry. Even cone-beam computed tomography (CBCT) synthesized cephalograms are difficult to accurately superimpose because of differences between the right and left sides, such as differences in scaling ratios, variations in head positioning, and overlapping of various cranial structures.[4] Three-dimensional (3D) cephalometric analysis has provided the ability to overcome the limitations of 2D cephalometrics and has also enabled a more accurate analysis of asymmetric structures, segmental movements using 3D digital operations, and comparisons of preoperative and postoperative facial profiles.[5] However, there is no international standard method for 3D cephalometric analysis; recent studies have focused on the identification of 3D cephalometric landmarks and the construction of 3D cephalometric reference frames.[2,3,6-8]

Determining the position of the midsagittal plane (MSP) practically is the most important aspect of 3D construction of a cephalometric reference frame. Recent studies have proposed several approaches to construct or determine the MSP. Most studies that used 3D computed tomography software have suggested the construction of the MSP by appointing 3 reference points: nasion, sella turcica, and basion,[9] or 2 midline structure points and making them perpendicular to a plane such as the

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Frankfort horizontal plane.[10] Grummons and Kappeyne van de Coppello[11] used a midsagittal line through crista galli and anterior nasal spine. Tuncer et al[12] used a plane through nasion, sella, and anterior nasal apine as the MSP for 3D analysis. Baek et al[13] used the most superior edge of the crista galli and the midpoint of the anterior clinoid processes to construct the MSP perpendicular to the Frankfort horizontal plane. These 3D cephalometric analyses relied on MSPs determined on the basis of midline structures; however, midline structures such as anterior nasal apine can deviate from the true plane of symmetry when there is asymmetry of the upper and midfacial skull regions. Nevertheless, all of these approaches have certain drawbacks and some kind of bias and cannot be applied to patients with skewed bones.[2] Three-dimensional analysis was selected because of its familiarity or feasibility based on traditional 2D cephalometric analyses; however, it is not yet known whether these planes are useful or accurate enough for 3D assessments of symmetry and patterns of dysmorphism.[14,15] Damstra et al[16] valuated 6 frequently used cephalometric MSPs described in the literature and concluded that these planes based on midline structures must be used extremely carefully for clinical diagnosis and treatment planning of craniofacial asymmetry because they might differ from the true plane of symmetry. Gateno et al[2] proposed a 3D external reference system, called the "global coordinate system," because these planes are easy to define and not altered by facial deformities or asymmetry. However, these planes are reliable only if the head is oriented in natural head posture, and it is difficult to ensure that each patient is in natural head posture during the CBCT scan. Damstra et al[16] used a morphometric method to determine the MSP, with visible facial anatomic landmarks in the supraorbital and nasal bridge regions as references for partial ordinary Procrustes analysis. Thus, the construction of the MSP for patients with orbital malformation may not be accurate.

The iterative closest point procedure, a 2-step algorithm wherein candidate correspondences and rotation and translation are updated until no change is observed in either, is a popular image registration algorithm[17] and is one of the most accurate methods for superimposition in the cranial base (excluding the peripheral zone).[18] For every point on a reference surface, the candidate correspondence is defined as the closest point on the target surface.[17] The iterative closest point is a perfect algorithm for a symmetric image. The normal human face and head have a rough symmetry. However, clinically, many patients exhibit facial bone asymmetry or even neurocranial bone asymmetry, and there is no consensus regarding the most symmetrical region of skull.[13] Most (>85%) of the cranial base growth is completed by about 5 to 6 years of age.[19,20] Hence, cranial base structures are good candidates to be used as reference points, and crista galli has generally been accepted as the midpoint of the cranium.[11,21] In traditional 2D analysis, superimposition using the anterior cranial base is used to visualize growth changes or changes due to orthodontic treatment.[22] Kwon et al[23] studied patients with dentofacial deformities; they reported no differences in the cranial base between the symmetric and asymmetric groups and concluded that structures of the cranial base were not the predominant factors that determined facial asymmetry.

