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The use of videofluoroscopy in the assessment of the pharyngeal airway in obstructive sleep apnoea

Ama Johal, Zahra Sheriteh, Joanna Battagel and Claire Marshall
Oral Growth & Development, Institute of Dentistry, Barts and The London School of Medicine and Dentistry, Queen Mary College University of London, UK

Correspondence to: Dr A Johal, Oral Growth & Development, Institute of Dentistry, Barts and The London School of Medicine and Dentistry, Turner Street, London E1 2AD, UK. E-mail: a.s.johal@qmul.ac.uk

SUMMARY This prospective cohort study evaluated the use of videofluoroscopy in assessing changes in both antero-posterior (A-P) and transverse pharyngeal airway dimensions in patients with obstructive sleep apnoea (OSA).

Forty patients [32 males and 8 females; mean age of 49.3 (SD = 10.79) years] with confirmed OSA, referred for mandibular advancement appliance (MAA) therapy were recruited. Patients received a customized Herbst MAA, adjusted for maximum comfortable protrusion. A standard lateral cephalogram, supine A-P, and transverse videofluoroscopic investigations were performed. Repeat supine videofluoroscopic investigations were undertaken with the MAA *in situ*. Parametric tests were used to evaluate the study hypotheses as the data were normally distributed. A paired *t*-test was employed to determine both the impact of posture on the airway using upright cephalometry and supine videofluoroscopy and the effect of MAA insertion on A-P and transverse pharyngeal airway dimensions.

Following a change in posture from upright to supine, highly statistically significant ($P < 0.001$) changes were observed for all lateral pharyngeal dimensions. Statistically significant increases in minimum lingual airway ($P < 0.001$) and maximum transverse pharyngeal airway ($P < 0.001$) were found following MAA insertion. A reduction in soft palate area ($P = 0.029$) and pharyngeal height ($P < 0.001$) was also noted.

Videofluoroscopy offers a useful dynamic assessment of the pharyngeal airway in both the A-P and transverse planes in patients with OSA.

Introduction

Obstructive sleep apnoea (OSA) is a common breathing disorder characterized by repeated collapse of the upper airway during sleep. The true prevalence of OSA according to data from the Wisconsin Sleep Cohort Study (Young *et al.*, 1993) is estimated at 4 per cent for males and 2 per cent for females aged 30–60 years. The aetiology of OSA is complex and not completely understood, though obstruction is thought to arise from a combination of anatomical and pathophysiological factors that result in narrowing of the pharyngeal airway space during sleep (Johal, 1998).

The mandibular advancement appliance (MAA) offers an alternative non-surgical treatment for OSA patients, providing temporary advancement of the mandible during sleep with the aim of maintaining a patent pharyngeal airway and preventing collapse. Use of such devices in OSA patients is based on disease severity [apnoea–hypopnoea index (AHI)]. MAAs are reported to work best in mild to moderate (AHI score 5–30 events per hour of sleep; Kushida *et al.*, 2006) and less well in subjects with more severe OSA (AHI score more than 30 events per hour of sleep; Marklund *et al.*, 1998).

The ability to visualize the pharyngeal airway has helped clinicians to understand and diagnose OSA, as well as assess treatment response. Methods are either direct (e.g. nasendoscopy) or indirect [e.g. cephalometry, acoustic reflection, magnetic resonance imaging (MRI), computed tomography (CT), and two-dimensional (2D) videofluoroscopy]. Cephalometry is a valuable diagnostic image in aiding understanding of craniofacial characteristics of patients with OSA. The static 2D nature of the cephalometric image, however, is limited by upper airway changes that accompany the supine position and the conscious state (Yildrim *et al.*, 1991; Johal and Battagel, 1999). Supine cephalometry and MRI investigations have shown alterations in pharyngeal shape in patients who responded well to MAA treatment (Tsuiki *et al.*, 2004). CT and MRI have been used in small sample studies to examine the effects of the MAA on the pharyngeal airway in OSA and healthy patients (Lowe *et al.*, 1986; Rodenstein *et al.*, 1990; Gale *et al.*, 2000; Gao *et al.*, 2004). These investigations are not viable for routine use due to expense, limited access, exposure to high levels of ionizing radiation (in the case of CT), and difficulty in assessing patients during sleep. Sleep nasendoscopy overcomes some of these issues and can be used to assess the dynamic airway during sleep. This reproducible technique can determine the site of airway obstruction and response to MAA treatment in OSA patients (Johal *et al.*, 2005).

