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ORIGINAL ARTICLE

Assessment of 3-D nasal airway morphology in Southeast Asian adults with obstructive sleep apnea using acoustic rhinometry

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Abstract The aim of the present study is to investigate nasal airway morphology in Asian adults with and without obstructive sleep apnea (OSA) using acoustic rhinometry (AR), principal components analysis (PCA), and 3-D finite-element analysis (FEA). One hundred eight adult Malays aged 18–65 years (mean ± SD, 33.2±13.31) underwent clinical examination and limited channel polysomnography, providing 54 patients with OSA and 54 non-OSA controls. The mean minimal cross section area 1 (MCA1) and the mean minimal cross sectional area 2 (MCA2) were obtained from AR for all subjects and subjected to *t* tests. The OSA and control nasal airways were reconstructed in 3-D and subjected to PCA and FEA. The mean MCA1 and MCA2 using AR were found to be significantly smaller in the OSA group than in the control group ($p<0.001$). Comparing the 3-D OSA and control nasal airways using PCA, the first two eigenvalues accounted for 94% of the total shape change, and statistical differences were found ($p<0.05$). Similarly, comparing the nasal airways using FEA, the 3-D mean OSA nasal airway was significantly narrower in the OSA group compared to the control group. Specifically, decreases in size of approx. 10–22% were found in the nasal valve/head of inferior turbinate area. In conclusion, differences in nasal airway morphology are present when comparing patients with OSA to controls. These differences need to be recognized as they can improve our understanding of the etiological basis of obstructive sleep apnea and facilitate its subsequent management.

Keywords Nasal morphology · Adult · Sleep apnea · Acoustic · Asian · Finite element

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Introduction

It is striking that a condition as common as obstructive sleep apnea (OSA) has only come to the forefront in the last 30 years [1]. Indeed, much of what we have learned about OSA has occurred in the very recent past. The first description of OSA that identified upper airway obstruction as the major pathogenic mechanism was reported in 1965 [2]. Since then, progress has been remarkable as the high prevalence of OSA has been revealed by further epidemiological studies [3]. Realizing that OSA is far from being rare, OSA was later recognized as a major public health issue [4].

In previous studies of OSA, many techniques have been used to measure upper airway morphology. These techniques include lateral cephalography, endoscopy during wakefulness (with or without the Muller maneuver), endoscopy during sleep (with or without nasal CPAP), fluoroscopy, CT scans, and MRI [5]. Although these techniques can be used to accurately measure upper airway morphology, the invasive nature of some of them is disadvantageous. Acoustic rhinometry (AR), which is less invasive, can also be used for the assessment of the nasal airway in patients with OSA [6]. For example, comparative assessments of pharynx size among snorers, non-snorers, and patients with OSA have been investigated using AR [7]. In addition, the effect of supine body position in snorers with sleep disordered breathing (SDB) was studied with AR [8]. The association of rapid eye movement (REM) sleep and nasal obstruction was investigated with AR as well. Non-REM sleep was found to be characterized by significant nasal decongestion [9]. Similarly, it has been reported that that AR along with nasal examination may be helpful in the evaluation and treatment of patients with SDB [10].

A few studies have used geometric morphometric techniques, such as finite-element analysis (FEA) to assess upper airway morphology. For instance, FEA was used as a model to assess the collapsibility of the upper airway [11], and it was concluded that FEA is an important technique for understanding upper airway physiology. Recently, FEA was used to assess functional airway impairments associated with 2-D size-reduction in the posterior cranial base of Malaysian patients with OSA [12]. Similarly, AR data were used to reconstruct the 3-D upper airway in patients with temporo-mandibular dysfunction; deficiencies in the upper airway were quantified and localized with FEA [13]. Using FEA, it is also possible to accurately calculate pharyngeal cross-sectional area (CSA) from pharyngeal pressure and flow [14]. The FEA technique has also been used to evaluate nasal airway dilation using an intraoral appliance [15]. Hence, this present study was undertaken using 3-D FEA to determine whether any morphologic differences can be identified in the nasal airway of adult Malays with and without OSA. The null hypothesis to be tested is that no differences in 3-D nasal airway morphology are present in adult Malays with and without OSA.

