# Changes in 3D nasal cavity volume after biomimetic oral appliance therapy in adults

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Objective: In this study, the authors investigated 3D changes in nasal volume, to test the hypothesis that nasal cavity volume can be changed in adults.
Methods: After obtaining informed consent, the authors undertook 3D cone-beam computerized axial tomographic (CBCT) scans of 11 consecutive adults (mean age: 37.9 years), before and after biomimetic oral appliance therapy (BOAT). The mean treatment time was 18.4±2.5 months. Volumetric reconstruction of the nasal cavity was undertaken, and the nasal volume was calculated in all cases. The findings were subjected to statistical analysis, using paired *t*-tests.
Results: The mean nasal cavity volume was 41.9±12.0 $cm^3$ before treatment. After BOAT, the mean volume increased to 44.0±12.7 $cm^3$ ($P$=0.022).
Conclusions: These data support the notion that nasal cavity volume can be changed in adults. Use of BOAT might improve continuous positive airway pressure (CPAP) compliance in adults diagnosed with obstructive sleep apnea (OSA), by increasing the nasal cavity volume and decreasing nasal airflow resistance.

**Keywords:** Nasal airway, Palatal expansion, Obstructive sleep apnea, Biomimetic oral appliance

## Introduction

Obstructive sleep apnea (OSA) is a sleep-related breathing disorder characterized by disruptive snoring, daytime somnolence, and abnormal sleep architecture. Contributory conditions to upper airway obstruction, such as jaw deformities, central nervous system disorders, and obesity, may lead to life-threatening systemic complications. Additional contributory factors for OSA include nasal airway obstruction (particularly hypertrophied inferior turbinates), and decreased oropharyngeal airway dimension (particularly adeno-tonsillar hypertrophy). In children, rapid maxillary expansion (RME) may provide a treatment option for OSA. For example, in preschool children with OSA, Marino *et al.*[1] reported that those with retrognathic jaws might find RME beneficial, while Villa *et al.*[2] noted the effects of RME can persist for some 2 years after treatment. Another treatment option for patients with OSA involves continuous positive airway pressure (CPAP), which acts as an upper airway stent to prevent pharyngeal collapse and consequent obstruction. However, many patients do not tolerate CPAP well. For example, using 4 h/day as effective CPAP usage, Boyaci *et al.*[3] report that less than half of adults were able to comply with CPAP therapy sufficiently. Other commonly used treatments for OSA include: oral appliances to reposition the mandible anteriorly, and orthognathic surgery to advance both the maxilla and mandible. For any of these treatments to be maximally effective, however, a patent nasal airway is required. Thus, nasal airway obstruction or occult nasal obstruction may hinder CPAP compliance, as well as the effectiveness of other treatment options for OSA.

There are several factors that can contribute to nasal airway obstruction and increased nasal airway resistance, including: narrow nostrils; nasal valve collapse; turbinate hypertrophy; nasal septal deviation; nasal congestion secondary to allergies; polyps; hyperplastic adenoidal tissues; parasympathetic nervous system activation, and choanal atresia. In addition, the transverse dimension of the nasal cavity may be excessively narrow, further diminishing the tolerance of CPAP. Singh *et al.*[4] reported variations

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in nasal cavity width, which may be secondary to a high-arch palate. Indeed, Banabilh *et al.*[5] confirmed that the upper dental arch is narrower in adults diagnosed with OSA when compared with controls. Similarly, comparing nasal airways using finite-element morphometry, Banabilh *et al.*[6] reported that the mean, 3D nasal airway was significantly narrower in Asian subjects with OSA compared to matched controls. Mehra and Wolford,[7] Morales-Ryan and Wolford,[8] and Wolford *et al.*[9] have identified specific, morphological characteristics that predispose to nasal airway obstruction and hypertrophied turbinates, including a retruded maxilla and mandible. Thus, craniofacial architecture may contribute significantly to CPAP impedance reaching the critical pressures required to overcome resistance from nasal and oropharyngeal airway obstructions. Therefore, the aim of this study is to determine 3D changes in nasal volume, to test the hypothesis that nasal cavity volume can be changed in non-growing adults.

