European Journal of Orthodontics 21 (1999) 363–376

Changes in airway and hyoid position in response to mandibular protrusion in subjects with obstructive sleep apnoea (OSA)

J. M. Battagel*, A. Johal**, P. R. L'Estrange***, C. B. Croft[†] and B. Kotecha[†]
*Departments of Orthodontics, St Bartholomew's and the Royal London School of Medicine and Dentistry, **Guy's, King's and St Thomas' Schools of Medicine and Dentistry, ***Department of Thoracic Medicine, UCL and the Middlesex Hospitals and [†]The Royal National Throat, Nose and Ear, and the Royal Free Hospitals, London, UK

SUMMARY This prospective clinical study examined the alterations in airway and hyoid position in response to mandibular advancement in subjects with mild and moderate obstructive sleep apnoea (OSA). Pairs of supine lateral skull radiographs were obtained for 13 female and 45 male, dentate Caucasians. In the first film, the teeth were in maximal intercuspation, while in the second the mandible was postured forwards into a position of maximum comfortable protrusion. Radiographs were traced and digitized, and the alterations in the pharyngeal airway and position of the hyoid were examined. Males and females were analysed separately. In males only, correlations were sought between the changes in hyoid and airway parameters, and the initial and differential radiographic measurements.

In males, mean mandibular protrusion at the tip of the lower incisor was 5.3 mm, increasing its distance from the posterior pharyngeal wall by 6.9 mm (or 9 per cent). Movement of the hyoid showed extreme inter-subject variability, both in the amount and direction. In relation to the protruded lower jaw, the hyoid became closer to the gonion by 6.9 mm and to the mandibular plane by 4.3 mm. With respect to the upper face, a 1.3-mm upward and 1.1-mm forward repositioning was seen. The percentage alterations in airway dimensions matched or bettered the mandibular advancement. The minimum distances behind the soft palate and tongue improved by 1.0 and 0.8 mm, respectively. Despite their smaller faces, females frequently showed greater responses to mandibular protrusion than males.

No cephalometric features could be identified which might indicate a favourable response of the airway to mandibular protrusion. Larger increments of hyoid movement were associated with an improved airway response, but the strength of the correlations was generally low.

Introduction

Obstructive sleep apnoea (OSA) is a medical condition in which periods of cessation of breathing occur during the night, despite continued inspiratory effort. Treatment is normally advised on medical grounds to preclude cardiac disability and improve the patient's quality of life (Kryger, 1994; Rapoport, 1994), although a recent report suggests that the medical effects of the disorder may have been exaggerated (Wright *et al.*, 1997). Treatment may involve conservative, medical, surgical or mechanical measures. Conservative methods encompass life style changes, such as weight loss and reduction in alcohol intake, whilst medical management includes the use of drugs to reduce nasal congestion or alter sleep architecture. Surgical techniques include palatoplasty, tonsillectomy, and mandibular or maxillo-mandibular osteotomies (Riley *et al.*, 1990; Ingrams *et al.*, 1996). Hyoid position may be altered as well. Mechanical alternatives include the use of nasal continuous positive airway pressure (nCPAP; Sullivan *et al.*, 1981) and mandibular advancement devices (Schmidt-Nowara *et al.*, 1995).

OSA subjects show both anatomical and physiological differences in their airways, when compared with normal individuals. The pharyngeal airway is narrower, and constriction may occur at one or more levels: behind the soft palate, posterior to the tongue base/epiglottis, or in the hypopharyngeal region (Haponik *et al.*, 1983; Rivlin *et al.*, 1984; Lowe *et al.*, 1986; Lyberg *et al.*, 1989; Rodenstein *et al.*, 1990; Battagel and L'Estrange, 1996). Such an airway is more susceptible to mechanical collapse under the negative pressures of inspiration (Anch *et al.*, 1982; Haponik *et al.*, 1983; Issa and Sullivan, 1984). Concomitant reductions in tone and abnormal muscle behaviour further favour airway occlusion during sleep (Remmers *et al.*, 1978; Gleadhill *et al.*, 1991; Adachi *et al.*, 1993).

Lateral cephalometry is an established tool in the investigation of the airway in OSA subjects. It has been employed for both diagnostic purposes (Haponik *et al.*, 1983; Lowe *et al.*, 1986; de Berry-Borowiecki *et al.*, 1988; Lyberg *et al.*, 1989; Eveloff *et al.*, 1994) and to monitor the response of the pharynx to mandibular protrusion (Bonham *et al.*, 1988; Schmidt-Nowara *et al.*, 1991; Eveloff *et al.*, 1994). In some OSA subjects, the mandible is relatively short and/or posteriorly placed (Rivlin *et al.*, 1984; Jamieson *et al.*, 1986; Lowe *et al.*, 1986; Tsuchiya *et al.*, 1992), forcing the tongue and soft palate back into the pharyngeal space. Maximal forward manipulation of the lower jaw with its associated opening improves pharyngeal airway patency (Bonham *et al.*, 1988; Schmidt-Nowara *et al.*, 1991; Isono *et al.*, 1995; L'Estrange *et al.*, 1996). Improvements have not been found at every level or by all investigators (Eveloff *et al.*, 1994).