Videofluoroscopy has been used to investigate upper airway dynamics during speech (Vig, 1968) and more recently to study OSA subjects during sleep (Pepin *et al.*, 1991). L'Estrange *et al.* (1996) used the technique in the antero-posterior (A-P) dimension only to investigate airway changes with mandibular protrusion and opening in a small number of supine, awake OSA subjects, and making comparison with lateral cephalometric findings in the same patients. Variable effects of mandibular protrusion were reported in the A-P pharyngeal airway dimension.

The aims of the present study were to compare the findings of standard lateral cephalometry and supine lateral videofluoroscopy in assessing the impact of posture on pharyngeal airway dimensions, and to assess changes in A-P and transverse pharyngeal airway dimensions of OSA patients following insertion of a MMA, using videofluoroscopy.

The following two null hypotheses were tested: there is no change in oropharyngeal airway dimensions accompanying a change in posture, and there is no change in oropharyngeal airway dimensions accompanying the insertion of a MAA.

Subjects and methods

Ethical approval from the Local Research Ethics Committee was obtained (P/98/270) and informed consent obtained prior to commencement of the study.

Subjects

Forty patients [32 males and 8 females; mean age of the group 49.3 (SD = 10.79) years] referred for MAA therapy, who had their diagnosis of OSA made in a multidisciplinary setting and confirmed by full hospital-based polysomnography, were recruited on the basis of the following selection criteria: over 18 years of age with confirmed OSA (AHI) of more than five episodes per hour, prepared to wear a MAA and with a sufficient number of healthy teeth to allow MAA construction. Patients were excluded if there was a history of poorly controlled epilepsy, allergy to metals, edentulous or insufficient healthy teeth to permit MAA retention, or evidence of temporomandibular joint dysfunction. In addition, body mass index (BMI) was recorded.

A sample size was determined using Altman's (1982) nomogram. The sample size was calculated based on a clinically relevant change in minimum lingual airway (Johal and Battagel, 1999). Based on the findings of that study, a standardized difference of 0.8 was calculated. Applying a clinically relevant difference of 1.6 mm at the 0.05 per cent level of significance and a power of 80 per cent, it was estimated that a sample of 40 patients was considered appropriate.

Methods

Lateral cephalometry. Standardized lateral head films were taken for each subject in the radiology department of the Dental Institute. The films were exposed in the natural head position with head stabilized with a cephalostat and each subject in an upright position. The subjects were asked to keep their teeth in light occlusion and exposures were taken at the end of expiration to standardize pharyngeal soft tissues and hyoid position. A thin layer of barium sulphate paste was applied to the dorsum of the tongue to enhance soft tissue identification, and the magnification of each radiograph was standardized.

Lateral cephalograms were traced onto high-quality acetate paper by a single operator (CM). Lighting conditions were standardized and the tracing was undertaken in a darkened room. The radiographs were orientated with the sella–nasion line inclined at 7 degrees to the horizontal. Fifteen conventional cephalometric landmarks and nine additional measurements relating to the oropharynx and soft palate were recorded (Figures 1–3). Each tracing was subsequently digitized using a Accutab digitizer (GTCO Corporation, Columbia, Maryland, USA) and customized software. Each tracing was digitized sequentially on two occasions to a tolerance of 0.2 mm. Magnification for each film was converted to life size and linear, angular, and area measurements relating to the lateral landmarks were then calculated. Definitions of the angular, linear, and area measurements are shown in Table 1.

Videofluoroscopy. Fluoroscopy of the pharyngeal airway was performed using a Polystar imaging system (Siemens Medical Solutions, Erlangen, Germany) on the same day the standardized lateral head films were obtained. Each subject was awake and supine during imaging, and head