## Sample and Methods

After obtaining informed consent, 13 consecutive patients were recruited for this study. The rights of the subjects were protected by following the Declaration of Helsinki. Inclusion criteria were: adults over age 21 years diagnosed with clinical, midfacial underdevelopment (such as a narrow palate or posterior crossbite); good oral appliance compliance; no history of hospitalization for craniofacial trauma or surgery; no congenital craniofacial anomalies, and a fully-dentate upper arch. The exclusion criteria included: age <21 years; lack of oral appliance compliance; active periodontal disease; tooth loss during treatment; poor oral hygiene, and systemic bisphosphonate therapy. The study protocol (#1022013) was reviewed and approved by the institution's review board. After careful history taking and craniofacial examination, the authors undertook 3D cone-beam computerized axial tomographic (3D CBCT) scans using an iCAT 3D CBCT machine (Imaging Sciences International, Hatfield, PA, USA). Strict positioning protocols were used, and a 20-second scan was performed using a wide (13 cm) field of view.

A neuromuscular bite registration was obtained in the upright-sitting position with corrected jaw posture in the vertical axis specific for each subject. The protocol for capturing the physiological rest position of the jaw[10] starts with baseline data collection of the initial bite, jaw position, and posture, using photography and K-7 data (Myotronics, Kent, WA, USA). The muscles of mastication are relaxed using ultra-low frequency, transcutaneous electrical neural stimulation (ULF-TENs) for a minimum of 45 minutes of cranial nerves V, VII, and XI that are accessed through the coronoid notch and the upper portion of the middle one-third of the posterior cervical triangle, just posterior to the sternocleidomastoid muscle (SCM). Cranial nerve XI innervates SCM and trapezius, and if stimulated with ULF-TENS, these muscles and associated muscles can be relaxed simultaneously without risk of direct stimulation of the carotid sinus nerve.[11] Following relaxation of the jaw and neck muscles, K-7 data are used to find the most relaxed position of the jaw where the muscles coordinate together, documented in a single point in space. The physiological rest position is captured using a polyvinylsiloxane bite registration material when the EMGs are the lowest. The bite position is then verified using K-7 data. The physiological rest position is thus determined by measurable and repeatable data.[12] Upper and lower polyvinylsiloxane impressions were also obtained. The upper model was then mounted using the hammular notch-incisive papilla plane method on a Stratos articulator (Ivoclar-Vivadent, Amherst, NY, USA), and the lower model was mounted relative to the upper model, using the bite registration captured in the physiological rest position.

**Figure 1 The wireframe Daytime-Nighttime Appliance (DNA appliance) that was used for each subject in this study. The wireframe DNA appliance shown in situ consists of: 6 (patented) anterior 3D axial springs; midline anterior and posterior omega loops; bilateral posterior occlusal rests; bilateral retentive clasps, and a wrap-around labial bow with U loops.**

Following diagnostics, a biomimetic, upper Daytime-Nighttime Appliance (DNA appliance®) (Fig. 1) was prescribed for each subject. Biomimetic oral appliance therapy (BOAT) is designed to correct maxillo-mandibular underdevelopment in both children and adults.[13–19] The BOAT used in this study had: six (patented) anterior 3D axial springs™, midline anterior and posterior omega loops, posterior occlusal rests,

