Original Article

The use of SPHARM-PDM and mean latitude axis to evaluate airway changes

Tung Nguyen[a]; Ceib Phillips[b]; Beatriz Paniagua[c]

ABSTRACT

Objective: To introduce new 3-D imaging techniques to characterize shape and volume changes of the oropharyngeal space after bilateral sagittal split osteotomy (BSSO) advancement.

Materials and Methods: Longitudinal cone-beam computed tomography (CBCT) scans were obtained for 20 patients undergoing BSSO advancement at three time points (T1 = presurgery, T2 = splint removal, and T3 = 1 year after surgery). Segmentation of the airway was performed using the following boundaries: hard palate/posterior nasal spine superiorly and lower border of C3 to the base of the epiglottis inferiorly. For shape measurements, point-based correspondent models and mean latitude axis were obtained for all the data using SPHARM-PDM software. All 3-D correspondent models were rigidly registered using Procrustes alignment. Absolute distance maps and corresponding vector maps were calculated to show shape and vector differences between each correspondent point. Mean latitude axis is a new imaging method to calculate minimum cross-sectional areas along the long axis of the airway independent of head position/alignment.

Results: The airway volume increased ($P < .01$) after BSSO advancement (2973.9 mm^3 $\pm$ 27882.0) and was stable (–439.9 mm^3 $\pm$ 3308.8) 1 year post-op. 3-D color maps and semitransparency overlays showed more lateral than anteroposterior expansion of the airway after BSSO advancement. Mean latitude axis was used to measure minimum cross-sectional area, showing a statistically significant increase (52.7 mm^2 $\pm$ 46.7) ($P < .01$) after surgery and remained stable (–10.3 mm^2 $\pm$ 43.3) 1 year after surgery.

Conclusions: SPHARM-PDM and mean latitude axis are useful tools to assess airway shape change. BSSO advancement produces a significant increase in pharyngeal airway volume and minimum cross-sectional area. The airway space increased more transversely than anteroposteriorly. (*Angle Orthod.* 0000;00:000–000.)

KEY WORDS: 3-D imaging; BSSO; Airway

INTRODUCTION

It is estimated that 3% of the US population has severe dentofacial deformities requiring orthognathic surgery.[1] For the Class II mandibular deficient patient, bilateral sagittal split osteotomy (BSSO) surgery is used to advance the mandible to correct skeletal disharmony, improve dental malocclusion, and enhance the soft tissue profile. In addition to skeletal, dental, and soft tissue changes, BSSO advancement has been shown to increase airway space for patients with severe obstructive sleep apnea (OSA).[2–4]

The effect of orthognathic surgery on airway volume has long been a topic of investigation. Some studies have shown that BSSO advancement and maxillomandibular advancement (MMA)[4–7] can increase upper airway volume, while others report limited changes.[8,9] Conflicting results in the literature exist because most of these studies were conducted using two-dimensional cephalometry to analyze a 3-D volume. The emergence of cone-beam computed tomography (CBCT) has brought new life to this area of research. CBCT imaging allows for accurate and repeatable 3-D

[a] Associate Professor, Department of Orthodontics, School of Dentistry, University of North Carolina, Chapel Hill, NC.
[b] Professor and Assistant Dean for Graduate/Advanced Education, School of Dentistry, University of North Carolina, Chapel Hill, NC.
[c] Research Assistant Professor, Department of Psychiatry and Computer Science, University of North Carolina, Chapel Hill, NC.
Corresponding author: Dr Tung Nguyen, Associate Professor, Department of Orthodontics, UNC School of Dentistry, CB#7450, Chapel Hill, NC 27599-7450
(e-mail: cara_134@hotmail.com)

Accepted: March 2016. Submitted: November 2015.
Published Online: May 3, 2016

Table 1. Demographic and Descriptive Statistics of BSSO Sample

	Age, y	ANB	Initial OJ	Surgical Movement (mm)
Mean	25.60	6.50	7.56	4.98
SD	4.12	1.54	2.70	2.36

airway measurements.[10,11] While volumetric measurements give a better estimate of the true dimensions of the airway, the minimum cross-sectional area is an important factor in diagnosing OSA.[12–14] A recent study by Mattas et al. showed that volumetric and linear measurements performed using CBCT are highly accurate, but cross-sectional measurements at the level of the vallecula and minimum cross-sectional area were unreliable.[15]

The purpose of this study was to use new 3-D techniques to evaluate corresponding shape and minimum cross-sectional area changes of the oropharynx after BSSO advancement.