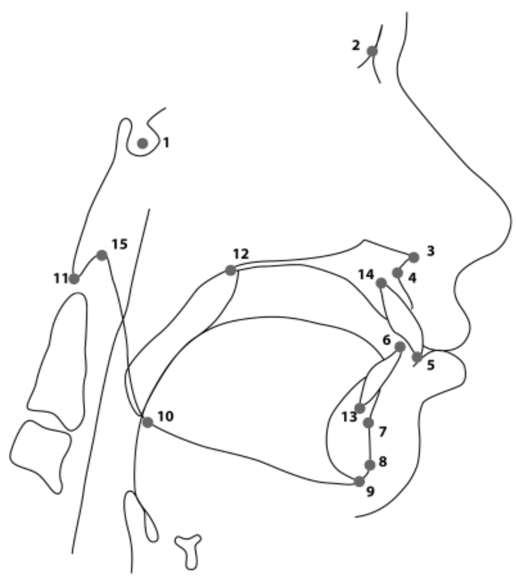

Figure 1 Lateral cephalometric landmarks used to define the skeletal, intermaxillary, and dental characteristics of the obstructive sleep apnoea subjects. 1. sella. 2. nasion. 3. anterior nasal spine. 4. point A. 5. upper incisor tip. 6. lower incisor tip. 7. point B. 8. pogonion. 9. menton. 10. gonion. 11. basion. 12. posterior nasal spine. 13. lower incisor apex 14. upper incisor apex. 15. articulare.

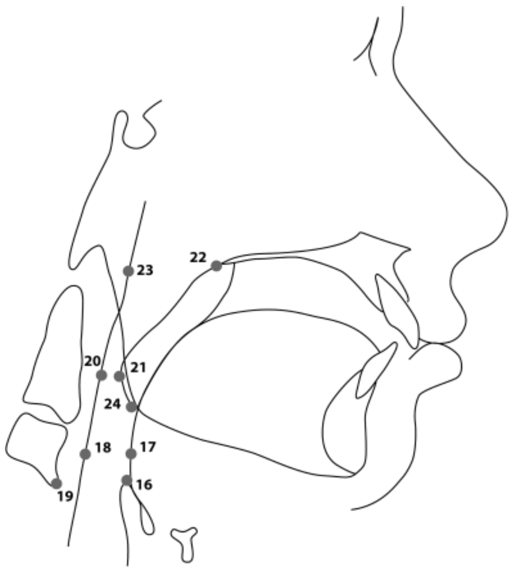

Figure 2 Lateral pharyngeal landmarks used to define the airway characteristics of the obstructive sleep apnoea subjects 16. tip of the epiglottis. 17. point on the tongue where the post-lingual airway is narrowest. 18. point on the posterior pharyngeal wall where the post-lingual airway is narrowest. 19. most inferior anterior point on C3. 20. point on the posterior pharyngeal wall where the post-palatal airway is narrowest. 21. point on the soft palate where the post-palatal airway is narrowest. 22. most superior posterior point on the soft palate (which may coincide with PNS). 23. point on the pharyngeal wall at level of the maxillary plane. 24. tip of the soft palate.

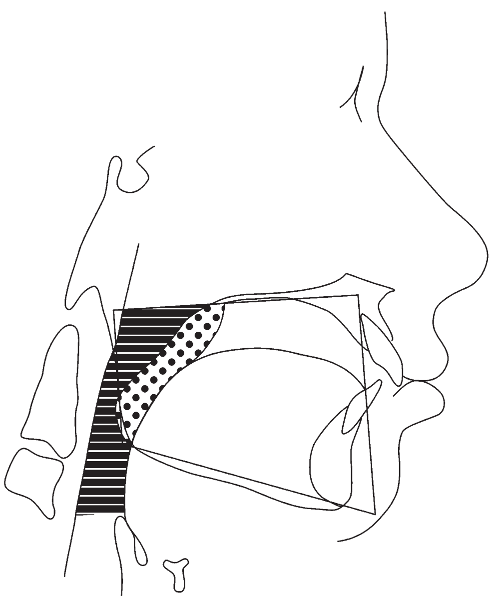

Figure 3 Oropharyngeal areas. Soft palate area (spotted): measured in an anticlockwise direction, starting at posterior nasal spine (PNS) around the soft palate tip up to the inferior part of the hard palate and back to PNS. Oropharyngeal area (striped): from PNS to the posterior pharyngeal wall horizontally opposite, measured in an anticlockwise direction. Continuing down the posterior pharyngeal wall to the level of the epiglottis tip, then to the posterior margin of the tongue, and soft palate to PNS.

position was controlled utilizing a modified facebow with ear rods and a standardized 10 cm foam head support. Barium sulphate paste was used to improve visualization of the soft tissues, and images obtained at end-expiration to standardize pharyngeal soft tissues and hyoid position. The same subject–machine distance was maintained for each A-P and transverse dimensional image, and a millimetre scale was included for verification of magnification. Selected freeze frames were recorded onto film in both the A-P and transverse dimensions pre- and post-insertion of the MAA (Figure 4). In view of the fact that there was no available software to permit analysis of the dynamic imaging, selected freeze frames in both dimensions, that clearly reflected the pharyngeal changes based on consensus between the investigator (AJ) and the radiologist, were selected for measurement.