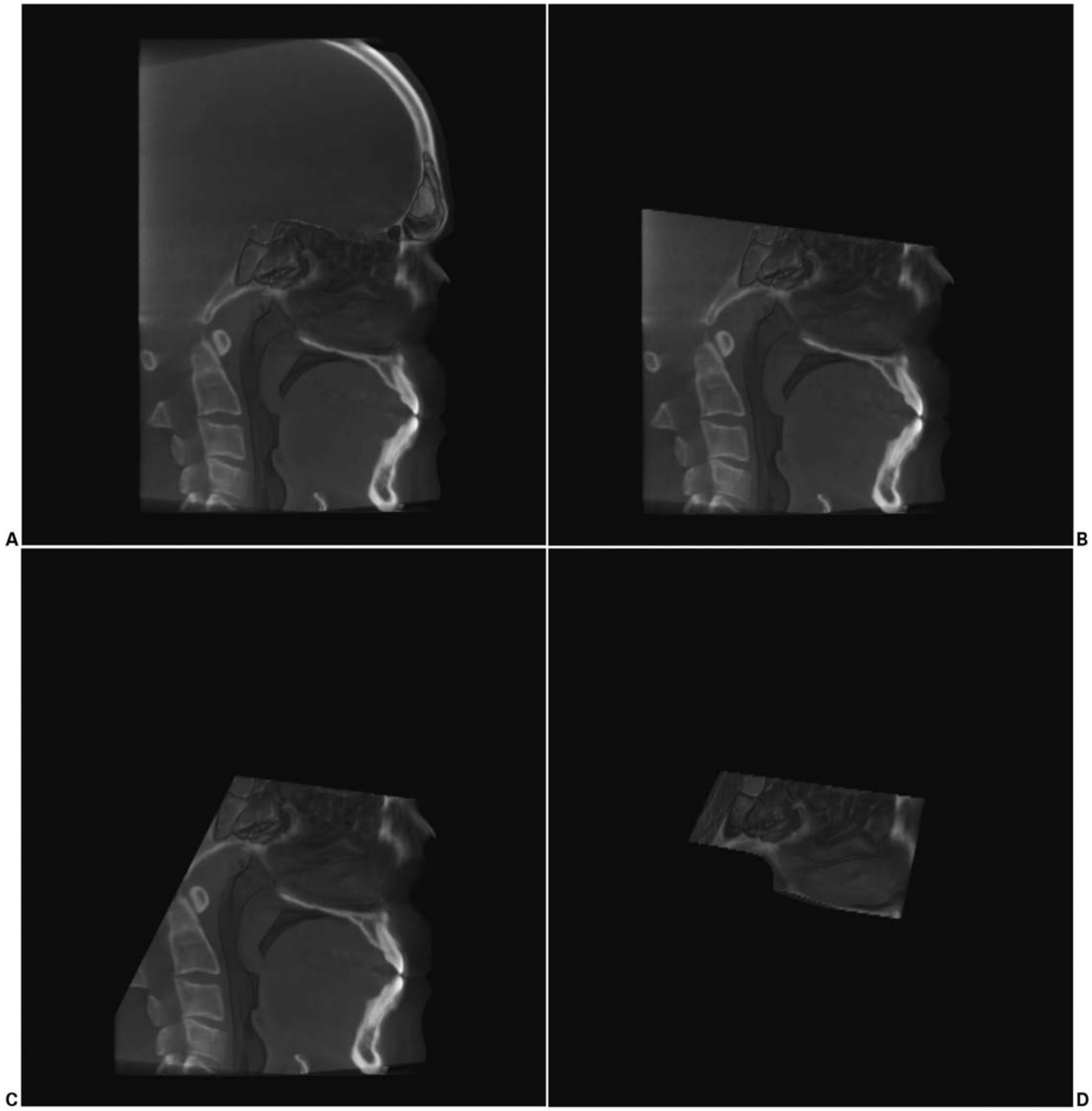

**Figure 2 (A) From the 3D CBCT scan data, gray-scale images were used to identify bony landmarks. To acquire the nasal cavity volume, the CBCT scan was trimmed anteriorly from nasion to the anterior nasal spine. (B) The superior aspect of the 3D CBCT image was trimmed from nasion to the most superior part of sella turcica. (C) From the previous 3D CBCT image, the posterior aspect was trimmed from the most superior point of the sella turcica to basion. (D) The inferior aspect of the 3D CBCT image was trimmed following the hard palate. This procedure was followed systematically for each pre-treatment and post-treatment volume, leaving only the nasal cavity for volumetric analysis.**

retentive clasps, and a labial bow (Fig. 1). All subjects were instructed to wear the appliance during the evening and at night-time (for approx. 12–16 hours in total), but not during the day time and not while eating, partly in line with the circadian rhythm of tooth eruption,[20] although this only occurs in children. Note that, according to Proffit and Fields,[21] an appliance needs to be worn for at least 8 hours to have a clinical effect. The appliance was adjusted every 4 weeks, approximately. The subjects were also instructed on how to perform an orofacial/myofunctional exercise (the "zygoma lift"),[22] and had to demonstrate successful implementation of the exercise routine prior to discharge. Written and verbal instructions were given to all subjects.