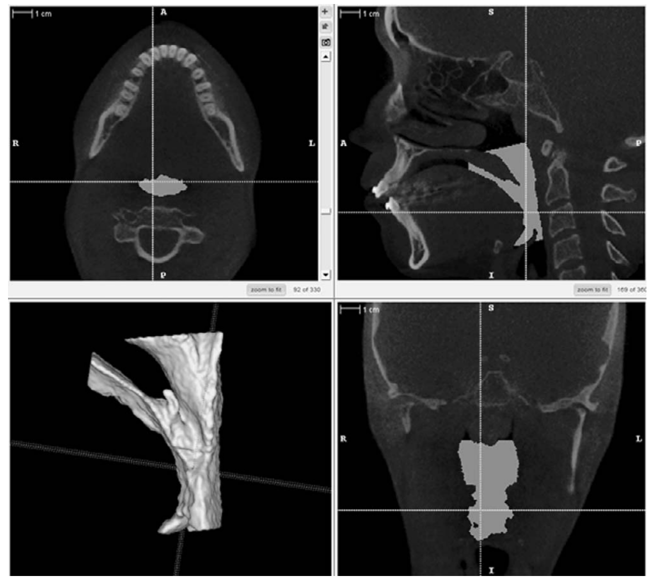

Figure 1. Image of a Class II patient and segmented airway. The superior border was defined by a plane connecting the posterior nasal spine and basion, while the inferior border was defined by a plane passing through the base of the epiglottis and inferior border of C3.

MATERIALS AND METHODS

Subjects

Twenty consecutive patients (16 females, 4 males, mean age 25.6 years) from the surgical stability database who received BSSO advancement at the University of North Carolina were selected for this study. No new CBCTs were taken for this study. The Institutional Review Board of the University of North Carolina approved the study, and all participants signed an informed consent agreement. All subjects had a skeletal Class II (ANB = 6.50° ± 1.54) jaw relationship with increased overjet (7.56 mm ± 2.70) (Table 1). Patients with craniofacial syndromes, asymmetries, disharmonies due to trauma, and genioplasty performed during surgery were excluded from the study.

Image Acquisition

CBCT images were acquired immediately before surgery (T1), after splint removal at 4–6 weeks post-op (T2), and 1 year post-op (T3) using the New Tom 3G (AFP Imaging, Elmsford, NY). The imaging protocol involved a 30-second scan time with a 12-inch field of view. All CBCT scans were acquired in centric occlusion in the supine position with a voxel resolution of $0.3 \times 0.3 \times 0.3$ mm. CBCT files were deidentified by conversion to GIPL format.

Segmentation

Semiautomatic airway segmentations were completed for using open-source software ITK-SNAP 2.4 (http://www.itksnap.org). The borders of the oropharyngeal space were defined superiorly by a plane passing the anterior and posterior nasal spine and hard palate and inferiorly by a plane passing through the lower border of C3 to the base of the epiglottis (Figure 1). 3-D airway models were generated from the segmentations, and airway volumes were calculated from these models. T1, T2, and T3 models were registered using Procrustes alignment.

Shape and Volume Analysis

SPHARM-PDM (open-source, http://www.nitrc.org/projects/spharm-pdm) toolbox are comprehensive tools designed to compute 3-D structural statistical shape analysis[16,17] and was used in this study to identify regions of the airway most affected by mandibular advancement. The segmented airway models were first processed to ensure spherical topology, then converted to surface meshes using the marching- cubes approach. Spherical parameterization was computed from the surface meshes using area-preserving, distortion-minimizing spherical mapping. The SPHARM description was then computed from the mesh and its spherical parameterization. A total of 4002 corresponding surface points from the SPHARM description were generated for the longitudinal airway models. Vector maps were created to provide visualization of displacements between paired correspondent points, indicating the direction and magnitude of displacements.