Videofluoroscopy scans were traced onto high-quality acetate paper by a single operator (CM) under standardized lighting conditions in a darkened room. In relation to the lateral videofluoroscopic image, nine measurements relating to the oropharynx and soft palate were recorded (Figure 2), along with the oropharyngeal and soft palate areas (Figure 3). In relation to the transverse videofluoroscopic image, the oropharyngeal width was recorded superior to the epiglottis. Each tracing was subsequently digitized and magnification converted to life size. Definitions of the angular and area measurements recorded are shown in Table 1.

Image validation exercise. A Little Anne® (Pontlottyn, Rhymney, Mid Glamorgan, UK) resuscitation doll was used to confirm validity of the technique in both the A-P and the transverse dimension. Validation of the A-P videofluoroscopic projections was undertaken by taping two vertical 4 cm sections of 19 × 25 inch stainless steel wire markers on the lateral aspects of the neck of the Little Anne® doll, following which, both upright A-P cephalometric and supine A-P videofluoroscopic films of the doll were obtained. Once magnification factors had been taken into account, no differences were found in the actual and projected image measurements.

Validation in the transverse dimension was undertaken by attaching two 4 cm sections of 19 × 25 inch stainless steel wires along the lateral internal airway of the mannequin at a known distance, confirmed using digital callipers (Mitutoyo Ltd, Andover, Hampshire, UK). The mannequin was then exposed using the videofluoroscopy imaging system and resultant films were verified to be accurate.

Mandibular advancement appliance. Inter-occlusal wax bite registrations were taken to record both the intercuspal position and maximum comfortable mandibular protrusion. In addition, alginate impressions of the upper and lower dentition were obtained. Study and working models were made, and the working model surveyed and used to construct a customized removable Herbst appliance based on the original design of Clark and Nakano (1989). This comprised separate maxillary and mandibular full occlusal coverage clear acrylic splints. Bilateral telescopic arms positioned buccally and extending from the maxillary first molar

Table 1 Definitions of cephalometric (skeletal, intermaxillary, and dental) and videofluoroscopy (oropharyngeal) measurements and areas.

Skeletal	
SNA (°)	Angle formed between the line SN to point A
SNB (°)	Angle formed between the line SN to point B
Gonion to point B (Go–B; mm)	Horizontal distance from gonion to point B
Intermaxillary	
ANB (°)	Difference between SNA and SNB
Maxillary mandibular planes angle (°)	Angle between the maxillary (line joining ANS–PNS) and mandibular (line tangent to the lower mandibular border) planes
Lower anterior face height (mm)	Vertical distance from ANS to menton
Protrusion (mm)	Anterior bony chin point from C3 (anterior inferior)
Opening (mm)	Inferior bony chin point from maxillary plane
Dental	
Upper incisor to maxillary plane (°)	Angle between constructed lines from the upper incisor tip to the upper incisor apex to the maxillary plane
Lower incisor to mandibular plane (°)	Angle between constructed lines from the lower incisor tip to the lower incisor apex to the mandibular plane
Overbite (mm)	Vertical distance from the lower incisor tip to the upper incisor tip
Overjet (mm)	Horizontal distance from the upper incisor tip to the labial surface of the lower incisor
Oropharyngeal	
Soft palate area (cm^2)	Measured in an anticlockwise direction, starting at PNS around the soft palate tip up to the inferior part of the hard palate and back to PNS
Minimum post-palatal airway (minimum palatal airway; mm)	Distance between points on the posterior pharyngeal wall and the soft palate where the airway is at its narrowest
Minimum post-lingual airway (minimum lingual airway; mm)	Distance between points on the posterior pharyngeal wall and the tongue where the airway is at its narrowest
Pharyngeal height (mm)	Vertical distance between the distal projection of the maxillary plane and the tip of the epiglottis
Oropharyngeal area (cm^2)	From PNS to the posterior pharyngeal wall continuing down the posterior pharyngeal wall to the level of the epiglottis tip, then up the posterior margin of the tongue, and soft palate to PNS measured in an anticlockwise manner
Transverse (mm)	Maximum transverse airway superior to the tip of the epiglottis

region to the mandibular first premolar area connected the two separate pieces, thus permitting advancement of the mandible in a stepwise progression. This provided greater potential for adaptability, therapeutic benefit, and comfort. This removable MAA permitted limited lateral and vertical movement but did not allow retrusion of the mandible. Opening during sleep could be limited by the placement of small bilateral intermaxillary elastics at the anterior of the MAA. The appliance was adjusted for maximum comfortable protrusion.