All subjects reported for review each month. At each monthly follow-up, examination for the progress of midfacial development was recorded. Adjustments to

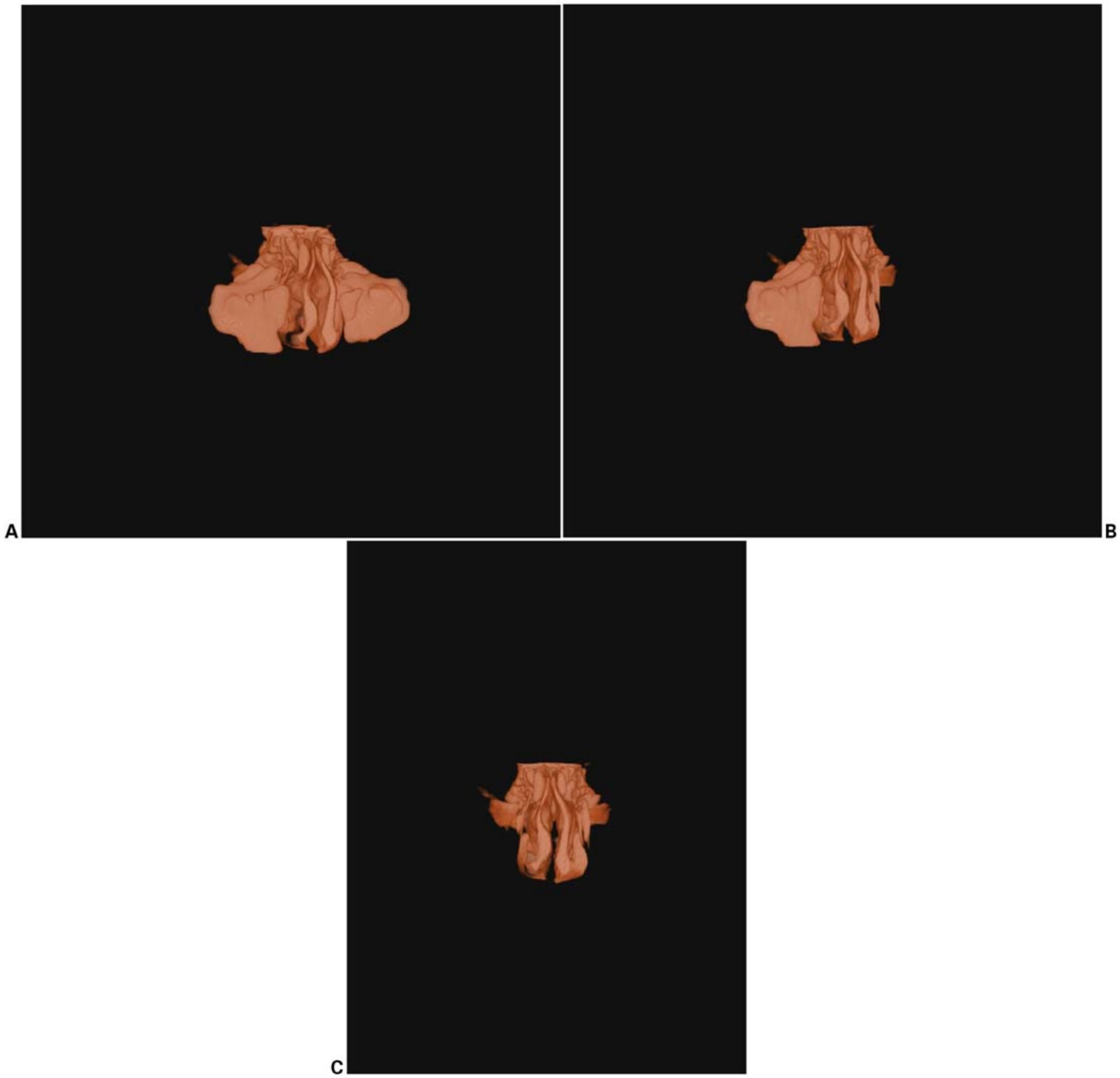

**Figure 3 (A) For 3D reconstruction of the nasal cavity, appropriate software was implemented (Anatomage; inVivo Dental, San Jose, CA, USA). Pseudo-color objects were used to work on inverse volume reconstructions, which allowed visualization of spaces and trimming away the maxillary sinuses. (B) Object visualization was undertaken at each step when trimming away data from the CBCT data so that, eventually, the only information left was for volumetric reconstruction of the nasal cavity. (C) Volumetric reconstruction of the nasal cavity was undertaken between the anterior and posterior nasal spines, extending superiorly from the palatine process of the maxilla and the palatine bone to the cribriform plate of the ethmoid bone.**