Accordingly, this study was conducted to determine a more accurate MSP based on the anterior cranial base for visible facial asymmetry so that a stable reference frame of 3D cephalometric analysis can be constructed to assist orthodontic and orthognathic diagnosis and treatment.

MATERIAL AND METHODS

CBCT scans (NewTom 3G volumetric scanner; Aperio Services, Verona, Italy), with a field of view of 15 cm transversal × 15 cm anteroposterior × 15 cm height, and 0.3-mm slice thickness, from 12 adult patients were selected from past orthodontic records at the department of orthodontics of Peking University of Stomatology School in Beijing, China. They were divided into 2 groups: symmetry ($n = 6$) and asymmetry ($n = 6$). Cranial asymmetry was defined as greater than a 4-mm deviation in the chin (menton and pogonion) from the cranial midline.[21]

The study protocol was approved by the ethics committee for human experiments at the Peking University School and Hospital of Stomatology (PKUSSIRB-201520027).

Step 1: Construction of the MSP

After we obtained the CBCT images from the raw study data, the images were converted into DICOM format. Mimics (version 17.0; Magterialise, Leuven, Belgium), a commercially available third-party software, was used to obtain primary reconstructed images on multiplanar reconstruction (axial, coronal, and sagittal) views as well as 3D reconstructions of images for landmark recognition and location. Orientation of the head was reset by using interactive multiplanar reconstruction online reslicing. The anterior cranial base region (anterior wall of sella, anterior clinoid processes, planum sphenoidale, lesser wings of the sphenoid, superior aspect of the ethmoid and cribriform plates, cortical ridges on the medial and superior surfaces of the orbital roofs, and inner cortical layer of the frontal bones) was

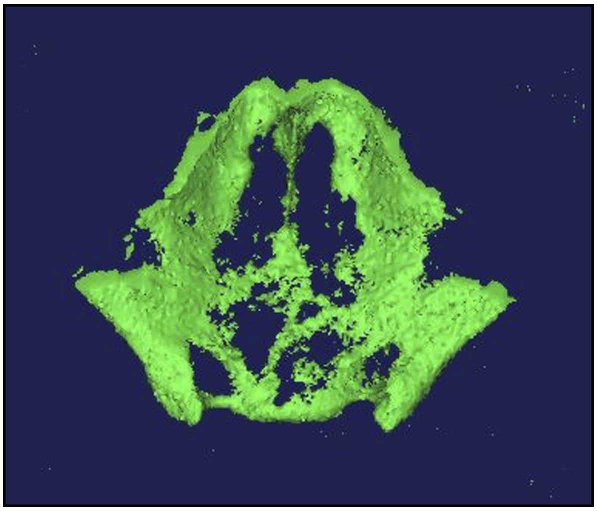

Fig 1. The 3D model of the anterior cranial base.

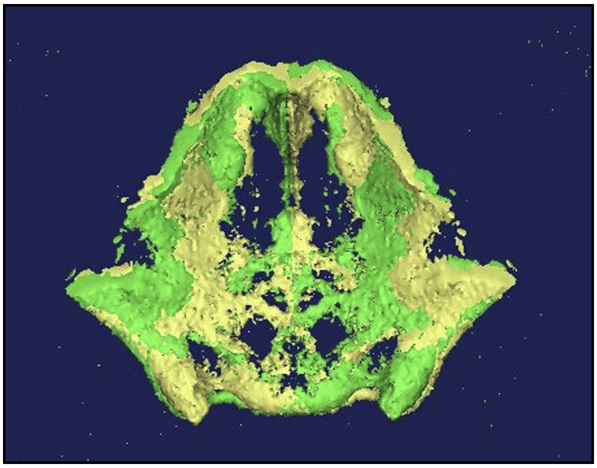

Fig 2. Three-dimensional models of the anterior cranial base (*green*) and its mirror model (*yellow*) based on the preliminary cephalofacial MSP, which is a plane passing through nasion, sella, and basion.

