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Evaluation of pharyngeal shape and size using anatomical optical coherence tomography in individuals with and without obstructive sleep apnoea

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SUMMARY This study compared shape, size and length of the pharyngeal airway in individuals with and without obstructive sleep apnoea (OSA) using a novel endoscopic imaging technique, anatomical optical coherence tomography (*a*OCT). The study population comprised a preliminary study group of 20 OSA patients and a subsequent controlled study group of 10 OSA patients and 10 body mass index (BMI)-, gender- and age-matched control subjects without OSA. All subjects were scanned using *a*OCT while awake, supine and breathing quietly. Measurements of airway cross-sectional area (CSA) and anteroposterior (A-P) and lateral diameters were obtained from the hypo-, oro- and velopharyngeal regions. A-P : lateral diameter ratios were calculated to provide an index of regional airway shape. In all subjects, pharyngeal CSA was lowest in the velopharynx. Patients with OSA had a smaller velopharyngeal CSA than controls (maximum CSA 91 ± 40 versus 153 ± 84 mm^2; $P < 0.05$) but comparable oro- (318 ± 80 versus 279 ± 129 mm^2; $P = 0.48$) and hypopharyngeal CSA (250 ± 105 versus 303 ± 112 mm^2; $P = 0.36$). In each pharyngeal region, the long axis of the airway was oriented in the lateral diameter. Airway shape was not different between the groups. Pharyngeal airway length was similar in both groups, although the OSA group had longer uvulae than the control group (16.8 ± 6.2 versus 11.2 ± 5.2 mm; $P < 0.05$). This study has shown that individuals with OSA have a smaller velopharyngeal CSA than BMI-, gender- and age-matched control volunteers, but comparable shape: a laterally oriented ellipse. These findings suggest that it is an abnormality in size rather than shape that is the more important anatomical predictor of OSA.

KEYWORDS imaging, obstructive sleep apnoea, optical coherence tomography, pharyngeal, pharynx

INTRODUCTION

Pharyngeal shape and size are thought to play an important role in the pathogenesis of obstructive sleep apnoea (OSA). A consistent finding among previous studies is that the upper airway, and particularly the velopharyngeal airway, is smaller in individuals with OSA compared with those without (Arens *et al*., 2005; Ciscar *et al*., 2001; Haponik *et al*., 1983; Horner *et al*., 1989; Schwab *et al*., 1993, 1995). A narrowed upper airway may be particularly susceptible to collapse in the presence of sleep-related loss of compensatory dilator muscle activity. Less clear is whether or not airway shape differs

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between individuals with and without OSA and, if present, whether differences in shape contribute to the predisposition to upper airway collapse. Several studies have reported that the apnoeic airway is narrower in the lateral dimension, giving it an anteroposteriorally oriented elliptical shape (Arens *et al.*, 2005; Rodenstein *et al.*, 1990; Schwab *et al.*, 1993). It has been suggested that such a shape may be mechanically disadvantageous for the upper airway dilator muscles, which attach to the anterior border of the pharynx and may contribute to the propensity for airway collapse in OSA (Leiter, 1996). However, the finding of an anteroposteriorally oriented ellipse is not universal with some studies reporting a laterally oriented elliptically shaped airway in apnoeics, similar to that observed in individuals without OSA (Pevernagie *et al.*, 1995; Ryan and Love, 1996). Characterizing pharyngeal morphology in OSA is important because it bears directly on the pathogenesis of the condition, on its clinical assessment, and on the likely efficacy of surgical and non-surgical treatments.

Anatomical optical coherence tomography (*a*OCT) is a novel, minimally invasive endoscopic technique based on near-infrared light that has been found to be useful in the quantitative assessment of upper airway shape and size (Armstrong *et al.*, 2006). Preliminary studies have shown *a*OCT to have excellent comparability with computed tomography (CT)-derived measurements of airway shape and size as well as excellent reproducibility and inter- and intra- observer reliability, particularly in the velopharyngeal region (Armstrong *et al.*, 2006). The real-time, quantitative cross sectional (axial) images can be temporally aligned with the respiratory cycle (Armstrong *et al.*, 2006). These capabilities, together with its non-radiological nature, make *a*OCT particularly suited for use in studies of pharyngeal morphology involving repeated measures under a variety of conditions in normal volunteers as well as OSA patients.

The present study utilized these capacities of *a*OCT to compare size, shape and length of the pharynx in individuals with and without OSA. We hypothesized that measurements of pharyngeal size, shape and length would be different in individuals, with and without OSA, who were matched for body mass index (BMI), age and gender. These morphological characteristics could be important in identifying predisposition to OSA.

METHODS

This study was conducted in two parts. In the first part, images of the upper airway were obtained during wakefulness in 20 randomly selected OSA patients attending an outpatient clinic. The purpose was to obtain preliminary measurements of upper airway shape and size and to demonstrate the feasibility of making such measurements in these individuals. In the second part of the study, images of the upper airway were obtained during wakefulness in a further 10 OSA patients and 10 BMI-, age- and gender-matched control volunteers without OSA.