Materials and methods

This multidisciplinary study took place in the Clinic of Otorhinolaryngology-Head and Neck Surgery (ORL-HNS), Hospital Universiti Sains Malaysia (HUSM). A comparative, cross-sectional study design was employed. Exclusion criteria for sample selection were: any subjects with psychiatric illness; sedative and/or alcohol intake; patient-specific disorders (such as neuromuscular disorders); any craniofacial deformity (such as cleft lip and/or palate); and lack of informed consent or willingness to participate in the study.

After obtaining informed consent, which was reviewed and approved at institutional level, 108 adult Malays aged 18–60 years were recruited for this study. The first group consisted of 54 consecutive, care-seeking, snoring patients with OSA (defined as an apnea–hypopnea index (AHI)> 5/h of sleep) diagnosed with ambulatory sleep studies. The second group consisted of 54 consecutive, healthy, non-OSA control subjects who did not have any apneic symptoms, including snoring, as evaluated by the attending physician and ambulatory sleep studies. The main sources of both groups included in the study were randomly selected subjects from the ORL-HNS clinic, as well as the orthodontic clinic. In addition, individual nurses, medical/dental students, and university staff were also asked to seek volunteers for the study. Each patient's age, sex, height, and weight was recorded. The BMI was calculated from the patient's height and weight in standard units (kg/m^2), and the neck circumference was measured at the level of the thyroid cartilage.

Sleep study

An overnight hospital type III sleep study was performed on each subject between 10:00 P.M. until 6:00 A.M. All variables were recorded simultaneously and continuously with a portable diagnostic device (Embletta, Somnologica, Iceland) at HUSM Sleep Science Laboratory. This device has been reported to be suitable for use both in hospitals and at home [16, 17] and has been validated against full polysomnography [18]. The parameters measured and full details of the sleep study for the same group of patients have been reported previously elsewhere [19, 20] and will not be repeated here.

Acoustic rhinometry

Acoustic measurements were successfully carried out on the sample of 54 adults with OSA and 54 adults without OSA, using a RhinoScan SRE2100 instrument (Interacoustic, AS, RhinoMetric, Denmark). The RhinoScan measures 2-D nasal airway dimensions by creating a wide band noise in the nose. As a result, the cross-sectional areas of the nose can be illustrated graphically as a function of the distance from the nostril. The AR was performed by applying the standard procedure [21].

All AR recordings were done in the same position, with the same operator (SMB) performing all the tests in the same room. The RhinoScan Standard Prop for adults was selected, and a thin layer of sealing gel (Seal gel, Interacoustic, AS, RhinoMetric, Denmark) was applied according to manufacturer's instructions. The reason for applying this gel was to provide an acoustically tight seal between the nostril and the nasal adapter to avoid any sound leaks between the adapter and the nostril. A good seal with minimal distortion of the nasal alae was maintained in all subjects tested. The minimal cross-sectional areas (MCA) and volumes at distances close to

Table 1 Acoustic rhinometry reliability measurements

Variables		Mean (SD)	Mean differences (95% CI)	p Value
MCA1 distance (cm)	R1	1.8 (0.02)	0.06 (−0.01, 0.02)	0.447
	R2	1.8 (0.02)		
MCA1 cross section (cm^2)	R1	0.5 (0.20)	0.04 (−0.02, 0.11)	0.215
	R2	0.4 (0.12)		
MCA1 volume (cm^3)	R1	1.8 (0. 39)	0.01 (0.03, 0.02)	0.135
	R2	1.8 (0. 37)		
MCA2 Distance (cm)	R1	2.3 (0. 09)	−0.01 (−0.06, 0.05)	0.801
	R2	2.3 (0. 09)		
MCA2 cross section (cm^2)	R1	0.7 (0. 44)	0.01 (0.01,0 .08)	0.167
	R2	0.7 (0. 43)		
MCA2 volume (cm^3)	R1	6.5 (3.63)	0.2 (−0.28, 0.71)	0.383
	R2	6.4 (3.59)		