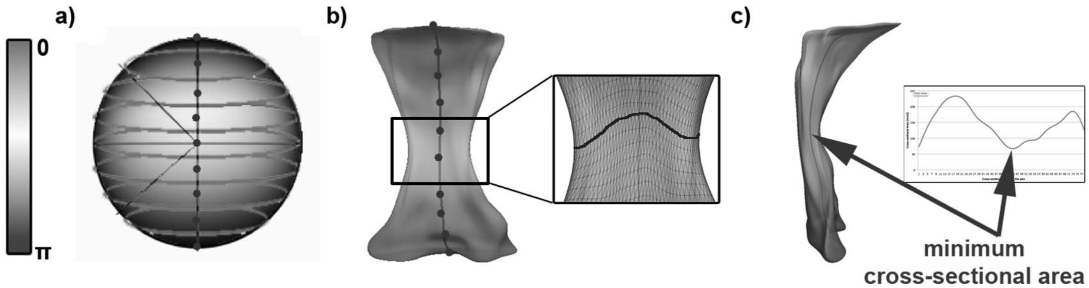

Figure 2. Mean latitude axis was used to calculate minimum cross-sectional area. (a) Theta parametric field where north pole = 0 and south pole = π. (b) Anterior view of the SPHARM medial mesh of our representative patient airway. The close-up shows the isolatitude lines (highlighted bold black lines). (c) Lateral view of the airway with corresponding cross-sectional chart.

Mean latitude axis is a new imaging method used to calculate minimum cross-sectional areas along the long axis of the airway independently of head position or alignment.[18] It utilizes boundary descriptions and shaped-constraint points correspondence defined from SPHARM-PDM computed models to calculate the most constricted area along a tubular volume (Figure 2). This idea was initially proposed by Kim et al.[19] However, our methodology differs due to the manner in which the mean medial axis is computed. After calculating a parameterization of all points of the initial 3-D voxel mesh, we computed a medial mesh by dividing the theta (θ) parametric field (Figure 2a) by values between 0 and π a fixed number of times, as specified by the user, called theta iterations. A number of theta iterations isolatitude lines were then placed at equally valued latitudes on the new SPHARM Mesh. A number of points (called phi iterations) were placed along the isolatitude lines (Figure 2b). The resulting new medial mesh incorporated both the theta and phi iterations along the vertices. The 3-D mean latitude axis was calculated by averaging all points along each isolatitude line to create a true geometric center within the tubular structure. Cross-sectional areas were calculated for each point along the mean latitude axis, using the plane defined by the point on the axis and all the points along its corresponding isolatitude (Figure 2c).

Statistical Analysis

Data analysis was conducted using SAS 9.3 (SAS Institute Inc, Cary, NC). One sample signed rank sum test was used to test whether differences between longitudinal time points were significant. The *P* values were adjusted by Hommel's method, and significance was set at .05.

Repeated measurements on 20 randomly selected time points were made after 1 week by an examiner, and intraexaminer correlation coefficients (ICCs) using a two-way mixed effect model were used to evaluate the reliability of repeated measures. One sample *t* test was performed on duplicate measurements to test for systematic error.

RESULTS

ICCs showed a high degree of reliability for repeated measures (greater than 0.98). A one-sample *t* test showed that (1) there is no significant difference between the repeated measurements and (2) the within-subject error is small enough, relative to between-subject variability, to indicate that there was no systematic bias.