Subjects

Preliminary study

Twenty patient volunteers were recruited from those who had recently undergone a laboratory-based polysomnogram that diagnosed OSA with an apnoea–hypopnoea index (AHI) >10. They were not currently receiving treatment for OSA nor had undergone upper airway surgery.

Matched groups study

Ten patient volunteers were recruited from those who had recently undergone a clinic-based polysomnogram that confirmed OSA (AHI >10). None of these patients participated in the preliminary study and all were otherwise healthy and had not previously received treatment for OSA including upper airway surgery. Ten BMI-, gender- and age-matched control subjects who were otherwise healthy and without a history of habitual snoring were recruited from local service clubs. A full night of laboratory-based polysomnography was performed to confirm the absence of OSA.

The Human Research Ethics Committee at Sir Charles Gairdner Hospital approved the project and informed written consent was obtained from all participants.

Protocol

On each occasion, in each subject, a catheter containing the *a*OCT probe was passed via the nares into the oesophagus (see Measurements section). A single *a*OCT 'pullback' scan was then performed from the level of the hypopharynx to velopharynx. Measurements of upper airway shape and size were determined on a *post-hoc* basis from these pullback scans.

All scans were made while the subject was supine, relaxed and awake. Because head and body position have been shown to influence airway size (Ono *et al.*, 2000) subjects were carefully positioned with the head and neck in a constant posture throughout all scanning. Specifically, the head was supported with a Shea headrest (Gyrus ENT, Memphis, TN, USA) and aligned with the Frankfort plane (line from infra-orbital rim to tragus of the ear) perpendicular to the bed. The subject was instructed to not to speak and to breathe normally via the nose during scanning. To ensure a constant tongue position was maintained during scanning, subjects were instructed to relax their tongue with the tip resting on the posterior surface of the upper incisors.

Standard anthropometric measurements were also collected from each subject, including height, body mass and neck circumference at the level of the cricoid cartilage.

Measurements

Upper airway imaging

The *a*OCT technique has been described in detail elsewhere (Armstrong *et al.*, 2003, 2006) Briefly, an optical probe is placed inside a sealed, transparent catheter (3.0 mm outside diameter) that is inserted via the nares to mid-oesophageal level. Prior to insertion, topical anaesthesic (10% lidocaine spray) is applied to the mucosa of the nose and throat to minimize any discomfort. Once in position, the catheter is taped to the external nares. The optical probe is able to be moved systematically within the catheter without displacing it.

The system operates by directing a light beam perpendicular to the catheter. The distance between the optical probe head and the air–tissue interface of the airway wall is determined from the reflected light using a low-coherence optical interferometer. The probe rotates at 1.25 Hz to capture quantitative cross-sectional images of the upper airway lumen, in much the same way that a radar system captures an image. A customised C++ program controls a motorised translation stage that allows the probe head to be precisely rotated and translated to various levels within the pharynx to record cross-sections of interest. The distance of the probe from the external nares is continuously recorded. The cross-sectional images are viewed graphically in real time on a computer and also reconstructed in video format for *post-hoc* analysis.

Each pullback scan was performed by systematically retracting the optical probe from the upper oesophagus to the nasal cavity at a constant speed (0.2 mm s^{-1}). The subject used a pre-arranged hand signal to indicate any swallowing, and an electronic tag was noted on the image at that time point. These images were excluded from subsequent analyses. Each pullback scan took between 9 and 12 min.

Phase of respiration

Respiratory data were recorded only during the matched groups study. Rib cage and abdominal motion were continuously monitored by respiratory inductance pneumography (Respitrace; Ambulatory Monitoring, Ardsley, NY, USA) with the transducers at the level of the nipples and umbilicus, respectively. These signals were calibrated by an isovolume manoeuvre and electronically summed to provide a measure of volume displacement. The ribcage, abdominal and summed signals were continuously digitally recorded at 1000 Hz on a Powerlab data acquisition and analysis system (model 16s; ADInstruments, Sydney, NSW, Australia).

Analyses

Images obtained from each pullback scan were reconstructed to provide a single quantitative video of the entire scan. In studies in which pneumography (Respitrace) was also recorded, the summed signal was time-synchronised and integrated into the video. Each frame of the video was available for analysis and provided a single cross-sectional (axial) image of the upper airway. Accompanying each axial image was an A-P (sagittal) longitudinal view, a lateral (coronal) longitudinal view and a summed pneumography signal. Each of these was marked with the precise temporal location at which the axial image was obtained.

Analyses of *a*OCT images were performed using ImageJ software (National Institutes of Health, Bethesda, MD, USA). For each image, the mucosa–lumen interface was manually traced and airway CSA calculated. A-P diameter was calculated at the widest point in the para-sagittal plane and lateral diameter was measured at the widest point in the coronal plane, perpendicular to the A-P diameter (Pevernagie *et al.*, 1995; Schwab *et al.*, 1993). In cases where images for successive respiratory cycles at a given location were analysed, each was performed independently and the mean value used for statistical analyses.

