

Evaluation of mandibular volume using cone-beam computed tomography and correlation with cephalometric values

Koshu Katayama^a; Tetsutaro Yamaguchi^b; Mami Sugiura^c; Shugo Haga^a; Koutaro Maki^d

ABSTRACT

Objective: To investigate the association between maxillofacial morphology and mandibular bone volume in patients with skeletal malocclusion.

Materials and Methods: Subjects were 118 adult Japanese (58 males and 60 females). Skeletal malocclusion was classified, based on cephalometric analysis, into skeletal Classes I ($-1^\circ \leq \text{ANB} < 4^\circ$), II ($\text{ANB} \geq 4^\circ$), and III ($\text{ANB} < -1^\circ$). Using cone-beam computed tomography and three-dimensional image analysis software, the dental crowns and mandible were separated, with only the mandible extracted. This was then reconstructed as a three-dimensional model, from which the mandibular volume was measured.

Results: No significant difference in mandibular volume was noted among skeletal Classes I, II, and III, nor was there any significant correlation between mandibular volume and the ANB, SNB, or mandibular plane angles. There was occasional and limited correlation between mandible volume and gonial angle and certain cephalometric distance parameters.

Conclusion: We conclude that proper understanding of the three-dimensional maxillofacial morphology requires not only cephalometric radiographic tracings but also high-resolution analysis of the mandibular area, width, and volume. (*Angle Orthod.* 2014;84:337–342.)

KEY WORDS: Cone-beam computed tomography (CBCT); Mandibular volume; Malocclusion; Maxillofacial morphology

INTRODUCTION

A plethora of environmental and genetic factors are involved in a complex interplay controlling maxillofacial morphological growth. Thus, in clinical orthodontics, an understanding of maxillary and mandibular growth is very important.¹ Occlusal pressure generated by the masticatory muscles influences mandibular size and morphology, notably affecting mandibular body length and ramus height.² It has also been reported³ that the

inclination of the masseter is involved in the mesiodistal growth of the mandible. Furthermore, the direction of growth is affected not only by the occlusal force but also by environmental factors such as orthodontic orthopedic treatment,^{4,5} parafunctional habits,⁶ and functional malocclusion.⁷ The involvement of genetic factors is illustrated by the similarity in facial growth patterns within families and the apparently race-dependent variation in the frequency of specific facial types within a population.¹

Recent advances in diagnostic imaging techniques have facilitated accurate three-dimensional computed tomography (CT) of maxillofacial morphology. The application of CT is limited in the dental field because the exposure dose is high and resolution in the axial direction is low. Cone-beam computed tomography (CBCT) for dental and maxillofacial use is useful because of its shortened scan time and high-resolution images, especially in the longitudinal direction. CBCT is used in various fields, including oral surgery, implant treatment, endodontics, periodontal treatment, treatment of temporomandibular joint disorder, pediatric dentistry, and orthodontics, and its benefits have been well documented.^{8–10}

^a Graduate student, Department of Orthodontics, School of Dentistry, Showa University, Tokyo, Japan.

^b Associate Professor, Department of Orthodontics, School of Dentistry, Showa University, Tokyo, Japan.

^c Research Assistant, Department of Orthodontics, School of Dentistry, Showa University, Tokyo, Japan.

^d Professor and Chairman, Department of Orthodontics, School of Dentistry, Showa University, Tokyo, Japan.

Corresponding author: Dr Koshu Katayama, Department of Orthodontics, School of Dentistry, Showa University, 2-1-1 Kitasenzoku, Ohta-ku, Tokyo 145-8515, Japan (e-mail: katayama@dent.showa-u.ac.jp)

Accepted: June 2013. Submitted: January 2013.

Published Online: July 18, 2013

© 2014 by The EH Angle Education and Research Foundation, Inc.

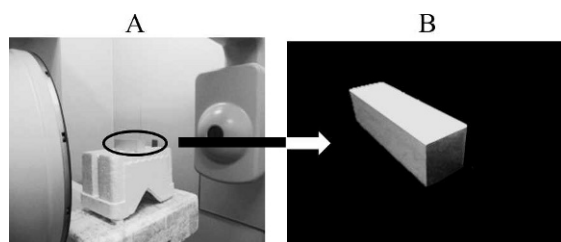


Figure 1. Validation of CBCT experimental conditions and measurement accuracy. (A) Aluminum block of known volume installed in CBCT device; (B) Enlargement of CBCT three-dimensional image of this block, acquired using optimized experimental parameters.