SD standard deviation; *CI* confidence interval; *R1* first measurements; *R2* second measurements

*$p<0.05$, paired t tests

the anterior nares of each nasal cavity were recorded using AR computer software (RhinoScan Version 2.6 ed. 1.1, Denmark). The mean of five measurements were displayed as one curve, which was updated four times per second. As a result, the measurements were displayed as a curve where the cross-sectional area (cm^2) is represented on the x-axis and the distance from nostril (cm) is represented on the y-axis. The curve usually shows two valleys (notches) after a straight line (which represents the nosepiece). The first valley in the curve (MCA1) corresponds to the nasal valve region, whereas the second valley (MCA2) corresponds to the head of inferior turbinate [22].

The cross-sectional areas (cm^2), distances (cm), and volumes (cm^3) for both sides of the nose were obtained. As a result, MCA1 and MCA2 were recorded. In this study, both MCA1 and MCA2 as plotted on the rhinogram were used. Therefore, MCA1 refers to the narrowest part of the nasal passage detected between 0 and 2.2 cm (22 mm) from the anterior nares. MCA2 refers to the second narrowest part of the nasal passage detected between 2.2 and 5.4 cm (22–54 mm) from the anterior nares. Finally, the values from the right and left nostrils for every subject were summed to derive the MCA and volume for that individual.

Using appropriate software, the mean nasal airways were also reconstructed in 3-D, and the data were subjected to PCA and FEA. A PCA can be used to compare different groups of patients, with specific characteristics [14]. Normally, a few modes (the principal components) are sufficient to describe all of the shapes approximately. Importantly, the points representing the shapes in the mode space are grouped according to their main characteristics. Thus, PCA is determining axes that account for the maximal variance. If PCA is applied, the two most significant modes can be used for classification purposes [15]. In addition, FEA was used to depict clinical changes in terms of allometry (size-related shape change). Initially, Procrustes superimposition is used to rotate, translate, and scale the nasal configurations to equivalent size. Using FEA, the change in form between the reference nasal configuration and the target nasal configuration can then be viewed as a continuous deformation, which can be quantified based on major and minor strains (principal strains). These methodologies have been described in detail elsewhere [13–15] and will not be repeated here. AR measurements were also evaluated for reproducibility by taking ten subjects from the OSA and control groups (five from each) and, after 2 weeks, retaking the measurements of the same volunteer subjects (see Table 1). Statistical Package for Social Sciences (SPSS) software for Windows version 11 (SPSS Inc., Chicago) was used for statistical analysis. Means and standard deviations (SD) were used to describe continuous variables, and independent t tests were used (after confirming normal distribution of continuous variables) to test the differences between the numerical variables. A p value of 0.05 or less was considered statistically significant with 95% confidence intervals.

Results

Table 2 shows the distribution of the study subjects according to age and sex, and Table 3 shows the demographic profile of the 108 subjects. Table 4 shows the limited channel PSG data and physical examination findings. The results of the statistical analysis indicated that cross-sectional areas at the nasal valve (MCA1) and at the head of inferior turbinate (MCA2) were significantly smaller in the OSA group compared with control subjects ($p<0.05$; Table 5). Furthermore, by superimposing the mean 3-D nasal airway configurations of the OSA and control groups (Fig. 1), it was found that the mean nasal airway was significantly narrower in the OSA group compared to the control group, especially anteriorly at a distance between 2.2 and 5.4 cm from the anterior nares (starting just distal to the nasal valve/head of inferior turbinate region; Fig. 1).