Image selection

Several landmarks are readily identifiable from *a*OCT-derived images of the upper airway (Fig. 1). These include the base of the epiglottis (as the probe exits the upper oesophageal sphincter), tip of the epiglottis, tip of the uvula, base of the uvula (just craniad to the palatal rim) and the posterior choanae (as the probe passes into one nasal chamber). These landmarks were used to define the following regions of interest: the hypopharynx (base to tip of epiglottis); the oropharynx (tip of epiglottis to base of uvula) and the velopharynx (distal portion of the nasopharynx immediately proximal to the base of the uvula). Images were selected for analysis in the middle of the hypo- and oropharygeal regions. Where the uvula was visible in the mid-oropharynx, images distal to the tip were selected. Velopharyngeal scans were obtained 5 mm craniad to the base of the uvula. Length of uvula was measured as the distance from the tip to base of the uvula.

Image analysis

For the preliminary study, phasic changes in airway CSA with inspiration and expiration were used to identify each respiratory cycle. At each of the three pharyngeal regions, images were selected for analysis at the maximum and minimum CSA within a single respiratory cycle. No assumptions were made as to the precise relationship between maximum and minimum CSA and phase of respiration.

For the matched groups study, measurements of pharyngeal CSA and lateral and A-P dimensions were obtained at the point of maximum and minimum CSA during three successive respiratory cycles at each of the velo-, oro- and hypopharynx. In cases where images from three respiratory cycles were not available for analysis, two successive cycles or one cycle was used if by inspection of the *post-hoc* video they were judged to be representative of that region. Images used for analysis had at least 75% of the airway circumference visible including both lateral extents. Where a complete airway profile was not visible a straight line connected the portions of the airway circumference that were visible. No assumptions were made as to the relationship between maximum and minimum CSA and phase of respiration; however, for all measurements the phase of respiration in which maximum and minimum CSA occurred was noted.

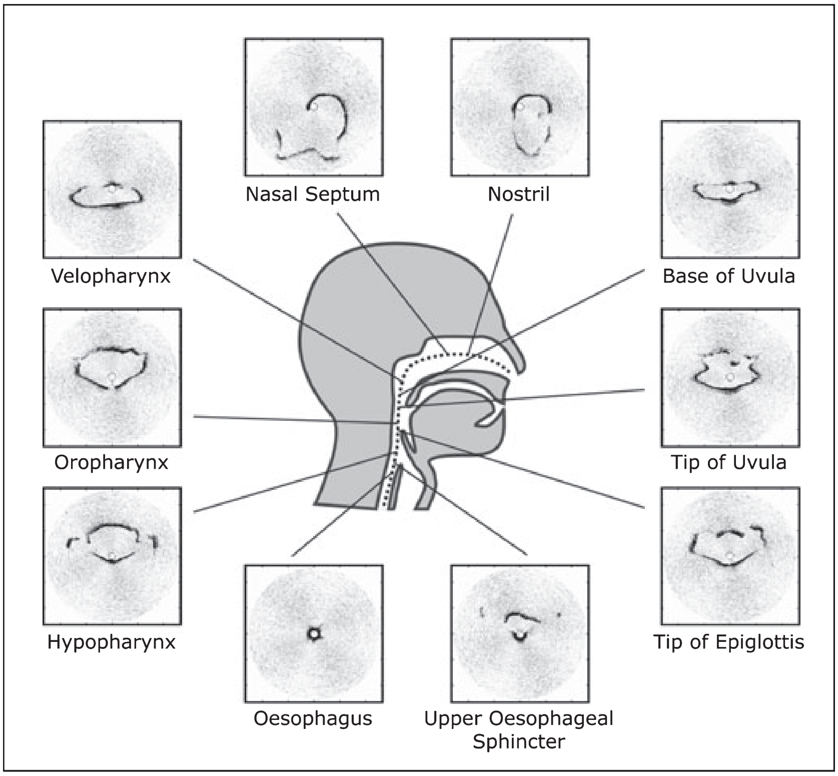

Figure 1. Selected cross-sectional (axial) images (52 mm × 52 mm) from a 'pullback' of a representative subject. The scan was initiated in the upper oesophagus and was completed in one nostril. The images show various anatomic landmarks and regions of the pharynx.

Statistical analyses

Student's unpaired *t*-test was used to compare longitudinal airway dimensions between the control and matched OSA groups. ANOVA was used to detect differences in regional pharyngeal dimensions between the groups. Pearson correlation coefficient analyses were performed between all physical characteristics, upper airway measurements and AHI and apnoea index (AI). A Holm and Sidak test was applied for all *post-hoc* comparisons. Significance was accepted at $P < 0.05$.

RESULTS

Characteristics of the 20 preliminary OSA subjects (OSA preliminary), 10 OSA subjects (OSA matched) and 10 BMI-, gender- and age-matched control subjects (control matched) are presented in Table 1. In some individuals, at some sites, it was not possible to view the complete circumference of the airway (see Image analysis in Methods section). An example of this is the hypopharyngeal region (see Fig. 1), in which the epiglottis shadows the lower aspect of the anterior retroglossal pharyngeal wall. In the 40 subjects examined in the present study, cross-sectional (axial) images with at least 75% of the airway circumference (including lateral extents) visible (see Image analysis in Methods section) were obtained in 91, 83 and 74% of scans performed in the velo-, oro- and hypopharyngeal regions, respectively. Of the images analysed, 55% were complete profiles with the remainder requiring straight line extrapolation to connect the visible portions of the airway profile. Straight line extrapolation was required in 56, 30 and 47% of scans performed in the velo-, oro- and hypopharyngeal regions, respectively, with the frequency of extrapolation being similar in subjects with and without OSA.