Increases in mandibular length, gonial angle, and mandibular plane angle are all characteristic maxillofacial morphological features of mandibular prognathism.¹¹ A significant difference was noted between the volumes of the bilateral heads of the mandible in patients with facial asymmetry.^{12,13} Regarding the relationship between mandibular volume and lateral cephalogram-based skeletal classification, an inverse correlation was noted only in ANB in dried Indian skulls,¹⁴ and no significant difference was noted among the skeletal classes in Japanese females,^{15,16} although the sample numbers in these reports were small. Moreover, neither the association between male mandibular volume and skeletal classification nor the correlation between mandibular volume and parameters of cephalometric analysis has been evaluated.

The objective of this study was to investigate the association between values derived from lateral cephalometry and the mandibular volume calculated from CBCT images.

MATERIALS AND METHODS

CBCT images and cephalograms were obtained from 58 Japanese men and 60 Japanese women. The subjects were patients at Showa University Dental Hospital. Those with congenital disorders (eg, cleft palate) or systemic disease were excluded from the sample. When the distance between the anterior nasal spine and the tip of the mental spine was 5.0 mm or greater in the axial image on CBCT multiplanar reconstruction, the morphology was judged as showing asymmetry, and the patient was excluded. This study was approved by the Showa University Dental Hospital Ethics Committee and related committees.

To analyze the craniofacial morphology, measurements were made on tracings of lateral cephalograms under standardized conditions and then computed with Power Cephalo software (ReazaNet, Tokyo, Japan). To evaluate the mandible, we measured four parameters for angle analysis (anteroposterior evaluation of the mandibular basal arch relative to the skull base [SNB angle]; anteroposterior relationship between the



Figure 2. Automated volume evaluation performed using Analyze image processing software. (A) The mandible was scanned and viewed using CBCT; (B) Segmentation threshold was adjusted; and (C) Ideal threshold values were determined. Total volume was quantified by automated segmentation of the artificial defect.

maxilla and mandibular basal arch [ANB angle]; mandibular plane angle [Mp]; and gonial angle [Go]; all measured in degrees) and three items for distance analysis (Gnathion-Condylion [Gn-Cd]; Pogonion'-Gonion [Pog'-Go]; and Condylion-Gonion [Cd-Go]; all measured in millimeters). The maxillofacial morphology was classified (based on ANB) into skeletal Classes I ($-1^{\circ} \leq \text{ANB} < 4^{\circ}$), II ($\text{ANB} \geq 4^{\circ}$), and III ($\text{ANB} < -1^{\circ}$). Nineteen males and 20 females were Class I, 20 males and 20 females were Class II, and 19 males and 20 females were Class III.

Images were acquired using a cone-beam X-ray CT system for dental and maxillofacial use (CB MercuRay, Hitachi Medico Technology, Tokyo, Japan) installed at the dental hospital radiology department of our University. Subjects were positioned with the Frankfort plane parallel to the floor. The scanning conditions were 100 kVp, 10 mA, F-mode 512 slices/scan (slice width: 377 μm), and 9.6-second acquisition time. Data obtained were reconstructed using Analyze three-dimensional reconstruction software (Biomedical Imaging Resource, Mayo Clinic and Foundation, Rochester, Minn).

In a preliminary experiment, CBCT was performed using an aluminum bar ($30 \times 30 \times 100.5 \text{ mm}$) under the same imaging conditions to examine the errors of volume measurements (Figure 1). Volumetry was performed using Analyze image processing software. The window of the Analyze region of interest (ROI) was displayed, thresholds were specified to define the area within the contour of the aluminum bar in all horizontal slice images, and autotracing was performed. An object map was prepared by overlapping the autotraces, allowing construction of three-dimensional images and completion of volumetry analysis.