Method error. Twenty cephalograms (A-P) and 20 videofluoroscopy images (A-P and transverse) selected at random were remeasured after a 2 week interval, by the same operator (CM), as recommended by Houston (1983). Dahlberg's (1940) equation, measuring error variance, and Houston's (1983) coefficient of reliability were used to calculate random error within the cephalometric analyses. Houston's coefficient of reliability and significance were defined as a value more than 1.725, at the 10 per cent level. A Bland–Altman plot was used to graphically examine the repeatability of the videofluoroscopy method of analysis (Bland and Altman, 1986).

Statistical evaluation. All data were analysed using the Statistical Package for social Sciences, version 13.1 (SPSS Inc., Chicago, Illinois, USA). Data analysis included descriptive and analytical statistics. Descriptives were used to summarize baseline characteristics in the sample. Parametric tests were used to test the study hypotheses as data were normally distributed. The level of significance was set at $P < 0.05$.

Results

Error study

Four cephalometric measurements [upper and lower incisor inclination, maxillary–mandibular planes angle (MMPA), and pharyngeal height] produced a Dahlberg value of more than 1. All cephalometric measurements with a Dahlberg value of more than 1 involved points with large envelopes of error, including PNS, menton, and gonion (Baumrind and Frantz, 1971). Systematic error (Houston, 1983) was noted for four cephalometric measurements (three hard tissue and one area measurement), showing bias, each of which was consistent with underscoring the measurement on the second occasion.

The mean difference for all pharyngeal variables assessed indicated good repeatability of the method of videofluoroscopy. The mean (SD) error for A-P measurements ranged from −0.1 (0.33) to 0.29 (3.45) and for transverse measurement −019 (2.08).

Baseline characteristics

The mean AHI and BMI scores were 22.4 (SD = 15.6) events per hour of sleep and 28.1 (SD = 3.79), respectively. Cephalometric data assessing craniofacial dimensions for all subjects are shown in Table 2. These data reveal that the patients