segmented, and 3D images were reconstructed to generate a 3D model of the anterior cranial base (Fig 1). A preliminary cephalofacial MSP was constructed passing through nasion, sella, and basion. Based on this plane, a mirror anterior cranial base was generated from the 3D anterior cranial base (Fig 2). Subsequently, the anterior cranial base model and its mirror model were constructed by global registration (Figs 3 and 4), and the position of the anterior skull base model could be fixed as before, whereas its mirror model was movable. The software program created the final MSP by constructing a plane through the middle of these anterior cranial base symmetrical configurations. Two

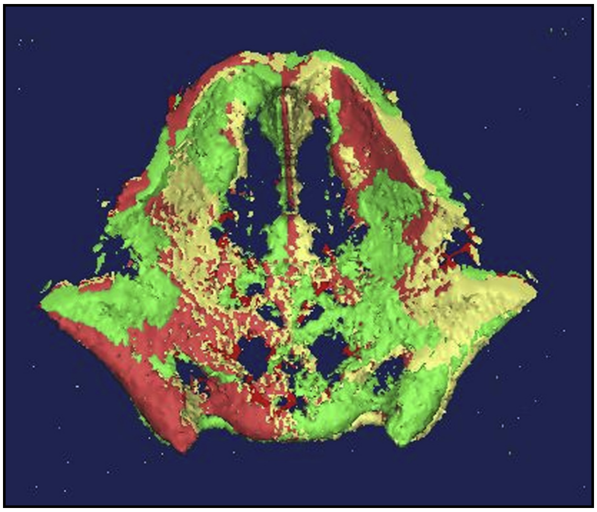

Fig 3. Global registration of the anterior cranial base model (*green*) and its mirror model (*yellow*). The position of the anterior skull base model (*green*) would be fixed as before, whereas its mirror model (*yellow*) would move to a new position (*red*) after global registration.

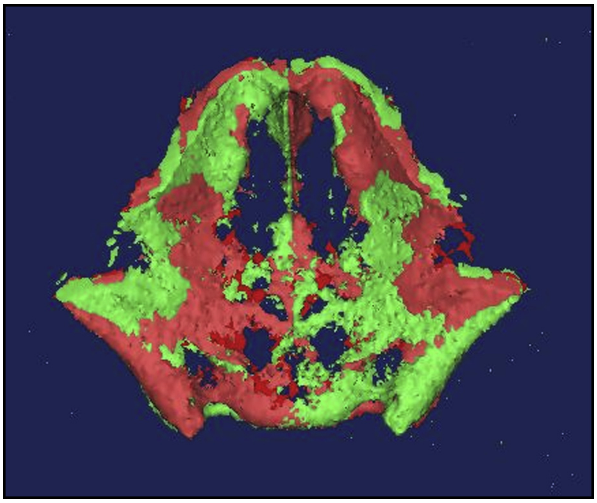

Fig 4. The final MSP is the plane through the middle of the symmetric configurations of the anterior cranial base.

investigators (D.Z., S.W.) entered the measurements and analysis interface, selected the Dada analysis method that was identified by 1 investigator (D.Z.), and selected the 3 most distant points on the plane of symmetry of the 2 models to determine the final MSP.