Table 1 Baseline characteristics and regional pharyngeal lengths for all obstructive sleep apnoea (OSA) patients and healthy control subjects

	OSA (preliminary) (n = 20)	*OSA (matched) (n = 10)*	*Control (matched) (n = 10)*
Gender (male/female)	13/7	10/0	10/0
Apnoea–hypopnoea index (*n* per hour)	42.6 ± 25.7*	29.5 ± 10.7*	3.1 ± 2.5
Apnoea index (*n* per hour)	6.8 ± 13.4*	3.3 ± 4.4*	0.3 ± 0.6
Age (years)	52 ± 13	57 ± 14	59 ± 10
Body mass index (kg m^{-2})	32.0 ± 6.2	28.0 ± 2.4	26.1 ± 1.6
Neck circumference (cm)	41.9 ± 5.3	40.3 ± 1.9	39.9 ± 2.0
Pharyngeal lengths			
Total airway (mm)	–	103.6 ± 3.5	104.5 ± 8.9
Hypopharynx (mm)	–	34.6 ± 3.4	35.5 ± 6.7
Oropharynx (mm)	–	27.4 ± 5.7	28.2 ± 3.7
Velopharynx (mm)	–	41.6 ± 3.5	40.8 ± 5.6
Uvula (mm)	–	16.8 ± 6.2 *	11.2 ± 5.2

Values are mean ± SD. *$P < 0.05$ versus control (matched) group.

Preliminary study

Maximum and minimum CSA during respiration and the corresponding lateral and A-P diameters are shown for all

Table 2 Cross-sectional area (CSA), anteroposterior (A-P) diameter, lateral diameter and ratio of A-P : lateral diameters at maximum and minimum airway CSA during respiration in the velo-, oro- and hypopharynx

	OSA (preliminary) (n = 20)		*OSA (matched) (n = 10)*		*Control (matched) (n = 10)*	
	Maximum CSA	*Minimum CSA*	*Maximum CSA*	*Minimum CSA*	*Maximum CSA*	*Minimum CSA*
Velopharynx						
CSA (mm^2)	87 ± 40*	60 ± 30*	91 ± 40*	64 ± 30*	153 ± 84	106 ± 29
A-P diameter (mm)	6.7 ± 1.8*	5.7 ± 1.6*	7.0 ± 1.3	6.1 ± 1.6	9.0 ± 2.5	7.8 ± 1.9
Lateral diameter (mm)	18.2 ± 7.3	15.5 ± 6.0	19.7 ± 7.0	16.4 ± 5.3	22.9 ± 6.2	20.5 ± 4.0
A-P : lateral ratio	0.36 ± 0.21	0.36 ± 22	0.27 ± 0.15	0.27 ± 0.15	0.29 ± 0.05	0.27 ± 0.07
Oropharynx						
CSA (mm^2)	258 ± 102	203.6 ± 95.3	318 ± 80	241 ± 81	279 ± 129	242 ± 116
A-P diameter (mm)	14.4 ± 4.9	13.1 ± 4.6	15.4 ± 4.4	13.6 ± 5.0	13.5 ± 3.0	11.8 ± 2.1
Lateral diameter (mm)	27.0 ± 7.2	23.7 ± 7.6	31.9 ± 6.2	29.2 ± 5.5	29.5 ± 8.0	28.8 ± 9.0
A-P : lateral ratio	0.56 ± 0..24	0.58 ± 0.29	0.46 ± 0.13	0.42 ± 0.15	0.44 ± 0.10	0.41 ± 0.09
Hypopharynx						
CSA (mm^2)	305 ± 151	243 ± 144	250 ± 105	162 ± 68	303 ± 112	191 ± 70
A-P diameter (mm)	16.4 ± 3.5	14.3 ± 4.9	13.2 ± 3.3	10.8 ± 3.1	15.6 ± 2.9	12.5 ± 2.8
Lateral diameter (mm)	27.1 ± 5.8	25.0 ± 9.4	29.4 ± 8.6	23.9 ± 7.6	30.8 ± 7.0	26.9 ± 9.4
A-P : lateral ratio	0.63 ± 0.26	0.61 ± 0.31	0.44 ± 0.05	0.47 ± 0.19	0.52 ± 0.17	0.55 ± 0.40

Values are mean ± SD. *$P < 0.05$ versus control (matched) group.

regions in Table 2. The increase in airway CSA from minimum to maximum was 53 ± 43, 33 ± 32 and 62 ± 134% in the velo-, oro- and hypopharynx, respectively. These changes were associated with an increase in A-P diameters of 19 ± 27, 12 ± 13 and 29 ± 54%, and lateral diameters of 21 ± 21, 17 ± 22 and 13 ± 33%, respectively.