The average BSSO advancement was 4.98 mm ± 2.36 (Table 1). The mean airway volume was 7967.9 mm^3 ± 2465.0 at T1; 10,941.7 mm^3 ± 3882.8 at T2; and 10,941.7 mm^3 ± 4489.8 at T3 (Table 2). BSSO advancement resulted in a statistically significant increase in airway volume (2973.9 mm^3 ± 2782.0) (P = .0001) and showed a small nonsignificant decrease (–439.9 mm^3 ± 3308.8) ($P = 0.56$) 1 year post-op (Table 3). The mean minimum cross-sectional area was 120.6 mm^2 ± 49.8 at T1, 173.3 mm^2 ± 71.29 at T2, and 163.0 mm^2 ± 70.6 at T3 (Table 2). Minimum cross-sectional area also showed a statistically significant increase after surgery (52.7 mm^2 ± 46.7) (P =

Table 2. Volumetric and Minimum Cross-sectional Area Airway Measurements

	Airway Volume, mm^3			Minimum Cross-sectional Area, mm^2		
	Pre-sx[a]	Post-sx[b]	1 y	Pre-sx	Post-sx	1 y
Mean	7967.87	10941.73	10501.78	120.59	173.29	162.98
SD	2465.06	3882.76	4489.82	49.79	71.29	70.57

[a] Sx indicates surgery.
[b] Splint removal 4–6 weeks postoperatively.

Table 3. Longitudinal Airway Changes

	Airway Volume (mm³)		Minimum Cross-sectional Area (mm²)	
	Pre–Post Sx[a]	Post Sx–1 year	Pre–Post Sx	Post Sx–1 year
Mean	2973.9	−439.9	53.0	−10.3
SD	2782.0	3308.8	46.7	43.3
P value	.0001*	.56	.001*	.31

[a] Sx indicates surgery.
* Statistical significance, which was set at .05.

.001) and remained stable (−10.3 mm^2 $\pm$ 43.3) ($P =$ .31) 1 year post-op (Table 3).

There was no correlation between the amount of surgical movement to change in airway volume or minimum cross-sectional area (Table 4). However, there was a strong correlation between the change in airway volume and minimum cross-sectional area.

3-D color maps and semitransparency overlays allow qualitative and quantitative assessment of treatment changes (Figure 3). SPHARM-PDM analysis showed that BSSO advancement produced more transverse/lateral expansion of the oropharyngeal space (14.54 mm $\pm$ 7.69) than anteroposterior expansion (9.40 mm $\pm$ 5.82) ($P = .04$) (Table 5).

DISCUSSION

Airway studies have been a topic of great interest in the medical and dental literature due to the increase in the prevalence of OSA,[20] yet they can be challenging to conduct. A large portion of airway studies was conducted using 2-D cephalograms. These x-rays superimpose right and left structures, and their inherent magnification make them prone to measurement errors. In addition, most studies report either linear or volumetric change, yet there is a lack of strong evidence correlating the overall size of the airway to physiological breathing or the development of OSA. We did not design our study to address airway changes in sleep apnea patients, but to introduce new techniques to evaluate shape and area changes of the airway and illustrate these changes in BSSO advancement patients. Another limitation of this study is the lack of untreated controls. A study by Schendel et al. showed that airway size increases until age 20 at which time a period of relative stability occurs.[21] After age 40, the airway decreases in size. The mean age of our sample was 25.6 years, with most of the samples in this range.

Minimum cross-sectional area ie, chock point has been shown to a have higher correlation with air turbulence[22,23] and corresponds with the severity of OSA.[12–14] However, most software calculates minimum cross-sectional area through axial slices that are dependent on head orientation. Neck posture and flexure could drastically change the calculated minimum cross-sectional area. A study by Mattos et al. showed that minimum cross-sectional area measurements were unreliable.[15] Therefore, we propose the use of mean latitude axis as a tool to calculate cross-sectional area to improve reliability of measurement and errors from head orientation.

Another challenge to airway studies is standardization of head posture or positioning during image capture. Most CBCT airways studies are performed in the upright position. Van Holsbeke et al. examined the airway of healthy adults using CBCT with the patient sitting upright immediately followed by a spiral CT exam with the patient in the supine position.[24] They showed that the shape and dimension of the oropharyngeal space decreases as much as 27% when the scans were performed in the supine position. The difference was even greater when OSA patients are examined. Camacho et al. reported total airway volume decreased by 33% and cross-sectional area measurements decreased as much as 76% when OSA patients were in a supine position.[25] In our study, all CBCTs were captured in the supine position with the patient standardized for exhalation at the start of image capture.