Step 2: Construction of the 3D coordinate system

The skull model was displayed in the multiplanar and 3D reconstruction views (Fig 5). Orbitale, porion on the

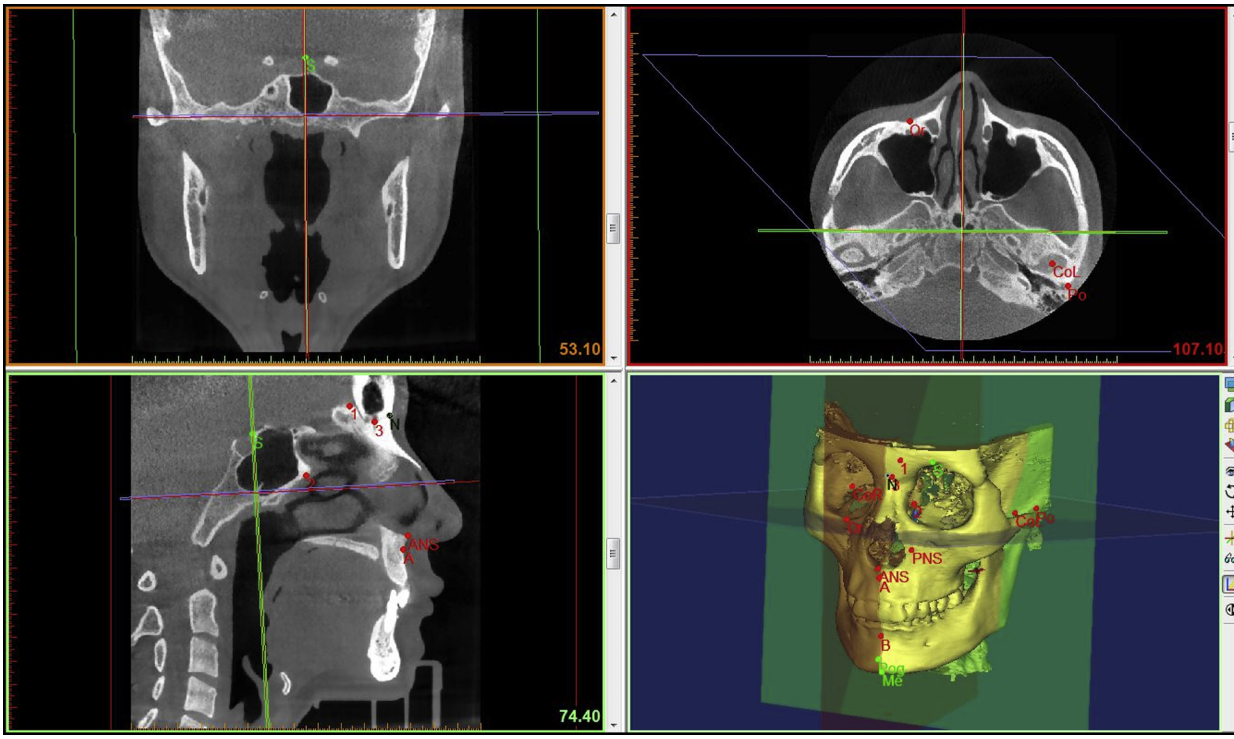

Fig 5. Investigators used the interactive multiplanar reconstruction until it overlapped the new reference system before landmark identification. The skull model was displayed in multiplanar reconstruction and 3D reconstruction views after landmark identification.

other side, and sella were identified, and the system automatically completed the establishment of the reference system. The Frankfort horizontal plane was defined as a plane perpendicular to the final MSP passing through orbitale and porion. The coronal plane passed through sella and was perpendicular to the Frankfort horizontal plane and the final MSP. The x-direction is in the Frankfort horizontal plane, the y-direction is in the coronal plane, and z-direction is in the final MSP.

Step 3: 3D-based identification

We first used the interactive multiplanar reconstruction function of the software to adjust the multiplanar windows. The investigators watched until they overlapped the reference system just constructed in the previous step. Subsequently, points A and B, anterior nasal spine, posterior nasal spine, menton, pogonion, left condylion, and right condylion were marked, and the system automatically provided coordinate values (x, y, and z) of each point in the 3D coordinate system.

Steps 1 through 3 was repeated twice each by 2 orthodontists (D.Z., S.W.) with a 2-week interval. Both examiners were previously trained in the use of the Mimics software and orthodontic landmark identification. For investigator blinding, the CBCT images were identified by code and analyzed in a random order.