The ratio of A-P to lateral diameters provides an index of the circularity of the airway, with a ratio of 1.0 representing a circle, a ratio less than 1.0 representing an ellipse with its long axis oriented laterally, and a ratio greater than 1.0 representing an ellipse with its long axis oriented in the A-P dimension. An A-P : lateral ratio of less than 1.0 was observed in all but two subjects in the oropharynx and one subject in the hypopharynx (Fig. 2). In the few cases where A-P : lateral ratio exceeded 1.0, the measurements were obtained at a time when CSA was at its least. Representative changes in airway shape and size for all subjects are shown schematically in Fig. 3.

Matched groups study

Cross-sectional area

Maximum and minimum CSA in the velo-, oro- and hypopharynx in both the OSA and control groups are listed in Table 2. Maximal CSA in the velopharyngeal region was significantly less in the OSA than in the control group ($P < 0.05$) but of similar size in the oropharyngeal ($P = 0.48$) and hypopharyngeal regions ($P = 0.36$) (Table 2). Minimum CSA showed a similar pattern with between-group differences noted in the velopharyngeal ($P < 0.01$) but not oropharyngeal ($P = 0.98$) or hypopharyngeal ($P = 0.45$) regions.

In the control group, the increase in airway CSA from minimum to maximum was 35 ± 45, 17 ± 9 and 51 ± 23% in the velo-, oro- and hypopharynx, respectively. In the OSA group, the increase was 58 ± 87, 36 ± 31 and 59 ± 48%, respectively.

There was no consistent relationship between the phase of respiration and maximum and minimum pharyngeal dimensions. For example, in the velopharynx maximum CSA was observed in the expiratory phase of the respiratory cycle in 72% of images from control subjects and 57% of images from OSA subjects.

Axial diameters

Lateral and A-P airway diameters were similar in the OSA and control groups in all pharyngeal regions at both maximum and minimum CSA (Table 2).

A-P : lateral ratio

The ratio of A-P : lateral diameters was similar in OSA and control groups in all pharyngeal regions at both maximum and minimum CSA (Table 2). The majority of subjects had an A-P : lateral ratio less than 1.0, indicating a laterally oriented elliptically shaped airway (Fig. 2). Only three OSA subjects and one control subject had an A-P : lateral ratio greater than 1.0. These few observations were only seen in the oro- and hypopharyngeal regions, predominantly when measurements were obtained at minimum CSA. These four subjects were all men but did not have other characteristics that were obviously different from the other subjects. An airway with a ratio >1.0 was not observed in the velopharynx (Fig. 2). Representative changes in airway shape and size for the groups overall are shown schematically in Fig. 3.

Pharyngeal length

Total and regional pharyngeal lengths for OSA and age-, BMI- and gender-matched control subjects are listed in Table 1. Total upper airway length from the base of epiglottis to the