For extraction of the mandible, we used Analyze image processing software (Biomedical Imaging Resource, Mayo Clinic and Foundation). The thresholds of the area within the perimeter of the mandibular cortex were determined on all slides, and the mandibular contour was autotraced. An object map was prepared by superimposing the autotraces to create a three-dimensional image, from which the volume was measured (Figure 2). Since separation of the upper and lower dental crowns is difficult as a

Table 1. Means and Standard Deviations (SDs) of the Measurements from Cone-Beam Computed Tomography (CBCT) and Lateral Cephalogram Analysis^a

	Males (n = 58)		Females (n = 60)	
	Mean $\pm$ SD	Range	Mean $\pm$ SD	Range
Mandibular volume, mm ³	63,235.2 $\pm$ 10,169.6	40,048.2 to 87,848.4	55,923.5 $\pm$ 9080.4	39,799.2 to 85,793.6
Class I, mm ³	60,682.1 $\pm$ 10,954.8	45,935.7 to 79,048.1	54,058.8 $\pm$ 7489.7	39,799.2 to 68,357.7
Class II, mm ³	65,618.7 $\pm$ 8534.7	50,996.2 to 79,565.7	58,448.5 $\pm$ 10,664.9	43,340.4 to 85,793.6
Class III, mm ³	61,752.9 $\pm$ 10,765.5	40,048.2 to 87,848.4	55,263.2 $\pm$ 8682.0	40,048.2 to 78,220.6
SNB, °	80.7 $\pm$ 5.6	69.1 to 96.2	79.3 $\pm$ 5.1	67.0 to 90.3
ANB, °	1.3 $\pm$ 4.3	−9.4 to 9.9	1.3 $\pm$ 4.2	−8.6 to 9.1
Mp, °	28.3 $\pm$ 5.2	17.1 to 41.0	30.2 $\pm$ 5.7	18.0 to 42.9
Go, °	126.5 $\pm$ 7.6	110.33 to 143.6	126.5 $\pm$ 7.2	113.5 to 140.8
Gn-Cd, mm	133.2 $\pm$ 8.5	117.5 to 151.2	123.6 $\pm$ 7.2	110.9 to 145.8
Pog'-Go, mm	84.1 $\pm$ 5.1	71.9 to 93.4	80.7 $\pm$ 5.0	71.6 to 94.8
Cd-Go, mm	67.8 $\pm$ 5.0	54.2 to 85.7	60.3 $\pm$ 5.2	50.8 to 73.9

^a n indicates number of subjects.

result of artifacts, dental crowns and the mandible were separated, and only the mandible was extracted. One investigator evaluated all cephalograms and CBCT measurements.

One-way analysis of variance was employed to compare the mandibular volume among the three classes of maxillofacial morphology. To investigate the relationship between the mandibular measurement parameters and mandibular volume, simple regression analysis and the Pearson's correlation coefficient test were performed, with the significance level set at 5%. To investigate operator errors, the mandibular volumes of five randomly selected samples were measured twice on different days, and the errors were tested using Dahlberg's formula. Statistical analysis was performed using Statcel2 statistical analysis software (OMS Publishing, Saitama, Japan).

RESULTS

The error (discrepancy between the values measured using image processing software and the actual

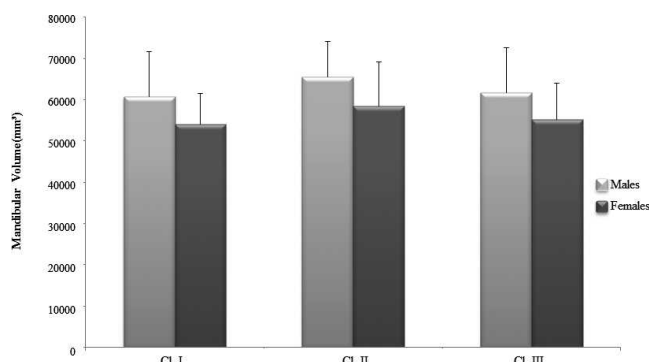


Figure 3. Mandibular volumes in the three skeletal patterns (Classes I, II, and III) by gender. Shown are the calculated mandible volumes of 58 male and 60 female Japanese, subclassified according to their skeletal maxillomandibular relationship. Volumes are expressed as mm³. Error bars denote the standard deviation.

volume) was 0.23%. The intraobserver measurement errors ranged from 1.3% to 2.4% for volumetric measurements. The means, standard deviations, and maximum and minimum values of the cephalometric and CBCT measurement parameters are shown in Table 1.

Figure 3 shows a comparison of the mandibular volumes in the three maxillofacial morphological classes. No significant difference was noted between males and females in any of these groups ($P > .05$).

The results of correlation analysis between the measured values of the mandibular morphology and mandibular volume are shown in Table 2. There was a significant correlation between mandibular volume and Go in male subjects ($P < .05$). Furthermore, analysis of cephalometric distances revealed significant positive correlations between mandibular volume and Pog'-Go in males and between mandibular volume and both Cd-Go and Gn-Cd in females.