Statistical analysis

Paired *t* tests were used for interexaminer comparisons of the mean coordinate values of each landmark in both groups. Intraexaminer reliability was assessed using intraclass correlation coefficients (ICC) of 2 measurements for each investigator. Moreover, ICC were used to calculate interexaminer reliability by comparing 1 investigator's average trial measurements with the corresponding measurements of the other. The ICC values ranged from 0 to 1; values from 0.61 to 0.8 indicated substantial agreement, and those from 0.81 to 1.0 indicated almost perfect agreement.[24] Statistical analysis was performed using SPSS software (version 20.0; IBM, Armonk, NY).

RESULTS

According to the paired *t* tests in the symmetry group, no significant differences were observed among the coordinate values of points A and B, anterior nasal spine, posterior nasal spine, menton, pogonion, left condylion, and right condylion recorded by both investigators using

Table I. Paired *t* test for comparing coordinate values (mm) of landmarks from the symmetry group between examiners 1 and 2

	Examiner 1		*Examiner 2*		
	Mean	*SD*	*Mean*	*SD*	P
ANSx	0.92	1.04	0.59	0.48	0.35
ANSy	64.55	3.46	64.01	3.02	0.15
ANSz	22.93	2.41	23.30	2.39	0.18
Ax	0.56	0.81	0.71	0.81	0.46
Ay	60.95	4.33	60.43	4.15	0.14
Az	30.21	1.62	30.57	1.60	0.12
Bx	0.06	2.14	0.00	2.08	0.92
By	56.37	5.23	55.67	5.77	0.22
Bz	72.91	7.70	73.13	7.91	0.76
CoLx	49.03	2.64	49.07	2.79	0.82
CoLy	10.30	3.31	10.73	3.07	0.06
CoLz	2.04	1.56	1.71	1.46	0.28
CoRx	48.68	2.04	48.77	1.62	0.16
CoRy	10.04	3.83	9.78	4.05	0.37
CoRz	3.31	2.34	2.98	2.20	0.35
Mex	−0.46	2.41	−0.14	2.14	0.56
Mey	51.83	5.25	50.60	5.80	0.14
Mez	90.47	6.50	90.76	6.44	0.19
PNSx	0.45	0.53	0.24	0.35	0.46
PNSy	17.15	2.24	16.66	1.67	0.16
PNSz	24.39	1.96	24.03	1.66	0.20
Pogx	−0.37	1.90	−0.18	2.04	0.72
Pogy	57.66	4.44	56.54	4.90	0.09
Pogz	82.74	6.42	82.99	7.05	0.65

Table II. Paired *t* test for comparing coordinate values (mm) of landmarks from the asymmetry group between examiners 1 and 2

	Examiner 1		*Examiner 2*		
	Mean	*SD*	*Mean*	*SD*	P
ANSx	1.55	0.62	1.69	0.72	0.19
ANSy	66.36	3.01	66.19	2.63	0.49
ANSz	26.32	2.99	26.04	3.26	0.42
Ax	0.49	1.80	0.53	1.85	0.76
Ay	64.22	3.20	64.07	2.85	0.60
Az	32.24	3.57	31.68	3.63	0.27
Bx	1.74	5.67	1.52	5.80	0.45
By	57.39	4.78	57.00	4.89	0.43
Bz	74.10	3.03	75.19	2.97	0.42
CoLx	50.13	117.58	49.98	3.27	0.67
CoLy	8.73	1.81	9.13	2.02	0.53
CoLz	0.98	0.57	0.61	0.91	0.10
CoRx	50.04	3.29	50.15	2.96	0.72
CoRy	9.00	1.80	8.98	1.78	0.87
CoRz	0.50	0.37	0.68	0.40	0.52
Mex	2.10	7.35	2.57	8.21	0.40
Mey	51.58	5.00	51.42	4.98	0.77
Mez	90.12	3.60	89.63	3.56	0.04
PNSx	0.62	1.49	0.45	1.00	0.59
PNSy	19.25	3.35	19.00	1.30	0.24
PNSz	24.69	2.30	23.96	2.25	0.00
Pogx	2.41	6.19	1.98	6.49	0.36
Pogy	57.87	5.32	57.57	5.46	0.59
Pogz	82.43	3.57	82.06	3.72	0.22