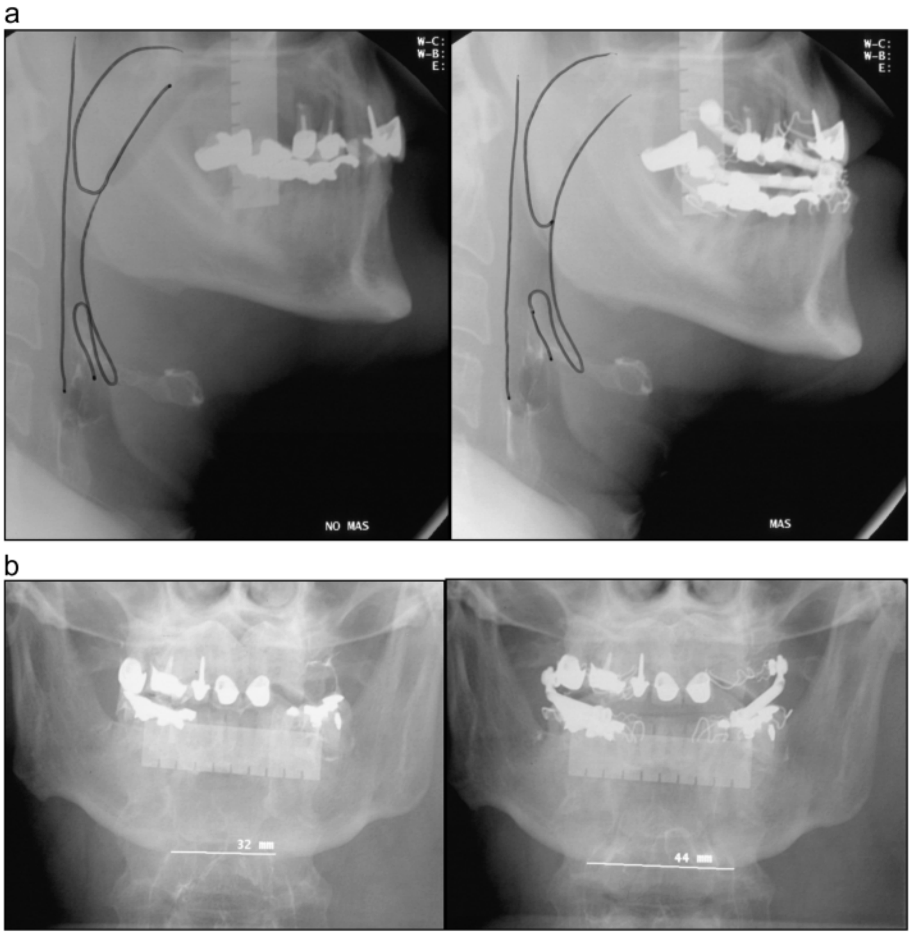

Figure 4 (a) Antero-posterior and (b) transverse videofluoroscopic images demonstrating changes in pharyngeal airway dimensions in response to mandibular advancement appliance insertion.

Table 2 Mean and standard deviation of the cephalometric characteristics of the obstructive sleep apnoea subjects.

Variable	Whole group (*n* = 40)
SNA (°)	80.86 (4.21)
SNB (°)	77.34 (4.4)
Go–B (mm)	67.67 (6.54)
ANB (°)	3.38 (2.73)
Maxillary mandibular planes angle (°)	29.01 (7.17)
Lower anterior face height (mm)	67.29 (5.74)
Protrusion (mm)	5.6 (1.9)
Opening (mm)	6.6 (2.9)
Upper incisor to maxillary plane (°)	108.31 (8.96)
Lower incisor to mandibular plane (°)	92.04 (9.4)
Overbite (mm)	3.4 (1.86)
Overjet (mm)	3.46 (1.81)
Soft palate area (cm^2)	3.62 (0.69)
Minimum palatal airway (mm)	5.26 (3.2)
Minimum lingual airway (mm)	10.43 (4.39)
Pharynx height (mm)	67.58 (9.33)
Oropharyngeal area (cm^2)	4.66 (1.77)

demonstrated a Class I skeletal pattern (ANB = 3.4 degrees) with average vertical facial dimensions (MMPA 29 degrees) and dental relations (overjet = 3.5 mm and overbite = 3 mm).

Changes in oropharyngeal airway dimensions accompanying a change in posture

The influence of posture on the pharyngeal airway was assessed by comparing standard upright cephalometry with supine A-P videofluoroscopy (Table 3). All A-P airway measurements assessed between upright and supine posture showed a highly statistically significant difference ($P < 0.001$). With the exception of the soft palate area, all remaining pharyngeal dimensions were reduced.

Assessment of pharyngeal airway dimensions accompanying insertion of MAA

There was a highly statistically significant increase in both minimum lingual airway and maximum transverse pharyngeal airway ($P < 0.001$) and a highly significant decrease in pharyngeal height ($P < 0.001$) after insertion of the MAA (Table 4). Soft palate area demonstrated a significant reduction with the MAA *in situ* ($P = 0.029$). Changes in minimum palatal airway and oropharyngeal area were not found to be significant.

Table 3 Postural antero-posterior changes affecting the pharyngeal airway.

Pharyngeal airway variables	Cephalogram, mean (SD)	Videofluoroscopy, mean (SD)	Mean difference (SD)	95% confidence interval	*P*-value
Minimum palatal airway (mm)	5.26 (3.2)	2.66 (2.53)	2.6 (3.75)	1.8 to 3.4	<0.001
Minimum lingual airway (mm)	10.43 (4.4)	8.75 (4.14)	1.68 (3.6)	0.91 to 2.44	<0.001
Oropharyngeal area (cm^2)	4.66 (1.77)	3.9 (1.6)	0.77 (1.76)	0.39 to 1.14	<0.001
Soft palate area (cm^2)	3.62 (0.69)	5.03 (1.1)	−1.4 (0.86)	−1.6 to −1.22	<0.001
Pharynx height (mm)	67.58 (9.33)	53.85 (8.47)	13.73 (8.93)	11.8 to 15.6	<0.001

Table 4 Mean and standard deviation of the videofluoroscopy assessment of changes in pharyngeal dimensions following insertion of mandibular advancement appliance (MAA).