Table 2 The distribution of study subjects according to age and sex

Subject	Sex	N	Mean age (years) (SD)	Range (min–max)
Normal	M 21 F 33	54	33.4 (13.32)	47 (18–65)
OSA	M 32 F 22	54	33.4 (13.32)	47 (18–65)
Total		108		

Table 3 Distribution of study subjects according to gender and OSA severity

Variables		Classification		Total
		Male (%)	Female (%)	Total (%)
OSA severity	Mild	3 (42.9%)	4 (57.1%)	7 (100%)
	Moderate	8 (57.1%)	6 (42.9%)	14 (100%)
	Severe	23 (69.7%)	10 (30.3%)	33 (100%)
Total		34 (63.0)	20 (37.0)	54 (100%)

Using PCA to compare the mean 3-D nasal airways, significant differences were also found ($p=0.008$), with the first two principal components accounting for some 94% of the total shape change (Fig. 2). In support of this finding, 3-D FEA showed that the mean 3-D nasal airway was also narrower in the OSA group compared to the control group in the nasal valve/head of inferior turbinate region at a distance between 2.2 and 5.4 cm from the anterior nares. Specifically, a decrease in size of ≈10–22% was found in the nasal valve/head of inferior turbinate region (Fig. 3; blue color).

Discussion

While several studies have reported on nasal airway measurements in patients with OSA, the strengths of the present study include: patients with OSA and control subjects that underwent limited hospital-based sleep studies and the use of robust 3-D geometric morphometric techniques for modeling and analysis. But, the value of secondary mathematical modeling using acoustic reflectometry remains unclear, and true 3-D reconstructions of the upper airway are now being undertaken [23]. Thus, the current study could not overcome some methodological limitations. First, the sample size was relatively small, limited by the number of subjects that met the criteria of the study. Second, generalization of the results to a larger population is limited because the sample subjects were care-seeking volunteers at a hospital clinic. This source of study subjects could introduce a potential selection bias into the investigation and make the results more applicable to hospital populations rather than the general public. Third, this study examined patients with OSA during wakefulness. Nevertheless, abnormalities of upper airway anatomy and physiology in subjects with OSA during wakefulness have been clearly documented [2]. Therefore, we believe that careful assessment of OSA data during wakefulness may provide some valuable information. Fourth, intranasal decongestant agents were not used in the current study, because the aim of using AR in this study was mainly to assess nasal airway morphology rather than the mucosal condition. However, most studies in the literature have made use of some type of decongestant during measurements to avoid the nasal cycle. The nasal cycle is recognized by some as a physiologic phenomenon that may cause a periodic change in nasal airway patency [24]. However, understanding of this unusual phenomenon is incomplete, and some suggest that there is little evidence for the nasal cycle effect [25]. In addition, it is believed that there is only a slight risk that the nasal cycle could affect the results of AR [26]. Fifth, male and female patients in this study were analyzed together, as endonasal geometry shows no statistical difference with regard to gender distribution [27]. However, Singh et al. [28] showed that, in general, the adult Malay male 3-D nasopharyngeal airway is narrower in the anterior nasal valve region closer to the nostril and wider in the distal regions of the 3-D nasopharyngeal airway compared to Malay females and teenage males. Sixth, even though the subjects were randomly selected and every attempt was made to match patients with OSA and control subjects for neck circumference and BMI, the OSA group was found to be somewhat more obese. Thus, it would have been useful to adjust the primary outcome parameters for sex and body weight. Therefore, this finding has to be taken into consideration when one interprets the results of this present study. Finally, generalization of the present results to different ethnicities, including other Asian populations, is limited because ethnic Malays may have unique anatomic/physiological differences in nasal structure and craniofacial features.

Table 4 Polysomnography data and physical examination findings

Variables	OSA (SD) (n=54)	Control (SD) (n=54)	Mean difference (95% CI)	p Value
Apnea–hypopnea index (events/h)	42.9 (29.65)	3.2 (3.95)	−39.6 (−47.76, −31.61)	0.001
Average oxygen saturation (%)	94.1 (4.44)	97.8 (1.07)	3.7 (2.50, 4.96)	0.001
Lowest oxygen saturation (%)	77.1 (10.15)	87.9 (7.02)	10.7 (7.46, 14.12)	0.001
Neck circumference (cm)	43.4 (5.64)	35.8 (3.58)	−7.8 (−9.58, −5.97)	0.001
Body mass index (kg/m^2)	33.2 (6.59)	22.7 (3.52)	−10.5 (−12.44, −8.62)	0.001