the devices were performed to optimize their efficacy. Only gentle pressures were transmitted to the teeth, and the functionality of the device was checked with the subject activating a mild force on biting. The subjects were encouraged to maintain their treatment regimen as outlined at the outset. Development of the lower arch was implemented using a lower appliance to permit arch re-coordination. A lower appliance was implemented between 6 and 12 months, depending on the subject's progress.

For the 3D CBCT scan data, gray-scale images were used to identify bony landmarks to enable digital trimming of the majority of the CBCT data set (Fig. 2). To acquire the nasal cavity volume, the CBCT scan was trimmed anteriorly from nasion to the anterior nasal spine. The superior aspect was trimmed from nasion to the most superior part of sella turcica. The posterior aspect was trimmed from the most superior point of the sella turcica to basion. The inferior aspect was trimmed following the hard

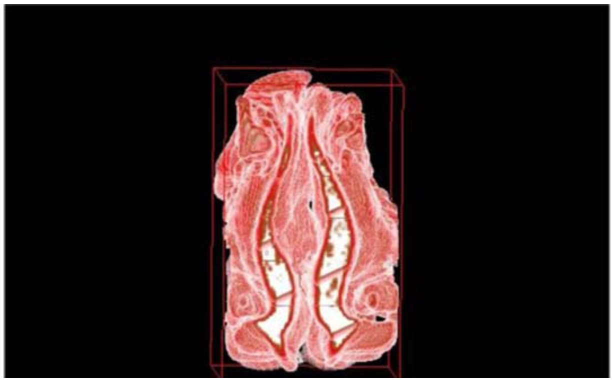

**Figure 4 The final nasal cavity model that was reconstructed. The nasal cavity volume of the model was calculated in all cases.**

palate. Next, the nasopharynx was trimmed out of the remaining volume, and laterally, the maxillary sinuses were trimmed out at their junction to the nasal cavity. This procedure was followed systematically for each pre-treatment and post-treatment volume, leaving only the nasal cavity for volumetric analysis. Next, pseudo-color objects were used to work on inverse volume reconstructions, which allowed visualization of spaces and trimming away of the maxillary sinuses. Object visualization was undertaken at each step when trimming away data from the CBCT data, so that, eventually, the only information left was for volumetric reconstruction of the nasal cavity. For 3D reconstruction of the nasal cavity (Fig. 3), appropriate software was implemented (Anatomage; inVivo Dental, San Jose, CA, USA). Volumetric reconstruction of the nasal cavity was undertaken between the anterior and posterior nasal spines, extending superiorly from the palatine process of the maxilla and the palatine bone to the cribriform plate of the ethmoid bone. Finally, the nasal cavity volume was calculated in all cases (Fig. 4). The 3D measurement protocol was repeated three times to determine the percentage measurement error. At 18 months, these volume measurements were repeated, and the findings were subjected to statistical analysis, using paired *t*-tests.

## Results

Two subjects were excluded from the study; one subject did not meet the age criteria for inclusion, and one subject had maxillary third molars removed during the active phase of BOAT. The mean treatment time was 18.4±2.5 months. The 3D measurement error was found to be 0.92%, so statistical analysis was warranted. The mean nasal cavity volume for the sample of 11 adults was 41.9±12.0 $cm^3$ before treatment. After BOAT, the mean nasal cavity volume increased to 44.0±12.7 $cm^3$ ($P$=0.022). The mean percentage increase in nasal cavity volume was found to be 5.6±8.7%. These results are summarized in Table 1. Figure 5 shows the external appearance of the nose pre- and post-treatment.