the 3D coordinate system ($P > 0.05$; Table I). Moreover, no significant differences were observed in the coordinate values of all landmarks in the asymmetry group, except for menton z value ($P = 0.04$) and posterior nasal spine z value ($P = 0$) (Table II).

The ICC values for intraexaminer and interexaminer reliabilities of the x, y, and z coordinates for all landmarks in the symmetry and asymmetry groups for both examiners were greater than 0.9, indicating almost perfect agreement (Table III). The final MSPs are shown in Figures 6 and 7.

DISCUSSION

The aim of this study was to determine the true MSP of the skull to establish a stable reference frame for 3D cephalometric analysis.

Based on the results, the coordinate values of almost all landmarks between the 2 examiners showed no statistically significant differences; this indicates that the MSPs constructed using our method are extremely stable and reliable. In addition, the reference frame created based on this MSP is universally accurate regardless of the presence or absence of facial symmetry.

Certain previous studies have suggested the use of morphometric methods to determine the MSP.[16] Most 3D computed tomography softwares use the iterative closest point procedure to accomplish the absolutely necessary step in the morphometric methods—registration. However, this algorithm has certain limitations. It focuses too much on local surface fitness and ignores global fitness; this results in reduced accuracy of the overall image. To overcome this limitation, the anterior cranial base region model and its mirror model were registered and used in our study to prevent any influence of symmetry on the registration of other parts of the skull, particularly for severely asymmetric facial bones. The investigators had to be careful to segment the anterior cranial base region, because the more lateral the structures included in this region, the greater potential impact on the resulting MSP. Thus, the clinical applicability of this new method for 3D cephalometric analysis can be expanded. The advantages of this method are that the accuracy of the MSP does not rely on the accuracy of other planes: eg, the Frankfort horizontal plane and the MSP are not influenced by maxillofacial deformities, orbital malformations, or even mild or moderate cranial asymmetry.

Table III. Intraclass correlation coefficients with 95% confidence intervals for intraexaminer and interexaminer agreements for coordinate values of all landmarks

	Examiner 1		*Examiner 2*		*Interexaminer*	
	ICC	*95% CI*	*ICC*	*95% CI*	*ICC*	*95% CI*
Symmetry group	0.999	0.999-0.999	0.997	0.994-0.998	0.996	0.992-0.998
Asymmetry group	0.999	0.999-1.000	0.999	0.998-0.999	0.988	0.977-0.994