We showed that BSSO advancement produces a significant increase in oropharyngeal airway space and minimum cross-sectional area, which remained stable 1 year after surgery. This is in agreement with other BSSO advancement studies.[4,5,23] Interestingly, our statistical analysis did not find a strong correlation between the degree of surgical movement and airway improvement. Perhaps there is a minimum threshold for mandibular advancement to produce an apprecia-

Table 4. Pearson Correlation Coefficients for Surgical Movement, Initial Overjet, Change in Airway Volume, and Minimum Cross-sectional Area[a]

	Surgical Movement	Overjet	Change in Volume	Change Cross-sectional area
Surgical movement		0.96	0.09	0.01
Overjet	< .0001*		0.08	0.02
Change in volume	0.71	0.73		0.53
Change in cross-sectional area	0.98	0.93	< .0001*	

[a] Top right region of the table shows the *R* values, and the bottom diagonal area shows the *P* values.
* Statistical significance, which was set at .05.

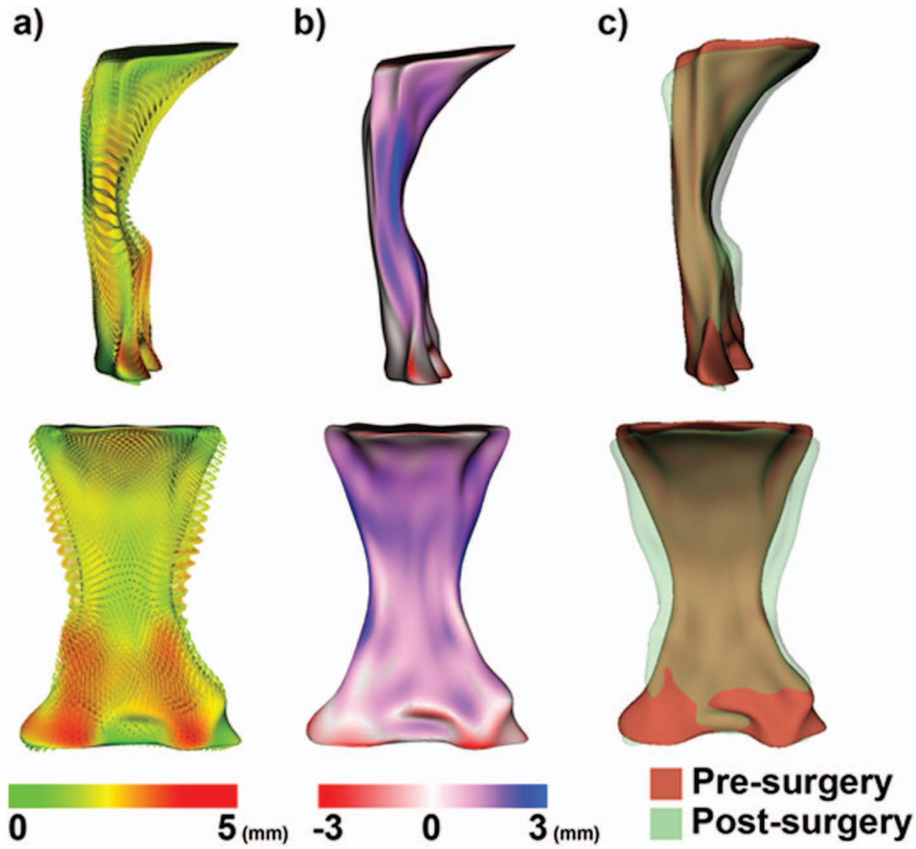

Figure 3. Shape analysis results for superimposed T1 and T2 airways displayed for one representative patient. (a) Absolute distances and difference vectors in a left sagittal (top) shows some anterior expansion while and frontal (bottom) view shows more transverse expansion, specifically at the retroglossal region. (b) Visualization of airway expansion using signed distances, where local increase of airway volume is shown in blue, local decrease of local airway volume in red. Note that the patient exhibited more lateral expansion at the top than anteroposteriorly. (c) Overlay of superimposed T1 and T2 airway. T1 airways are represented in brown and T2 is shown in semitransparent green.

ble increase in airway dimension. For OSA patients, the recommended amount of mandibular advancement is 8–12 mm.[7] In our sample, the average surgical movement was only 5 mm. Another possible explanation is that our sample was relatively small, with a large range of surgical movement (3 mm to 9.7 mm of BSSO advancement). Future studies with a larger sample size, tighter range of mandibular movement, and the enrollment of sleep apnea patients might shed more light on this topic.