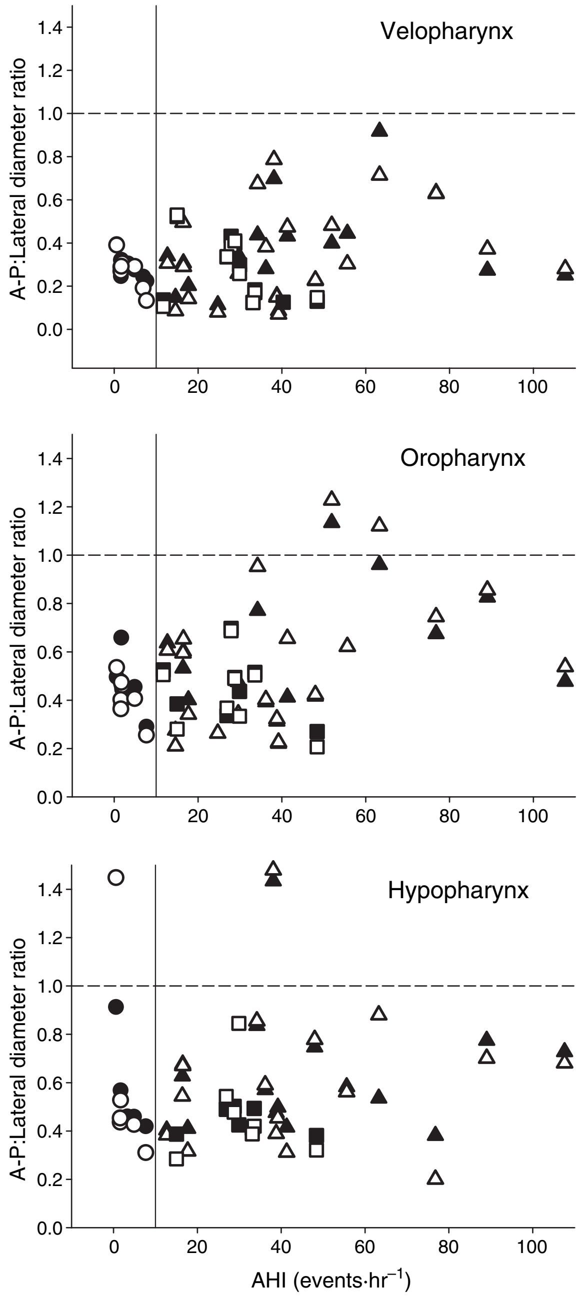

Figure 2. Anteroposterior/lateral (A-P:L) diameter ratios for all preliminary OSA patients (triangles), control subjects (circles) and BMI-, gender- and age-matched OSA patients (squares) and in the velopharynx (upper), oropharynx (middle) and hypopharynx (lower) at the time of maximum (closed symbols) and minimum (open symbols) airway CSA. A solid vertical line separates OSA and control subjects. A dotted horizontal line defines a ratio = 1.0. A ratio less than 1.0 indicates an airway with a laterally oriented ellipse. A ratio greater than 1.0 indicates an airway with an ellipse-oriented anteroposteriorly.

posterior choanae was similar in the OSA and control groups ($P > 0.7$). The lengths of each of the pharyngeal regions were also similar between the groups (all $P > 0.7$). However, within the oropharynx the length of the uvula (tip to base of uvula) was 50% longer in the OSA group than in the control group ($P < 0.05$; Table 1).

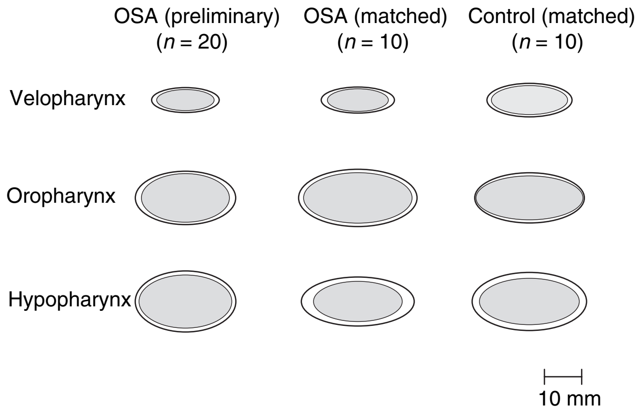

Figure 3. Schematic view (to scale) of the maximum (open ellipses) and minimum (filled ellipses) airway size and shape of the velopharynx (upper), oropharynx (middle) and hypopharynx (lower) in healthy control subjects and BMI-, gender- and age-matched OSA patients, as well as OSA patients who participated in the preliminary study.

Relationship between upper airway dimensions, physical characteristics and AHI

The relationship between AHI and maximum and minimum velopharyngeal CSA for healthy control and age-, BMI- and gender-matched OSA subjects is shown graphically in Fig. 4. There was a significant inverse correlation between AHI and minimum CSA ($r = -0.63$; $P < 0.01$; Fig. 4), but not maximum CSA ($r = -0.30$; $P = 0.2$). The A-P diameter at minimum CSA was inversely correlated with AHI ($r = -0.53$; $P < 0.05$) but the A-P diameter at maximum CSA ($r = -0.39$; $P = 0.09$) and the lateral dimensions at both maximum and minimum were not (both $P > 0.05$). There was no relationship between the A-P : lateral diameter ratios at both maximum and minimum CSA and AHI (all $P > 0.05$). Oro- and hypopharyngeal airway dimensions were not related to AHI (all $P > 0.05$). The AI correlated with the AHI ($r = 0.64$, $P < 0.01$) but not with any upper airway dimension (all $P > 0.05$).

There was a significant correlation between AHI and BMI ($r = 0.50$; $P < 0.05$) but not between AHI and neck circumference ($r = 0.26$; $P = 0.30$). BMI correlated directly with uvula length ($r = 0.51$; $P < 0.05$) and the A-P/lateral diameter ratio at minimum CSA ($r = 0.52$; $P < 0.05$) and inversely with the lateral diameter at maximum and minimum CSA ($r = -0.49$ and -0.64; both $P < 0.05$). Neck circumference did not correlate with any upper airway dimension (all $P > 0.05$).

DISCUSSION

This study used *a*OCT to compare pharyngeal shape, size and length in 10 individuals with and 10 without OSA, matched for age, gender and BMI. Relative to healthy controls, velopharyngeal CSA was approximately 40% less in those with OSA, even when matching for respiration-related changes in airway size. In contrast, oro- and hypopharyngeal sizes were similar