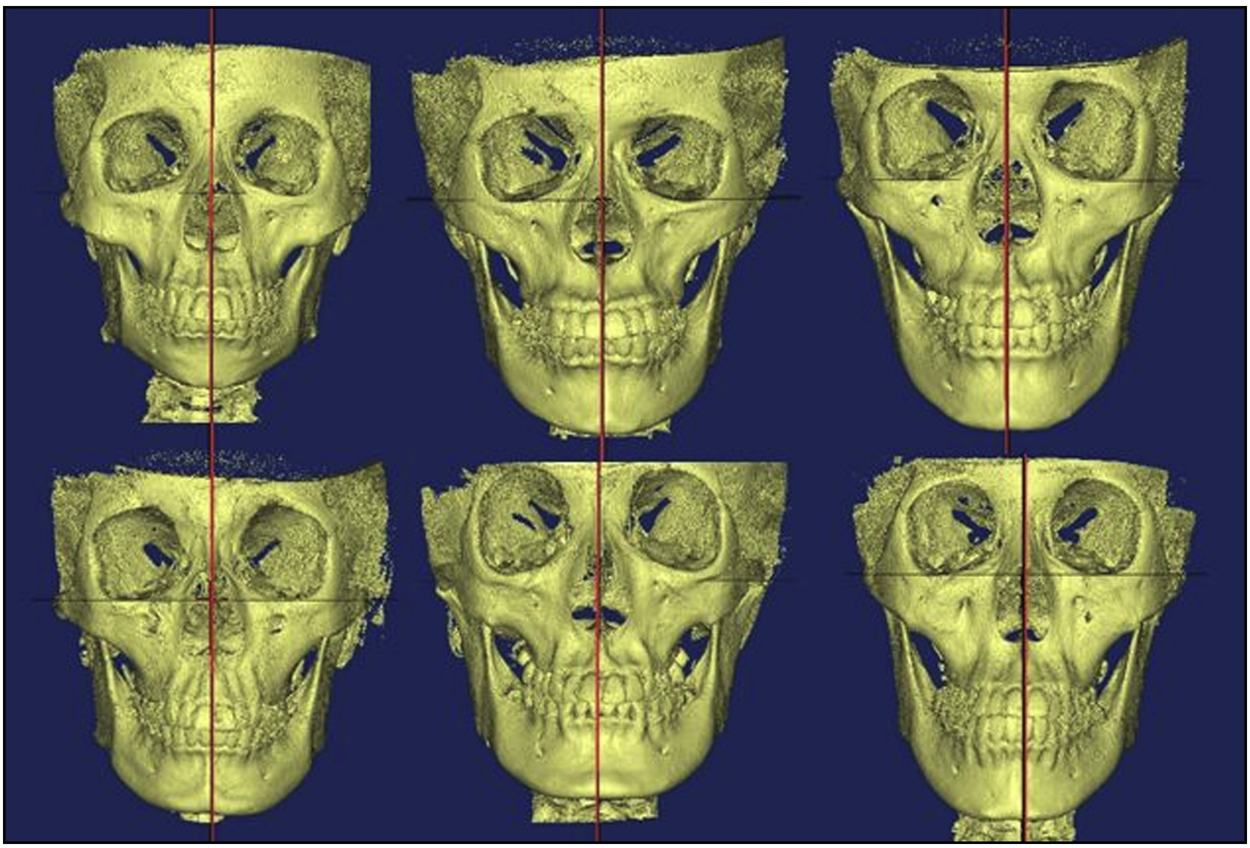

Fig 6. Frontal views of MSPs (*red lines*) in the symmetry group.

Neiva et al[8] affirmed that the frequency of highly reliable values in the identification of cephalometric landmarks with CBCT was greater in the visualization of multiplanar reconstruction compared with 3D image reconstructions because some errors may occur during the segmenting process of the 3D surface models. Moreover, to enhance the accuracy of identification of cephalometric landmarks in our study, the landmarks were plotted by visualizing both multiplanar reconstruction and volume-rendered views. The highly precise reference points of this experiment included sharp points such as anterior nasal spine and posterior nasal spine. The precision of landmark identification is subject-sensitive: a potential reason for this is that certain landmarks and bony structures are more difficult to visualize in CBCT scans of some patients, and image noise can be a critical issue in certain CBCT scans. To maximize the accuracy of landmark identification and minimize the errors, we selected landmarks of midline structures (points A and B, anterior nasal spine, posterior nasal spine, menton, and pogonion).