DISCUSSION

Our results showed no significant association between mandibular volume and skeletal classification and only a weak correlation with isolated cephalometric values.

Table 2. Regression Analyses between Mandibular Morphology and Volume^a

	Male		Female	
	<i>r</i>	<i>P</i> -Value	<i>r</i>	<i>P</i> -Value
SNB	−0.10	.44	0.20	.11
ANB	0.15	.25	0.05	.68
Mp	−0.01	.99	−0.24	.07
Go	−0.27	.04*	0.03	.82
Gn-Cd	0.20	.13	0.36	.004**
Pog'-Go	0.37	.004**	0.19	.15
Cd-Go	0.29	.03*	0.44	.0004***

^a *r* indicates correlation coefficient.* $P \leq 0.05$; ** $P \leq 0.01$; *** $P \leq 0.001$.

The accuracy of CBCT was verified using an aluminum block in the preliminary experiment. The relative error of the values on CBCT from the actual volume was 0.2% (relative error [%] = [(value on CBCT – actual value)/actual value] × 100). Pinsky et al.¹⁷ investigated the accuracy of volume measurement by CBCT using an acrylic block and found the error to be 2% of the actual volume. The values recorded here are an order of magnitude lower, demonstrating the superior accuracy of our volume measurements using CBCT.

Separation of the upper and lower dental crowns is problematic owing to artifacts, so the dental crowns and mandible in the CBCT image were separated, and the mandible was extracted as reported by Ilknur et al.,¹³ Nair et al.,¹⁵ and Deguchi et al.¹⁶ Cortical bone comprising many lamellar structures forms the outer region of bone and was used here as the outer circumference of the mandible for our measurements. Cancellous bone has a trabecular pattern containing many reticular spaces in the inner region. The trabecular thickness is 100–150 µm. However, the voxel size of the acquired CBCT data was 0.376 mm, and the spatial resolution was 0.75 mm in an isotropic direction, making detection of trabeculae challenging. Thus, we calculated the total volume of the mandible, using the cortical bone to demarcate its perimeter. The mandibular volume was measured with the dental roots remaining in the mandible. The average mandibular volume was reported by Ilknur et al.¹³ to be 56.3 cm³. When subclassified into skeletal Class I and Class II relationships, these volumes were 60.0 and 51.6 cm³, respectively, according to a report from Hashiba,¹⁴ and 46.0 and 38.6 cm³ in two reports by Nair et al.¹⁵ and Deguchi et al.,¹⁶ illustrating appreciable variation between investigators. In the present study, the average mandibular volume was 63.2 cm³ in males and 55.9 cm³ in females. The voxel value on CBCT is not an absolute value, unlike the CT value on systemic CT, but it is a relative value representing bone density.¹⁸ When segmentation of an object is performed with different thresholds, the threshold values must be changed.¹⁹ For example, since the bone density is low and multiple bones overlap in the mandibular head region, segmentation is more difficult than in other regions.²⁰ In this study, the mandible was displayed in the Analyze ROI window, and the thresholds for the area within the perimeter of the mandibular cortex were defined on all slides. The border between cortical bone and soft tissue was clear, and the perimeter of the mandibular cortex could be traced.²¹

Hashiba¹⁴ reported that the mandibular volume was significantly larger in skeletal Class I than in Class II, whereas Deguchi et al.¹⁶ observed no significant

differences among the maxillofacial morphology classifications in 30 adult female Japanese. Our findings in 58 adult male and 60 female Japanese were similar to those reported by this latter study. To investigate whether specific cephalometric features are correlated with mandibular volume and maxillofacial morphology, we performed regression analysis, but we found no significant difference in the mandibular volume in relation to any of the angle analysis parameters representing the positional relationship, confirming the conclusions of Hashiba¹⁴ that the angles are not directly correlated to the size or volume of the mandible.

Hashiba also reported a significant positive correlation between Ar-Go (which represents the ramus length on lateral cephalography) and total mandible volume but also that the ramus length was most highly correlated to the mandibular body volume, whereas its correlation with the ramus volume was weaker.¹⁴ We observed a positive correlation between mandibular volume and certain cephalometric distance parameters in both genders, but the correlation coefficients were only 0.01–0.44, indicating that the correlation was weak. Thus, we conclude that values derived from two-dimensional figures cannot adequately substitute for values from three-dimensional images.