## Discussion

The first line of treatment for OSA is typically CPAP, but poor compliance due to nasal obstruction/nasal resistance often hinders effective CPAP use. But, if the nasal airway volume could be increased, patient compliance with CPAP might be improved. Patients diagnosed with OSA require higher CPAP pressures,[23] because in cases of nasal obstruction, the cross-sectional area in the nasal cavity may be decreased. Using Ohm's law for electrical circuits (which corresponds to Poiseuille's law for fluid flow), where the pressure drop is analogous to the voltage and volumetric flow rate is analogous to the current, the resistance ($R$) is given by:

$$R = \frac{8\eta\Delta x}{\pi r^4}$$

where $\eta$ is the flow rate and $\Delta x$ is the pressure gradient.

This concept is useful because it illustrates that the effective resistance to flow in a tube ($R$) is inversely proportional to the fourth power of its radius ($r$). Therefore, a small decrease in the radius of the aperture will increase resistance to (nasal) airflow significantly. In addition, Fajdiga[24] discussed Bernoulli forces that can cause a vacuum effect that may disturb laminar fluid flow, which could be associated with snoring, and possibly sinusitis. Thus, patients with OSA who require higher CPAP pressures experience a change in the physics of nasal breathing, and the basis of this study is to address that issue.

Kim and Guilleminault[25] noted that craniofacial structures limiting nasal breathing can be considered to be risk factors for sleep disordered breathing, and

**Table 1 Nasal cavity volume ($mm^3$)**

| Subject | Pre-treatment | Post-treatment |
|---|---|---|
| ASE | 33 247 | 33 596 |
| FEA | 55 344 | 56 001 |
| HFT | 49 453 | 50 067 |
| CHD | 55 240 | 55 534 |
| KHN | 40 802 | 43 614 |
| NNR | 27 505 | 30 981 |
| KRI | 35 183 | 35 785 |
| JDH | 66 291 | 68 923 |
| EAN | 31 439 | 33 515 |
| TRR | 30 217 | 29 460 |
| ATE | 36 604 | 47 114 |
| Mean | 41 938 | 44 053 |
| *P* value | | 0.022789 |

Figure 5 (A) The external appearance of the nose before biomimetic oral appliance therapy. Note the width and asymmetry of the nares with some evidence of alar cartilage collapse. (B) The external appearance of the nose of the same subject as A after biomimetic oral appliance therapy. Note the improved width and symmetry of the nares.

are identifiable during clinical assessment of craniofacial features in patients being screened for OSA. For example, hypertrophied nasal turbinates commonly contribute to nasal airway obstruction. Typically, the enlargement extends along the entire length of the inferior turbinate, so in order to provide structural patency, the anterior, middle, and posterior aspects of the hypertrophied turbinates need to be addressed. In general, otolaryngologists focus on the anterior one-third of the turbinate due to the highest level of nasal airway resistance occurring in the nasal valve region. Therefore, turbinate surgery is focused on this region. Alternatively, increasing nasal cavity volume could more easily accommodate the hypertrophied inferior turbinates.

A deviated nasal septum and/or septal spurring can also play a significant role in nasal airway obstruction, and these features may require a septoplasty to eliminate their contributions to airflow resistance in patients with OSA.[26] Indeed, if other functional nasal airway obstructions are present, such as narrow nostrils (Fig. 5A), collapsed nasal valves, presence of nasal polyps, etc., they must also be identified and addressed to provide a patent nasal airway. In addition, Wang *et al.*[27] report adverse changes in pharyngeal airway size and hyoid bone position, following conventional orthodontic treatment, which may also lead to occult upper airway obstruction (presumably by retracting the anterior teeth, decreasing the oral cavity volume and displacing the tongue posteriorly). Alternatively, BOAT may be proposed to reduce nasal airway resistance. In this particular study, the authors were able to demonstrate increased nasal cavity volumes post-treatment (Table 1), so it is possible that decreased nasal airway resistance may be a clinical consequence, but further studies are required to determine this, as within-sample heterogeneity could possibly confound the results.