Variable	No MAA	MAA *in situ*	Mean difference	SD	*P*-value
Minimum palatal airway (mm)	2.66 (2.53)	3.1 (2.35)	−0.43	2.23	0.073
Minimum lingual airway (mm)	8.75 (4.14)	10.5 (4.06)	−1.75	2.67	<0.001
Oropharyngeal area (cm^2)	3.89 (1.61)	4.09 (1.61)	−0.2	1.42	0.193
Soft palate area (cm^2)	5.03 (1.09)	4.88 (1.06)	0.14	0.61	0.029
Pharynx height (mm)	53.85 (8.47)	50.95 (8.77)	2.9	5.06	<0.001
Transverse pharyngeal airway (mm)	25.95 (9.31)	30.27 (9.84)	−4.32	5.03	<0.001

Discussion

Changes in pharyngeal airway dimensions accompanying a change in posture

All A-P airway measurements assessed showed differences that were highly statistically significant ($P < 0.001$) between upright and supine posture. A highly significant reduction in minimum palatal airway (2.6 mm) was found in this sample, accompanied by a highly significant increase in soft palate area of 1.4 cm^2. Increases in the soft palate area in the supine position have been reported in both OSA subjects (Yildrim *et al.*, 1991) and simple (non-apnoeic) snorers (Smith and Battagel, 2004). This may be explained by the effect of gravity displacing the soft palate in the supine position and thus appearing to increase the area, in this 2D representation. The post-lingual airway showed a highly significant reduction of 1.68 mm with positional change from upright to supine, similar to previous studies (Pae *et al.*, 1994; Johal and Battagel, 1999). However, others have found no change (Miyamoto *et al.*, 1997) or an increase (Yildrim *et al.*, 1991) in the post-lingual airway, though these variable findings may be explained by the lack of control for the phase of respiration during image exposure.

The highly significant reductions found in the oropharyngeal area noted in the sample have been previously reported by Johal and Battagel (1999). In the current study, a highly significant mean reduction in pharyngeal height (13.73 mm) was observed. Others have shown this to increase (Pae *et al.*, 1997) or decrease (Johal and Battagel, 1999) in OSA, accompanying a change from upright to supine posture. It has been suggested that maintenance of pharyngeal height in the study of simple (non-apnoeic) snorers moving from an upright to supine position may have been due to the reduced collapsibility of the pharyngeal muscles (Smith and Battagel, 2004). The variation seen in previous studies may be the result of the subjects being investigated while awake, with different levels of muscle tone being present (Malhotra *et al.*, 2002).

Impact of insertion of a MAA on the pharyngeal airway assessed by videofluoroscopy

Patients underwent imaging once they had been reviewed to ensure maximum comfortable mandibular protrusion had been achieved. This was felt to be important as it permitted a more representative change in the pharyngeal airway to be assessed in response to MAA wear. A previous investigation using supine lateral radiographs to assess the airway of simple (non-apnoeic) snorers (Smith and Battagel, 2004) reported similar findings to the current study's use of supine videofluoroscopic measurements, when comparing the A-P pharyngeal airway. Each of the measurements assessed were similar to those noted by Smith and Battagel (2004) and within 1 SD of the mean.

A small (3 per cent), but statistically significant, decrease in the soft palate area was found in the current study ($P = 0.029$). Previous investigations have detected increases ranging from 17 (Johal and Battagel, 1999) to 47 (Battagel *et al.*, 2002) per cent in OSA patients assessed using cephalometry.

CT evaluation of the pharyngeal airway, in OSA, during sleep indicates the post-palatal region to be the primary site of obstruction (Horner *et al.*, 1989). Studies have produced conflicting results in terms of response in the minimum palatal airway to MAA. The current research demonstrated no overall change in minimum palatal airway, a finding similar to that of Eveloff *et al.* (1994), who noted most cephalometric variables to vary considerably. The reason for the variable response may relate to the lateral pharyngeal wall having been identified as being significantly different in OSA patients compared with normal subjects (Schwab *et al.*, 1995). Improvement in the AHI with successful MAA treatment may not be reflected in A-P airway investigations as the effects of the lateral pharyngeal wall on the airway may only be seen in the transverse dimension.

Highly significant increases in minimum lingual airway were found in the study sample ($P < 0.001$). The improvement of 20 per cent was similar to previous findings recorded in the supine position but greater than changes seen when assessment was made in an upright position (Johal and Battagel, 1999).