SD standard deviation; *CI* confidence interval

*$p<0.05$, independent t test

Table 5 Acoustic rhinometry findings

Variables	Control (n=54) Mean (SD)	OSA (n=54) Mean (SD)	Mean differences (95% CI)	p Value
MCA1 cross section (cm^2)	0.49 (0.16)	0.35 (0.18)	0.13 (0.06, 0.19)	0.001[a]
MCA1 volume (cm^3)	1.6 (0.34)	1.5 (0.44)	0.1 (−0.02, 0.27)	NS
MCA2 cross section (cm^2)	0.61 (0.25)	0.37 (0.27)	0.23 (0.13, 0.33)	0.001[a]
MCA2 volume (cm^3)	5.3 (1.75)	3.1 (1.70)	2.2 (1.56, 2.88)	0.001[a]

SD standard deviation; *CI* confidence interval; *NS* not significant

[a] Independent *t* test

Despite the above limitations, in this current study, nasal airway configurations were assessed using AR. AR is a quick, painless, and noninvasive method that can be used to estimate the degree of nasal obstruction, evaluate nasal cavity geometry, monitor nasal disorders, differentiate between obstruction due to mucosal hypertrophy and that due to skeletochondral deformity, and assess surgical outcomes [29]. Because of these advantages, AR became popular in a short period of time [30]. The sensitivity of AR in the anterior nasal cavity has been reported in previous studies [30–33]. Furthermore, differences in the nasal valve region suggest that patients with OSA may have relatively greater nasal congestion in the anterior nasal cavity, which might contribute to the development of OSA [34]. We believe this idea is not surprising as the internal nasal valve region is the narrowest part of the nasal passage and is the major source of nasal resistance. However, the location and nature of the nasal valve in the acoustic graph is still not clear. In some subjects, the MCA is located at the nasal valve, while in others, especially in cases of turbinate hypertrophy, it is located in the anterior part of the inferior turbinate [32]. Using AR in a non-decongested nasal cavity, the first minimum is attributed to the nasal valve, the second to the head of the inferior turbinate (concha), and the third minimum is usually attributed to the head of the middle turbinate [6]. Others consider the head of the inferior turbinate to be a component of the nasal valve area [30]. These studies highlight the deficiency of AR; while size information is mathematically calculated, anatomical shape information is absent. Thus, although this technique for 3-D airway reconstruction is potentially useful, it is simply a mathematical reconstruction based on CSA as a function of distance [13] and the subsequent 3-D reconstruction cannot represent true nasal airway anatomy, such as those obtained from CT scans [15], as shape information is not available through AR. Nevertheless, we believe that segmentation of measurements into the nasal valve region and the head of the inferior turbinate region as proposed by a previous study [22] is sufficient to meet the aims of our present study. We, therefore, believe that the AR technique may be useful for diagnosis, treatment planning, patient education, and assessment of snoring, SDB, OSA, and other nasopharyngeal conditions.

Additionally, as this current study used AR to construct 3-D nasal airways, and AR is a function of positional variation during data acquisition [35], all AR was performed in the upright position in all cases at all times with the patient sitting in the same chair. The same chair was used by the same author with patients sitting in it with a similar head position. Furthermore, the accuracy of AR has been tested by various imaging methods in clinical trials. These studies have revealed significant correlations between the CSA obtained by imaging techniques and the CSA obtained by AR, with particularly high agreement in the anterior nasal cavity [36, 37]. This

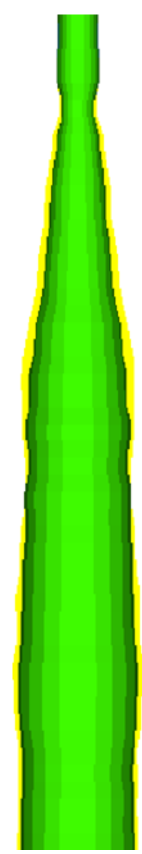

Fig. 1 Superimposition of mean OSA and control 3-D nasal airway configurations. The mean OSA airway (*green*) is narrower than the control 3-D nasal airway configuration (*yellow*) in the nasal valve/head of inferior turbinate region as well as further posteriorly