The craniofacial region is one of the most complex regions of the human skeleton and is thus challenging to analyze. Cephalograms are used to describe the morphology and growth of the craniofacial complex and to predict growth, develop treatment plans, and evaluate treatment outcomes. Their main drawback is radiographic projection error, which can magnify or distort the geometric relationships displayed in the image.²² Reliable and accurate evaluation is difficult because of this inherent geometric magnification, distortion, and superimposition of craniofacial structures.^{23–27} The use of cephalometry as an adjunct to clinical examination as a basis for predicting craniofacial growth is thus questionable.^{28,29} Imaging is increasingly favored for perceiving the size and form of craniofacial structures in orthodontics and has the advantage of replicating anatomical detail accurately in three dimensions.

The mandible is a complex three-dimensional structure.³⁰ Our research suggested that cephalometric analysis as a perspective chart cannot represent a real mandible. The mandible changes its morphology depending on its dynamic environment and forms trabeculae to achieve maximum strength with minimum material according to biodynamic principles.³¹ In addition to conventional two-dimensional and serial cephalography, the study of changes in the mandibular volume could be invaluable in exploring the mechanisms that control mandibular morphogenesis during

the growth process and in evaluating the effects of orthopedic and orthodontic treatments. If quantitative measurements can be made in a larger number of dimensions, the evaluation of the relationship between quantitative and qualitative changes may be expedited, contributing to better clinical diagnosis and treatment selection.

CONCLUSIONS

- Mandibular volumes among skeletal Classes I ($-1^\circ \leq \text{ANB} < 4^\circ$), II ($\text{ANB} \geq 4^\circ$), and III ($\text{ANB} < -1^\circ$) are not significantly different.
- A significant (albeit weak) correlation was noted between mandibular volume and both cephalometric distance parameters and the gonial angle.

ACKNOWLEDGMENTS

We are deeply grateful to the people participating in this study. The authors thank Hitoshi Fukase and Ryosuke Kimura for their help. This work was supported by the Japan Society for the Promotion of Science–KAKENHI (Grant-in-Aid for Scientific Research [B] 22390393) (Dr Yamaguchi) and by the Ministry of Education, Culture, Sports, Science and Technology (MEXT)–Supported Program for the Strategic Research Foundation at Private Universities, 2012–2017.