Supine A-P radiographic (Johal and Battagel, 1999; Battagel *et al.*, 2002) and videoendoscopic investigations (Ferguson *et al.*, 1997) have previously detected increases in the oropharyngeal area with mandibular advancement. The present study showed no change in the oropharyngeal area with MAA. Ryan *et al.* (1999) used videoendoscopy during wakefulness, in a small sample ($n = 15$) of OSA subjects, to demonstrate no change and suggested that MAA use increases transverse airway dimensions more than A-P, facilitating the reductions in AHI associated with MAA use. The limitations of A-P imaging alone in assessing the oropharyngeal area are apparent as the influence of changes in the transverse dimension cannot be visualized or calculated. A highly significant increase in maximum transverse airway dimensions at the level of the oropharynx ($P < 0.01$) was found following MAA insertion. Ryan *et al.* (1999) suggested that MAA use increased lateral dimensions the most at the level of the velopharynx, more than A-P, resulting in reductions in the AHI associated with MAA use. The current study was unable to confirm the transverse width change in the region of the velopharynx and was limited to observing the changes at the oropharynx. The lack of observed effect by Ryan *et al.* (1999) in the oropharynx could be related to differences in the method of airway visualization. Ryan *et al.* (1999) used an intraluminal catheter to assess the cross-sectional diameter of the upper airway; however, no estimation of method error was provided.

Highly significant reductions ($P < 0.001$) in pharyngeal height dimensions were found following insertion of the MAA. Pae *et al.* (1997) observed that the pharynx becomes considerably longer in OSA subjects after a body position change from upright to supine and suggested that pharyngeal length in the supine position may be more important in the diagnosis and treatment of OSA than measurement of the most constricted area. However, that study evaluated only postural change and not the impact of MAA insertion on pharyngeal length. It is plausible to hypothesize that when the oropharyngeal airway expands laterally and transversely, oropharyngeal length shortens and the area remains unchanged.

Reproducibility and validity of imaging

A standardized technique was employed throughout the study to limit magnification error. Head position was stabilized using a cephalostat, and to enhance soft tissue identification, a thin layer of barium sulphate paste was applied to the dorsum of the tongue. Finally, all exposures were taken at end-expiration to standardize hyoid position and control for the effect of lung volume on the upper airway. Lack of standardization in imaging at end-expiration may explain the variable results seen in cephalometric studies of the pharyngeal airway. Images were traced by one operator and digitized sequentially on two occasions to a tolerance of 0.2 mm.

Videofluoroscopy is a validated and established tool in assessment of the A-P pharyngeal airway and has previously been used in the study of OSA subjects (Suratt *et al.*, 1983; Pepin *et al.*, 1991; L'Estrange *et al.*, 1996). Pepin *et al.* (1991) highlighted the ability of the technique in examining the dynamics of the airway and in determining patterns of pharyngeal closure. However, previous studies have involved small numbers of patients and the use of videofluoroscopy in evaluating the transverse airway has not previously been undertaken.

Limitations of methodology

Both cephalometric and videofluoroscopy imaging are subject to the inherent limitations of examining a three-dimensional (3D) subject two dimensionally. While A-P measurement limitations have been studied, the use of transverse videofluoroscopy in the measurement of the pharyngeal airway is difficult due to superimposition of structures, such as the cervical spine. True 3D imaging of the airway using CT, and MRI techniques have been used to investigate the airway but are expensive and even with low dose CT cannot be routinely justified. The use of videofluoroscopic imaging nevertheless does involve the patient undergoing exposure to ionizing radiation. The investigations were performed in a low-dose room, with a screening time of 1 minute. The resulting radiation levels were determined to be 25 μSv (0.025 mSv), the equivalent to 4 days' natural radiation exposure and thus significantly less than CT.

The study was limited by imaging the subjects during the awake state, whereas OSA symptoms manifest during sleep. The effect of sleep on pharyngeal size is known to be significant and increased collapsibility has been found in both normal and OSA patients (Malhotra *et al.*, 2002). However, measurement of the pharyngeal airway during wakefulness still provides useful information of the mechanics during sleep. Malhotra *et al.* (2002) reported a significant correlation between measurements in the two states.

Consideration could have been given to performing a dynamic assessment of the pharyngeal airway, such as a Muellar procedure, during the videofluoroscopic examination (Croft and Pringle, 1991). However, this was not performed as the literature questions the validity of the technique (Croft and Pringle, 1991) and furthermore, the objectives of the current study were to evaluate pharyngeal change in response to MAA insertion.

Conclusions

1. The impact of posture on all measured pharyngeal airway dimensions was highly significant. A-P pharyngeal airway dimensions change when assessed in an upright posture compared with a supine position.
2. Videofluoroscopy is a useful tool in the assessment of both the A-P and the transverse airway. Significant changes occur in the pharyngeal airway of OSA patients following insertion of a MAA when assessed using videofluoroscopy.

Funding

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