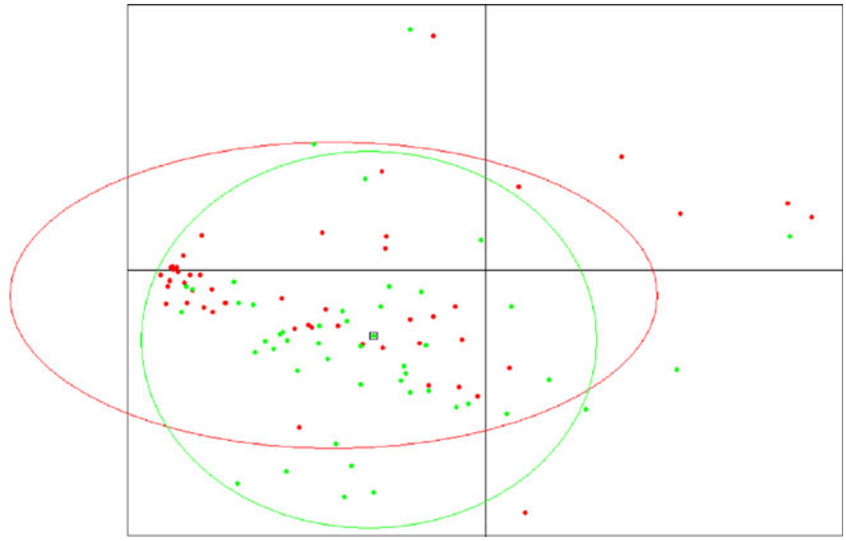

Fig. 2 Principal components analysis comparing the OSA nasal airways (*red dots*) to the control nasal airways (*green dots*). Using the first two principal components, which account for 94% of the total shape change, a significant difference was detected (p=0.008)

finding of a significant correlation between AR data and CT data shows that AR is a valuable method for measuring nasal valve area. Therefore, we believe the results of the present study, which indicate differences in the anterior nasal valve region using a 3-D reconstruction technique, are reliable.

The present study using AR indicates that the control MCA for in Malays was 0.49±0.16 cm^2, while it has been reported that the mean MCA in oriental Asians is 0.62±0.19 cm^2 [38]. Similarly, the MCA among Vietnamese, Korean, and Siamese Asians was found to be 0.59±0.16 cm^2 [39], which is higher than our Malaysian control value. We believe that the variations in MCA are probably due to anatomic, ethnic differences in nasal structure as well as physiological differences in the degree of mucosal swelling. In addition, differences in the manufacture of the