REFERENCES

1. Moyers RE. Handbook of orthodontics. In: Enlow DH, ed. *Growth of the Craniofacial Skeleton*. Chicago, Ill: Year Book Medical Publishers; 1973:51–117.
2. Ringqvist M. Isometric bite force and its relation to dimensions of the facial skeleton. *Acta Odont Scand*. 1973;31:35–42.
3. Sassouni V. Orthodontics in dental practice. In: Sassouni V, ed. *Facial Types and Malocclusions*. St Louis, Mo: CV Mosby Company; 1971:121–144.
4. Peter DW, Ravindra N, Sakamoto T, Nakamura S. The effects of chin cup therapy on the mandible: a longitudinal study. *Am J Orthod*. 1985;87:265–274.
5. Jose AA, Markus B, Antonio R, Julia M. Chincup treatment modifies the mandibular shape in children with prognathism. *Am J Orthod Dentofacial Orthop*. 2011;140:38–43.
6. Moore MB, McDonald JP. A cephalometric evaluation of patients presenting with persistent digit sucking habits. *Br J Orthod*. 1997;24:17–23.
7. Chris VK, Guy M, Luc D. Unilateral posterior crossbite and chin deviation. *Eur J Orthod*. 2004;26:283–288.
8. Maki K, Inou N, Takanishi A, Miller AJ. Computer-assisted simulations in orthodontic diagnosis and the application of a new cone beam X-ray computed tomography. *Orthod Craniofac Res*. 2003;6:95–101.
9. Yamamoto K, Ueno K, Seo K, Shinohara D. Development of dento-maxillofacial cone beam X-ray computed tomography system. *Orthod Craniofac Res*. 2003;6:160–162.
10. Araki K, Maki K, Seki K, et al. Characteristics of a newly developed dentomaxillofacial X-ray cone beam CT scanner (CB MercuRay™): system configuration and physical properties. *Dentomaxillofac Radiol*. 2004;33:51–59.
11. Chang HP, Liu PH, Yang YH, Lin HC, Cang CH. Craniofacial morphometric analysis of mandibular prognathism. *J Oral Rehabil*. 2006;33:183–193.
12. You KH, Lee KJ, Lee SH, Baik HS. Three-dimensional computed tomography analysis of mandibular morphology in patients with facial asymmetry and mandibular prognathism. *Am J Orthod Dentofacial Orthop*. 2010;138:540.e1–540.e8.
13. Ilknur V, Tancan U, Torun O, Faruk IU, Murat E. Mandibular asymmetry in unilateral and bilateral posterior crossbite patients using cone-beam computed tomography. *Angle Orthod*. 2011;81:966–974.
14. Hashiba C. A study of craniomaxillofacial morphology by X-ray computed tomography [in Japanese]. *Shigaku*. 1987;75: 865–906.
15. Nair R, Deguchi T, Li X, Katashiba S, Chan Yh. Quantitative analysis of the maxilla and the mandible in hyper- and hypodivergent skeletal Class II pattern. *Orthod Craniofac Res*. 2009;12:9–13.
16. Deguchi T Sr, Katashiba S, Inami T, Foong KWC, Chan YH. Morphologic quantification of the maxilla and the mandible with cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2010;137:218–222.
17. Pinsky HM, Dyda S, Pinsky RW, Misch KA, Sarment DP. Accuracy of three-dimensional measurements using cone-beam CT. *Dentomaxillofac Radiol*. 2006;35:410–416.
18. Naitoh M, Hirukawa A, Katsumata A, Aiji E. Evaluation of voxel values in mandibular cancellous bone: relationship between cone-beam computed tomography and multislice helical computed tomography. *Clin Oral Implants Res*. 2009; 20:503–506.
19. Liu Y, Olszewski R, Alexandroni ES, Enciso R, Xu T, Mah JK. The validity of in vivo tooth volume determinations from cone-beam computed tomography. *Angle Orthod*. 2010;80: 160–166.
20. Engelbrecht WP, Fourie Z, Damstra J, Gerrits PO, Ren Y. The influence of the segmentation process on 3D measurements from cone beam computed tomography-derived surface models. *Clin Oral Invest*. 2013 Jan 31.
21. Ullrich CG, Binet EF, Sanecki MG, Kieffer SA. Quantitative assessment of the lumbar spinal canal by computed tomography. *Radiology*. 1980;134:137–143.
22. Chidiac JJ, Shofer FS, Al-Kutoub A, Laster LL, Ghafari J. Comparison of CT scanograms and cephalometric radiographs in craniofacial imaging. *Orthod Craniofac Res*. 2002; 5:104–113.
23. Adams GL, Gansky SA, Miller AJ, Harrell WE Jr, Hatcher DC. Comparison between traditional 2-dimensional cephalometry and a 3-dimensional approach on human dry skulls. *Am J Orthod Dentofacial Orthop*. 2004;126:397–409.
24. Moshiri M, Scarfe WC, Hilgers ML, Scheetz JP, Silveira AM, Farman AG. Accuracy of linear measurements from imaging plate and lateral cephalometric images derived from cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2007;132:550–560.
25. Lamichane M, Anderson NK, Rigali PH, Seldin EB, Will LA. Accuracy of reconstructed images from cone-beam computed tomography scans. *Am J Orthod Dentofacial Orthop*. 2009;136:156.e1–156.e6.
26. Gribel BF, Gribel MN, Frazão DC, McNamara JA Jr, Manzi FR. Accuracy and reliability of craniometric measurements on lateral cephalometry and 3D measurements on CBCT scans. *Angle Orthod*. 2011;81:26–35.
27. Olmez H, Gorgulu S, Akin E, Bengi AO, Tekdemir I, Ors F. Measurement accuracy of a computer-assisted three-dimensional analysis and a conventional two-dimensional method. *Angle Orthod*. 2011;81:375–382.

28. Bookstein FL. The geometry of craniofacial growth invariants. *Am J Orthod*. 1983;83:221–234.
29. Moyers RE, Bookstein FL. The inappropriateness of conventional cephalometrics. *Am J Orthod*. 1979;75:599–617.
30. Maki K, Inou N, Takanishi A, Miller AJ. Modeling of structure, quality, and function in the orthodontic patient. *Orthod Craniofac Res*. 2003;6:179–182.
31. Wolff J. *The Law of Bone Remodeling*. Berlin, Germany: Springer Publishers; 1986.