Skeletal and dental changes after RME have been reported in the orthodontic literature, and RME has long been used to correct transverse discrepancies of the maxillary arch. For example, in children, the Haas expansion appliance produces increased nasal, as well as maxillary width.[28] Similarly, when the Haas, Minne, Hyrax, and Quad-Helix appliances were compared,[29] RME resulted in increased nasal width, with significant effects on the palatine, lacrimal, and zygomatic bones in children. While most of the widening is usually observed in the dento-alveolar areas, the width of the floor of the nasal cavity can also be increased. Despite these reports, nasal improvements that might occur using similar techniques in adults have not been fully investigated. But, in recent studies, increased maxillary bone width and bone volume has been reported in adults following BOAT[30] as an alternative to increasing maxillary bone width using surgery[31]. As the roof of the mouth is the floor of the nose, it appears that the target of nasal obstruction might be addressed by increasing nasal volume in adults using a palatal approach. Indeed, in a recent study, Nada *et al.*[32] reported that after 22 months of combined treatment, nasal airway volume increased by 9.5% in the surgical group treated in combination with the Hyrax appliance, and by 13% in the surgical group treated in combination with RME, although statistically no difference between the two groups was found. Their results are similar to the 5.6% volume increase reported in this present study after 18 months, which were achieved without any surgical interventions. Therefore, use of BOAT before, or in conjunction with, CPAP therapy might potentially improve CPAP compliance in adults diagnosed with OSA, by increasing the nasal cavity volume and decreasing nasal airflow resistance. But, the findings of this preliminary study need to be viewed with some caution, as many dental professionals are not familiar with the technique-sensitive protocol employed in this particular investigation. Nevertheless, future studies will use sleep indices to correlate functional airway changes in clinical trials on subjects with OSA, using BOAT with those on CPAP therapy.

## Disclaimer Statements

**Contributors** None.

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**Conflicts of interest** Prof. Singh is CEO of BioModeling Solutions, Inc.