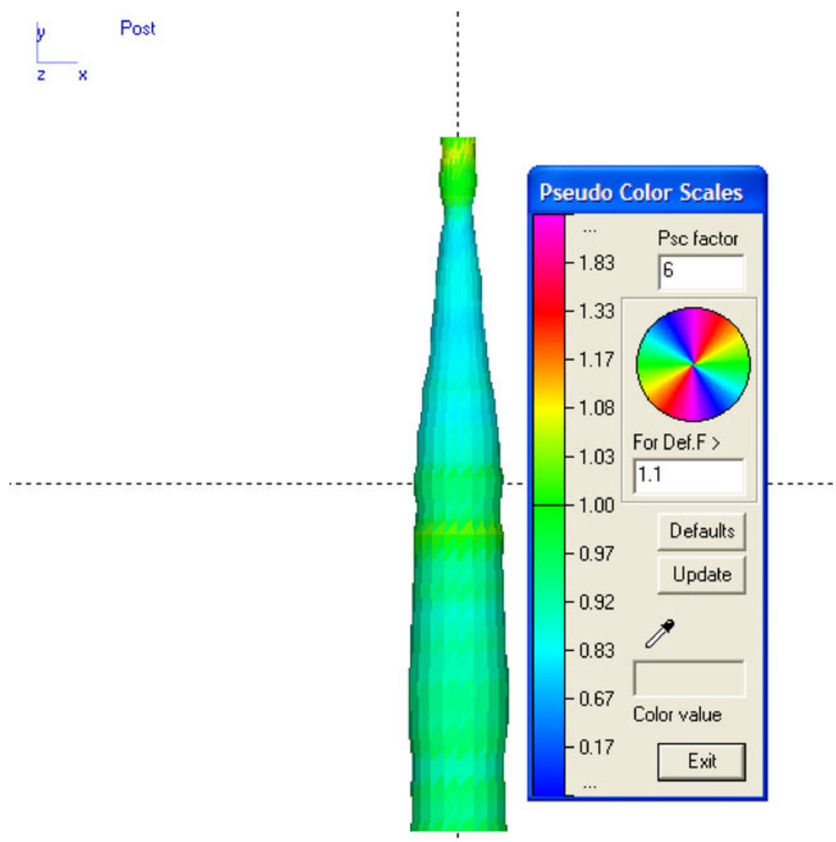

Fig. 3 Finite-element analysis of mean OSA and control 3-D nasal airway configurations by size. The *vertical pseudo-color scale bar* indicates the degree of size change. A size decrease of approx. 10–22% (*light blue color*) appears in the nasal valve/head of inferior turbinate region predominantly, at a distance between 2.2 and 5.4 cm from the anterior nares

rhinometer, the nasal adapter, the inclusion criteria in subject selection, and the amount of local decongestant might explain the differences in the values found in this study and others.

The present study using AR indicates that cross-sectional areas in the nasal valve (MCA1) and at the head of inferior turbinate (MCA2) are significantly smaller in the OSA group compared with control subjects (Table 5). In support of these statistical findings, 3-D nasal cavity reconstruction indicated that the mean 3-D nasal airway of the OSA group was narrower, especially in the nasal valve region (Figs. 1 and 3). Based on these findings, we hypothesize that the constriction in the nasal valve region in adult Malays might explain the increased tendency for snoring, SDB, and OSA in this group of patients. However, weight reduction does not seem to have any effect on nasal resistance or volume in overweight patients with mild OSA. Indeed, patients with OSA and impaired nasal breathing need specific medical or surgical treatment to restore nasal airflow [40]. Therefore, we suggest that widening of the internal nasal airway using nonsurgical management [15] might be a treatment option for Malaysians. However, previous studies demonstrated that the accuracy of AR diminishes at locations posterior to the nasal valve area [30–32]. This lack of precision occurs as the acoustic pulses lose power as they contact and pass through narrowed regions, which makes it difficult to assess the actual areas of the more posterior sections of the nasal passages. This lack of precision might explain why no differences in 3-D nasal cavity volume were found in this present study. Fortunately, the nasal valve area is located in the anterior portion of the nasal cavity, and we limited our AR measurements to 5 cm, which is considered an acceptable and valid limit [22, 41].

It can also be noted that in this present study, subjects with severe OSA had a smaller MCA (Table 5). Therefore, our findings agree with a study of Taiwanese subjects with sleep disorders, which also concluded that patients with severe OSA tend to have smaller MCAs when compared with patients with mild or moderate OSA (AHI of <30 events/h) [42]. Indeed, having a smaller nasal CSA might not only contribute to the development of OSA but might also have an adverse effect on CPAP use. Standard CPAP devices can provide therapeutic levels of pressure to overcome upper airway resistance. However, it has been found that CPAP use is lower in those patients with smaller nasal CSAs compared with those that have larger nasal passages [42]. According to Bernoulli's principle, when patients demonstrate smaller nasal passages, the airflow velocity might increase; thus, the effort of breathing discomfort might increase and subsequently decrease the wish to use CPAP [43]. Thus, we suspect that Malaysian patients with OSA with nasal obstruction due to small MCAs may not be comfortable or compliant with CPAP. This notion provides a promising area for a future study. In addition, when FEA was used to determine the effect of a removable orthodontic appliance [44], nonsurgical airway remodeling or a pneumopedic effect was found that enhanced the upper airway in children. This approach provides yet another avenue of further research.

Conclusions

Differences in 3-D nasal airway morphology when comparing patients with OSA to control subjects are identifiable. These differences need to be recognized as they can improve our understanding of the etiological basis of OSA and facilitate its management.

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Conflict of interest The authors declare that they have no conflict of interest.

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