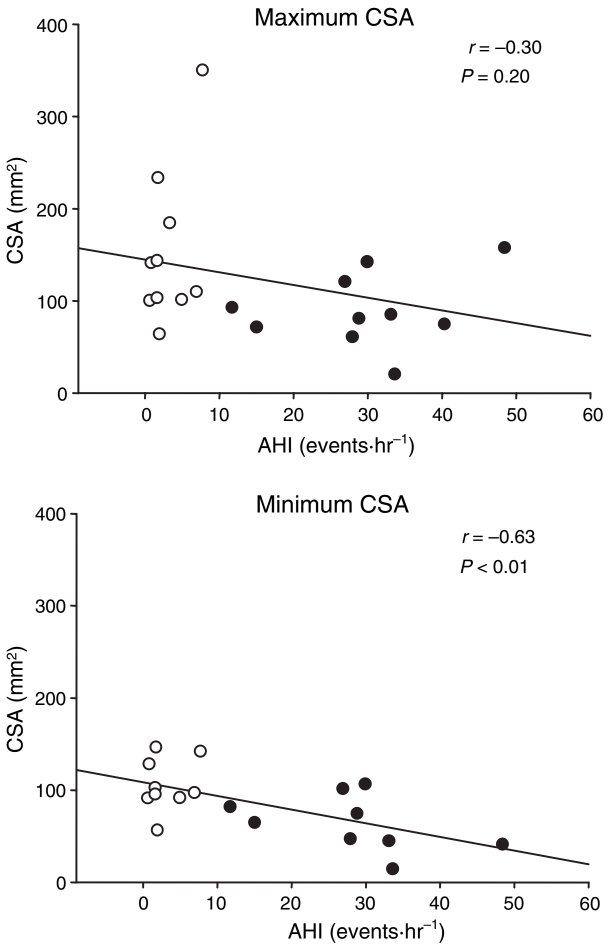

Figure 4. The relationship between apnoea-hypopnoea index (AHI) in healthy control (open symbols) and BMI-, gender- and age-matched OSA subjects (closed symbols) and maximum (left panel) and minimum (right panel) velopharyngeal cross-sectional area (CSA). Minimum data from one OSA and one control subject are missing due to incomplete profiles.

between groups, irrespective of respiration-related changes in airway size. Relating A-P to lateral dimensions, indicative of airway shape, showed that both groups had a transversely oriented, elliptically shaped airway with the largest dimension in the lateral axis. This shape was observed at all sites in the upper airway in these subjects, as well as in an additional 20 subjects with OSA who participated in preliminary studies.

Airway size

The airway size findings obtained with this novel technique are largely consistent with those obtained using other techniques such as MRI, CT and videoendoscopy, which have identified the velopharynx as the narrowest upper airway region in both OSA (Arens *et al*., 2005; Ciscar *et al*., 2001; Haponik *et al*., 1983; Horner *et al*., 1989; Hsu *et al*., 2004; Kuna *et al*., 1988; Schwab *et al*., 1993, 1995, 2003; Suratt *et al*., 1983) and normal subjects (Arens *et al*., 2005; Ciscar *et al*., 2001; Haponik *et al*., 1983; Horner *et al*., 1989; Hsu *et al*., 2004; Kuna *et al*., 1988; Schwab *et al*., 1993, 1995, 2003; Suratt *et al*., 1983). Furthermore, the present findings support previous work showing the velopharynx to be narrower in apnoeic patients than controls (Arens *et al*., 2005; Ciscar *et al*., 2001; Haponik *et al*., 1983; Schwab *et al*., 1993, 1995) and confirm the relationship between minimum CSA and the AHI (Vos *et al*., 2007). Our data show that these differences are specific to the velopharynx, as oropharyngeal and hypopharyngeal dimensions were similar in OSA and normal subjects.

Anatomical OCT permits the measurement of dynamic changes in upper airway dimensions in the same individual over many breathing cycles, enabling changes in airway calibre to be related to the phase of breathing. In the present study, the maximum calibre of the narrowest segment (the velopharynx) was frequently seen during expiration, a finding consistent with that of others (Morrell and Badr, 1998; Morrell *et al*., 1998; Schwab *et al*., 1993). However, this pattern was not always observed: maximum CSA occurred during inspiration in 35% of velopharyngeal images analysed. Such inter- and intra-subject variability in the relationship of pharyngeal CSA to phase of respiration has previously been reported (Launois *et al*., 1996; Morrell *et al*., 1998). It is likely that this variability reflects the conflicting influences of transmural pressure gradients, pharyngeal muscle recruitment and the stabilizing effect of longitudinal traction associated with increases in lung volume (Heinzer *et al*., 2006; Van De Graaff, 1988). The specific relationship between airway size and respiratory phase is a consequence of the relative contribution of each of these influences, along with other factors such as anatomy; head, neck and body posture; and state (Morrell and Badr, 1998; Morrell *et al*., 1998).

Most previous studies using other imaging modalities have not accounted for these dynamic changes and have reported a mean CSA obtained across multiple respiratory cycles or during a single breath-hold at the end of expiration (Fogel *et al*., 2003; Kuna *et al*., 1988; Rodenstein *et al*., 1990; Schwab *et al*., 1995; Suratt *et al*., 1983). Recent studies of within-breath changes in pharyngeal CSA using MRI have reported a significantly smaller minimum velopharyngeal CSA in apnoeics than controls (Arens *et al*., 2005; Ciscar *et al*., 2001). These findings are consistent with those of the present *a*OCT study and with our observation that minimum CSA was significantly inversely correlated with AHI.