**Ethics approval** #1022013

## References

1 Marino A, Ranieri R, Chiarotti F, Villa MP, Malagola C. Rapid maxillary expansion in children with Obstructive Sleep Apnoea Syndrome (OSAS). Eur J Paediatr Dent. 2012;13:57–63.
2 Villa MP, Rizzoli A, Miano S, Malagola C. Efficacy of rapid maxillary expansion in children with obstructive sleep apnea syndrome: 36 months of follow-up. Sleep Breath. 2011;15:179–84.
3 Boyaci H, Gacar K, Bariş SA, Başyiğit I, Yildiz F. Positive airway pressure device compliance of the patients with obstructive sleep apnea syndrome. Adv Clin Exp Med. 2013;22:809–15.
4 Singh GD, Rozihan MH, Nidzam MTM, Shamim AK, Samsudin AR, Suhaimi D. 3-D reconstruction of nasopharyngeal airways in Malaysian subjects. IFMBE Proc. 2007;15: 8–11.
5 Banabilh SM, Suzina AH, Dinsuhaimi S, Samsudin AR, Singh GD. Dental arch morphology in South-east Asian adults with obstructive sleep apnoea: geometric morphometrics. J Oral Rehabil. 2009;36:184–92.
6 Banabilh SM, Suzina AH, Mohamad H, Dinsuhaimi S, Samsudin AR, Singh GD. Assessment of 3-D nasal airway morphology in Southeast Asian adults with obstructive sleep apnea using acoustic rhinometry. Clin Oral Investig. 2010;14:491–8.
7 Mehra P, Wolford LM. Surgical management of obstructive sleep apnea. Bayl Univ Med Cent Proc. 2000;13:338–42.
8 Morales-Ryan CA, Wolford LM. Hypertrophic turbinates: prevalence, surgical indications and outcomes in the orthognathic surgery patient. J Oral Maxillofac Surg. 2001;59:35–6.
9 Wolford LM. Surgical planning in orthognathic surgery (Chapter 60). In: Booth PW, Schendel SA, Hausamen JE, editors. Maxillofacial surgery. Vol. 2. St Louis, MO: Churchill Livingstone; 2007. p. 1155–210.
10 Jankelson R. Neuromuscular dental diagnosis and treatment. Vol. 1. St Louis, MO: Ishiyaku EuroAmerica; 2005. p. 87–96.
11 Raman P. Neurally mediated ULF-TENs to relax upper cervical and upper thoracic musculature as an aid to obtaining improved cervical posture and mandibular posture. In: The application of the principles of neuromuscular dentistry to clinical practice (Anthology Vol. IX). Seattle, WA: The International College of Cranio-Mandibular Orthopedics; 2010. p. 77–85.
12 Heit T, Derkson C, Bierkos J, Saqqur M. The effect of the physiological rest position of the mandible on cerebral blood flow and physical balance: an observational study. Cranio 2014; Jul 18:886963414Z00000000063. [Epub ahead of print]
13 Singh GD, Lipka G. Case report: introducing the wireframe DNA appliance™. J Am Acad Gnathol Orthop. 2009;26:8–11.
14 Singh GD, Wendling S, Chandrashekhar R. Midfacial development in adult obstructive sleep apnea. Dent Today. 2011;30:124–7.
15 Singh GD, Utama J. Effect of the DNA appliance™ on migraine headache: case report. Int J Orthod. 2013;24:45–9.
16 Singh GD, Cress SE. Craniofacial enhancement using a biomimetic oral appliance: case report. Dent Today. 2013;329:92–4.
17 Singh GD, Callister JD. Use of a maxillary oral appliance for the resolution of obstructive sleep apnea. Cranio. 2013;31:171–9.
18 Singh GD, Ataii P. Combined DNA appliance™ and Invisalign™ therapy without interproximal reduction: a preliminary case series. J Clin Case Rep. 2013;3:1–3.
19 Harris WG, Singh GD. Resolution of 'gummy smile' and anterior open bite using the DNA appliance™: case report. J Am Orthod Soc. 2013;13:30–4.
20 Proffit WR, Frazier-Bowers SA. Mechanism and control of tooth eruption: overview and clinical implications. Orthod Craniofac Res. 2009;12:59–66.
21 Proffit WR, Fields HW. Contemporary orthodontics. New York: Mosby Inc.; 2005.
22 Singh GD, Krumholtz JA. Epigenetic orthodontics in adults. Chatsworth: Appliance Therapy Group; 2009. p. 155–6.
23 Patra AL, Gooya A, Ménache MG. A morphometric comparison of the nasopharyngeal airway of laboratory animals and humans. Anat Rec. 1986;215:42–50.
24 Fajdiga I. Snoring imaging: could Bernoulli explain it all? Chest. 2005;128:896–901.
25 Kim JH, Guilleminault C. The nasomaxillary complex, the mandible, and sleep-disordered breathing. Sleep Breath. 2011;15:185–93.
26 Takahashi R, Ohbuchi T, Hohchi N, Takeuchi S, Ohkubo J, Ikezaki S, *et al.* [Effect of septoplasty and turbinectomy on obstructive sleep apnea syndrome]. Nihon Jibiinkoka Gakkai Kaiho. 2013;116:789–92. Japanese.
27 Wang Q, Jia P, Anderson NK, Wang L, Lin J. Changes of pharyngeal airway size and hyoid bone position following orthodontic treatment of Class I bimaxillary protrusion. Angle Orthod. 2011;82:115–21.
28 Haas AJ. Rapid expansion of the maxillary dental arch and nasal cavity by opening the midpalatal suture. Angle Orthod. 1961;73–90.
29 Cross DL, McDonald JP. Effect of rapid maxillary expansion on skeletal, dental and nasal structures: a posteroanterior cephalometric study. Eur J Orthod. 2000;22:519–28.
30 Singh GD, Heit T, Preble D. Changes in 3D midfacial parameters after biomimetic oral appliance therapy in adults. J Ind Orthod Soc. 2014;48:104–8.
31 Nada RM, Fudalej PS, Maal TJ, Bergé SJ, Mostafa YA, Kuijpers-Jagtman AM. Three-dimensional prospective evaluation of tooth-borne and bone-borne surgically assisted rapid maxillary expansion. J Craniomaxillofac Surg. 2012;40:757–62.
32 Nada RM, van Loon B, Schols JG, Maal TJ, de Koning MJ, Mostafa YA, *et al.* Volumetric changes of the nose and nasal airway 2 years after tooth-borne and bone-borne surgically assisted rapid maxillary expansion. Eur J Oral Sci. 2013;121:450–6.