Understanding the transverse dimension of the airway is important. Li et al. showed that the main anatomic difference between a healthy and an OSA airway was the transverse dimension at the level of the oropharynx.[26] Accurate assessment of the transverse airway dimension using a headfilm is difficult due to the great variability in the shape of the airway, as well as superimposition of adjacent structures.[27] Even with CBCT imaging, reliable selection of landmarks can be difficult and is often influenced by the axial plane selected for orienting the head. The use of SPHARM-PDM analysis reduces operator bias and reliability of landmark identification because the tool automatically selects 4002 corresponding points along the airway from different longitudinal time points. Direction vectors can be generated to show specific regional corresponding changes (Figure 3a), or displacement maps can be used for qualitative and quantitative assessment of these changes (Figure 3b). In our study, BSSO advancement produced more transverse airway expansion compared with anteroposterior expansion (Table 5 and Figure 3). SPHARM-PDM tools can be used in future sleep apnea studies to evaluate shape changes in the airway following mandibular advancement devices or orthognathic surgery.

Table 5. SPHARM-PDM Analysis of Airway Displacement from Presurgery to Postsurgery

	AP[a]	Transverse	*P* Value
Mean max distance	9.40 mm	14.54 mm	.001*
Mean min distance	0.42 mm	0.31 mm	.31

[a] Anteroposterior displacement.
* Statistical significance set at .05.

CONCLUSION

- SPHARM-PDM and mean latitude axis are useful tools to assess airway shape and volume changes.
- BSSO advancement produces a significant increase in pharyngeal airway volume and minimum cross-sectional area. The airway space increased more transversely than anteroposteriorly.

ACKNOWLEDGMENTS

We thank Sharon Chen and Josiah Rich for their assistance on the project and the NIDCR (DE005215) for their support.