Airway shape

The shape of the pharyngeal airway has been thought to be an important potential contributor to airway collapsibility in OSA (Leiter, 1996). It has been suggested that an elliptically shaped airway with its long axis oriented in the A-P direction increases susceptibility to collapse because of the proximity of the lateral walls to each other. Such a shape was thought to be disadvantageous, as pharyngeal dilating muscles, which mostly act to stabilize and increase airway diameter in the A-P direction, would have less effect on airway CSA than if the airway was oriented with its long axis in the lateral dimension

(Leiter, 1996). Several studies have suggested that this mechanism may contribute to OSA pathogenesis as they have demonstrated that the upper airway in individuals with OSA is elliptical with its long axis in the A-P direction, in contrast to healthy individuals who have an elliptically shaped airway with its long axis in the lateral direction (Arens *et al*., 2005; Fogel *et al*., 2003; Rodenstein *et al*., 1990; Schwab *et al*., 1993).

Contrary to these findings, our measurements demonstrated an airway that was oriented with its long axis in the lateral dimension for all pharyngeal regions, for all individuals with (n = 30) and without OSA (n = 10), regardless of whether the measurements were obtained at maximum or minimum CSA. Similar findings have been reported using other techniques in individuals with and without OSA (Ciscar *et al*., 2001; Hsu *et al*., 2004; Kuna *et al*., 1988; Pevernagie *et al*., 1995; Ryan and Love, 1996; Ryan *et al*., 1999; Schwab *et al*., 1995, 2003; Stanford *et al*., 1988). The reasons for these discrepancies are not entirely clear, but may relate to differences in BMI between studies. Mayer *et al*. (1996) has reported airway shape to be more dependent on BMI than the presence of OSA in lean, young subjects. Our findings also demonstrate a relationship between BMI and shape: velopharyngeal lateral airway dimensions decrease and the A-P/lateral diameter ratio increases with increasing BMI. However, such a relationship may not necessarily exist in individuals with a greater BMI (i.e. > 30 kg m^{-2}) as obese subjects were not studied.

Differences in observed airway shape between studies may also arise because of: differences in location and orientation of images; the degree of head flexion/extension (Rodenstein *et al*., 1990); whether images were averaged over several breaths (Rodenstein *et al*., 1990); or during a breath-hold (Fogel *et al*., 2003); or the effect of adenotonsillar hypertrophy (Arens *et al*., 2005). The real-time, breath-by-breath quantitative cross-sectional images presented by *a*OCT help avoid these potential deficiencies in a convenient and minimally invasive manner.

The similarity between *a*OCT-derived measurements of airway shape in individuals with and without OSA implies that airway shape may not be a primary factor in the pathogenesis of airway obstruction. Supporting this conclusion is the absence of any relationship between severity of OSA and airway shape. However, a limitation of the current study is that measurements were obtained only during wakefulness. It is possible, although unlikely, (Ciscar *et al*., 2001) that an individual's airway shape may change substantially from wakefulness to sleep, in which case wakeful measures of airway shape may not reflect susceptibility to collapse during sleep. While our study was designed to investigate the association between wakeful upper airway morphology and OSA, the next logical step is to perform these *a*OCT measurements during both wakefulness and sleep.

Airway lengths

Several landmarks are clearly identifiable from *a*OCT-derived images of the upper airway including the base of the epiglottis, the tip of the epiglottis, tip of the uvula, the base of the uvula and the posterior choanae. These landmarks were used to determine the lengths of specific segments of the pharyngeal airway. Comparison of images from individuals with and without OSA showed similar total airway length between the two groups, but a longer uvula in those with OSA. This is the first report of a difference in uvula length between individuals with and without OSA. It is possible that a longer uvula is a result of the trauma of snoring and obstruction, with the accompanying highly negative distal pharyngeal pressures (Demin *et al*., 2002), or to the increased muscular and fat tissue that is described in this population (Stauffer *et al*., 1989) These factors could also be responsible for thickening of the uvulae in individuals with OSA (Schellenberg *et al*., 2000). Apart from being a potential consequence of these influences, it is also possible that a large uvula plays a role in the genesis of upper airway obstruction.

It is notable that despite the OSA subjects having longer uvulae and our requirement for oropharyngeal *a*OCT-imaging to be distal to the tip of the uvula, uvula length precluded obtaining oropharyngeal images in only one OSA subject. In the remaining OSA and control subjects, relative to the tip of the epiglottis, the mean scanning location of oropharyngeal images was 6.1 ± 4.2 and 10.0 ± 3.4 mm craniad, respectively. It is possible that this difference in scanning location could influence pharyngeal size or shape between the groups. However, we believe this to unlikely given the relative constancy of shape and size of the oropharyngeal region, which averaged 28 mm in length in our subjects.

CONCLUSIONS

This is the first study to use *a*OCT imaging to compare waking pharyngeal dimensions between individuals with OSA and a group of matched control subjects. Pharyngeal airway size varied with respiratory cycle and, although there was no consistent relationship between CSA and phase of respiration, the minimum airway size was related to the severity of OSA. The results corroborate the findings from other studies using different imaging modalities that show the velopharynx to be the smallest region of the upper airway, particularly in individuals with OSA, although there was no difference in oro- or hypopharyngeal dimensions between OSA and control subjects. The shape of the airway was consistently elliptical with its long axis oriented in the lateral plane. This shape was similar in individuals with and without OSA and was not related to the severity of OSA, suggesting that airway shape may not be a primary factor in the pathogenesis of airway obstruction.

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