This study had a few limitations. Errors could have occurred during the reproduction procedure because the virtual head position is set manually according to the reference lines. Bone segmentation in CBCT is not as simple as in computed tomography, and this could be an additional source of error.[25] Hence, further research is warranted to define the precise parameters for error quantification in 3D volumetric images.[26]

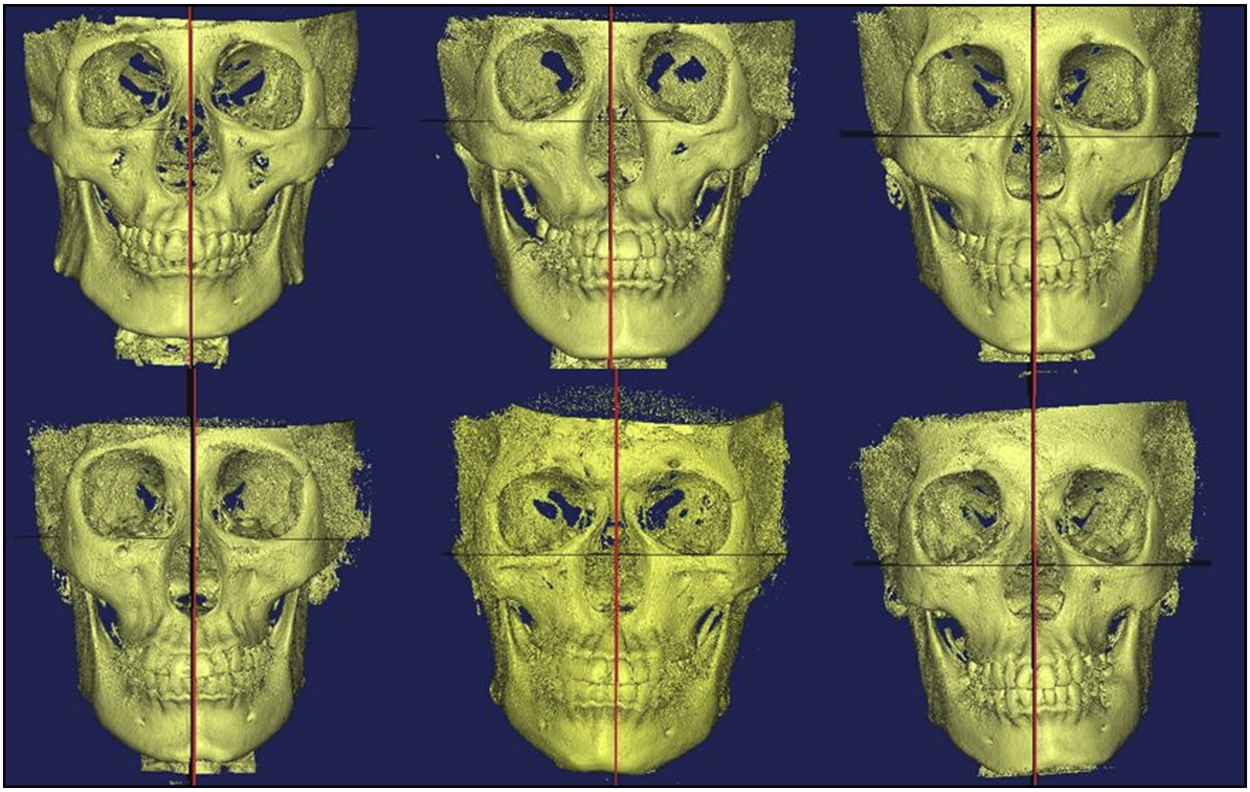

Fig 7. Frontal views of MSPs (*red lines*) in the asymmetry group.

Moreover, to determine the final MSP, we had to choose the 3 most distant points on the middle plane of symmetric configurations of the anterior cranial base with commercially available third-party software; this may have increased the possibility of inaccurate measurements. Nevertheless, we are working to develop a promising alternative algorithm or software that can overcome the need for appropriate landmark identification on the final MSP.

CONCLUSIONS

The candidate reference planes constructed using our method are thought to be reliable for 3D cephalometric analysis and may expand the clinical applicability of this method in patients with cranial or facial asymmetry.

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