REFERENCES

1. Proffit WR, Fields HW, Moray LJ. Prevalence of malocclusion and orthodontic treatment need in the United States: estimates from the N-HANES III survey. *Int J Adult Orthod Orthog Surg*. 1998;13:97–106.
2. Bear SE, Priest JH. Sleep apnea syndrome: correction with surgical advancement of the mandible. *J Oral Surg*. 1980;38:543–549.
3. Farole A, Mundenar MJ, Braitman LE. Posterior airway changes associated with mandibular advancement surgery: implications for patients with obstructive sleep apnea. *Int J Adult Orthod Orthognath Surg*. 1990; 5:255–258.
4. Yu LF, Pogrel MA, Ajayi M. Pharyngeal airway changes associated with mandibular advancement. *J Oral Maxillofac Surg*. 1994;52:40–43.
5. Mehra P, Downie M, Pita MC, Wolford LM. Pharyngeal airway space changes after counterclockwise rotation of the maxillomandibular complex. *Am J Orthod Dentofacial Orthop*. 2001;120:154–159.
6. Waite PD, Wooten V, Lachner J, Guyette RF. Maxillomandibular advancement surgery in 23 patients with obstructive sleep apnea syndrome. *J Oral Maxillofac Surg*. 1989;47:1256–1261.
7. Riley RW, Powell NB, Guilleminault C. Maxillary, mandibular, and hyoid advancement for treatment of obstructive sleep apnea: a review of 40 patients. *J Oral Maxillofac Surg*. 1990;48:20–26.
8. De Ponte FS, Brunelli A, Marchetti E, Bottini DJ. Cephalometric study of posterior airway space in patients affected by Class II occlusion and treated with orthognathic surgery. *J Craniofac Surg*. 1999;10: 252–259.
9. Mattos CT, Vilani GN, Sant'Anna EF, Ruellas AC, Maia LC. Effects of orthognathic surgery on oropharyngeal airway: a meta-analysis. *Int J Oral Maxillofac Su*rg. 2011;40:1347–1356.
10. El H, Palomo JM. Measuring the airway in 3 dimensions: a reliability and accuracy study. *Am J Orthod Dentofacial Orthop*. 2010;137:S50.e1–S50.e9.
11. Ghoneima A, Kula K. Accuracy and reliability of cone-beam for airway volume analysis. *Eur J Orthod*. 2013;35:256–261.
12. Avrahami E, Englender M. Relation between CT axial cross-sectional area of the oropharynx and obstructive sleep apnea syndrome in adults. *AJNR Am J Neuroradiol*. 1995;16:135–140.
13. Avrahami E, Solomonovich A, Englender M. Axial CT measurements of the cross-sectional area of the oropharynx in adults with obstructive sleep apnea syndrome. *AJNR Am J Neuroradiol*. 1996;17:1107–1111.
14. Yucel A, Unlu M, Haktanir A, Acar M, Fidan F. Evaluation of the upper airway cross-sectional area changes in different degrees of severity of obstructive sleep apnea syndrome: cephalometric and dynamic CT study. *Am J Neuroradiol*. 2005;26: 2624–2629.
15. Mattos C, et al. Reliability of upper airway linear, area, and volumetric measurements in cone-beam computed tomography. *Am J Orthod Dentofacial Ort*hop. 2014;145: 188–197.
16. Paniagua B, Cevidanes L, Zhu H, Styner M. Outcome quantification using SPHARM-PDM toolbox in orthognathic surgery. *Int J Comput Assist Radiol Surg*. 2011;6:617–626.
17. Nguyen T, Cevidanes L, Paniagua B, Zhu H, de Paula L, De Clerck H. Use of shape correspondence analysis to quantify skeletal changes associated with bone-anchored Class III correction. *Angle Orthod*. 2014;84(2):329–336.
18. Paniagua B, Lyall A, Berger J-B, et al. Lateral ventricle morphology analysis via mean latitude axis. SPIE Medical Imaging. 2015;9413. p. ii: 94130U.
19. Kim H, Bernasconi N, Bernhardt B, Colliot O, Bernasconi A. Basal temporal sulcal morphology in healthy controls and patients with temporal lobe epilepsy. *Neurology*. 2008;70:2159–2165.
20. Peppard PE, Young T, Barnet JH, et al. Increased prevalence of sleep-disordered breathing in adults. *Am J Epidemiol*. 2014;177:1006–1014.
21. Schendel SA, Jacobson R, Khalessi S. Airway growth and development: a computerized 3-dimensional analysis. *J Oral Maxillofac Surg*. 2012 2012-09-01;70:2174–2183.
22. Sung SJ, Jeong SJ, Yu YS, Hwang CJ, Pae EK. Customized three-dimensional computational fluid dynamics simulation of the upper airway of obstructive sleep apnea. *Angle Orthod*. 2006;76: 791–799.
23. Wootton DM, Luo H, Persak SC, et al. Computational fluid dynamics endpoints to characterize obstructive sleep apnea syndrome in children. *J Appl Physiol*. 2014;116:104–112.
24. Van Holsbeke CS, Verhulst SL, Vos WG, De Backer JW, Vinchurkar SC, Verdonck PR, et al. Change in upper airway geometry between upright and supine position during tidal nasal breathing. *J Aerosol Med Pulm Drug Deliv*. 2014;27:51–57.
25. Camacho M, Capasso R, Schendel S. Airway changes in obstructive sleep apnea patients associated with a supine versus an upright position examined using cone beam computed tomography. *J Laryngol Otol*. 2014;128:824–830.
26. Li KK, Guilleminault C, Riley RW, Powell NB. Obstructive sleep apnea and maxillomandibular advancement: an assessment of airway changes using radiographic and nasopharyngoscopic examinations. *J Oral Maxillofac Surg*. 2002;60:526–530.
27. Aboudara C, Nielsen I, Huang JC, Maki K, Miller AJ, Hatcher D. Comparison of airway space with conventional lateral headfilms and 3-dimensional reconstruction from cone-beam computed tomography. *Am J Orthod Dentofacial Orthop*. 2003;135:468–479.