Because posture has a significant effect on upper airway dimensions (Yildirim *et al.*, 1991; Mohammed *et al.*, 1994), the use of supine, rather than the traditional upright radiographs has been recommended (Lowe and Fleetham, 1991). However this technique is less commonly reported (Yildirim *et al.*, 1991; Pae *et al.*, 1994, 1997; Pracharktam *et al.*, 1994; Lowe *et al.*, 1996; Ono *et al.*, 1996). Eveloff *et al.* (1994) and Lowe (1994) have indicated that the use of supine films is a satisfactory method of demonstrating the airway changes in patients with mandibular advancement splints in place, but the method does not appear to have been used in a diagnostic capacity.

The hyoid bone and its related musculature are also implicated in the maintenance of airway patency. The hyoid is frequently described as being inferiorly placed in OSA subjects, (Jamieson *et al.*, 1986; de Berry-Borowiecki *et al.*, 1988; Tsuchiya *et al.*, 1992), but whether this is a precursor or a consequence of the tongue position is unclear. Furthermore, it has been suggested that a low hyoid position may be associated with a poor response to mandibular advancement splint therapy (Eveloff *et al.*, 1994; Yoshida, 1994), but only a single measurement of the hyoid in relation to the mandibular plane has been described. Additionally, both good and poor responders described by Eveloff *et al.* (1994) showed equal amounts of hyoid elevation when their lower jaws were postured forwards.

Information on the behaviour of the hyoid during mandibular protrusion is both meagre and diverse, and the results of this manoeuvre on pharyngeal opening are equally unresolved. It was therefore decided to investigate the matter further, employing pairs of radiographs taken in the supine position as suggested by Lowe (1994). The aims of the present study were therefore two-fold: first, to examine the changes in hyoid position when the lower jaw was postured forwards into a position selected for future mandibular advancement splint construction and, secondly, to describe the concomitant alterations in oropharyngeal dimensions.

Subjects

The material for this study comprised pairs of lateral skull radiographs of 58 dentate, Caucasian subjects, recorded in the supine position. Forty-five patients were male and 13 were female. All individuals had a diagnosis of OSA, which had been confirmed by polysomnography, and were seen at one of two centres in London: the Royal National Throat, Nose and Ear Hospital or the Middlesex/UCL Hospitals. The 29 male and seven female subjects from the Royal National had been assessed nasendoscopically during Midazolam-induced sleep, as well as in the awake position, as being likely to benefit from the construction of a mandibular advancement splint (Pringle and Croft, 1993). The 16 males and six females at Middlesex/UCL were participating in a clinical trial to compare the efficacy of these devices with that of nasal continuous positive airway pressure.

Methods

Radiographic technique

As part of the diagnostic protocol at both centres, pairs of supine radiographs were obtained. The first film was exposed with the teeth in light occlusion and the second with the lower jaw in a position of maximum comfortable protrusion. A wax wafer maintained the mandible in the required position. Subjects were instructed to hold their tongues in as normal a position as possible and all films were exposed at the end of expiration to ensure consistency of hyoid location. A thin layer of barium sulphate paste was applied to the dorsum of the tongue to enable its outline to be clearly seen.

Because films were being taken in the supine position, it was not normally possible to position the subjects in a cephalostat. Subjects were placed with a foam head support in a position that resembled as closely as possible that which they adopted during supine sleep. Lateral head position was carefully aligned and checked by the radiographer, and the magnification associated with each film was recorded.

Cephalometric analysis

Radiographs were traced, orientated with the maxillary plane horizontal, and 11 hard tissue points identified (Figure 1). Sixteen additional points relating to the cervical vertebrae, oropharynx, epiglottis, soft palate, and tongue were recorded also (Figure 2). Definitions of the additional landmarks and of those points not conforming to British Standards (British Standards Institution, 1983) are given in the accompanying legends. Points were digitized twice in a predetermined sequence by one author (AJ) to a tolerance of 0.1 mm and the mean value taken. The outlines of the tongue, soft palate, and oropharynx were also recorded (Figure 1).

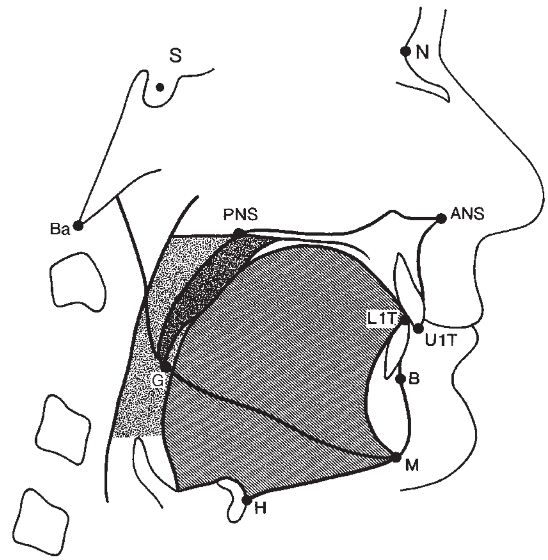

Figure 1 The cephalometric points recorded. Except where listed below, points, lines and planes conformed to British Standard definitions (British Standards Institution, 1983). ANS, anterior nasal spine; B, point B; Ba, basion; G, gonion, the point where the bisector of the angle between the posterior and lower mandibular border tangents meets the mandibular angle; H, hyoid, the most anterior point on the hyoid bone; L1T, lower incisor tip; M, menton, the point of intersection of the lower mandibular border and the symphysial outline; N, nasion; PNS, posterior nasal spine; S, sella; U1T, upper incisor tip. Oropharyngeal area: bounded superiorly by a backward extension of the maxillary plane and inferiorly by a line drawn through the tip of the epiglottis.

Films were automatically realigned to the maxillary horizontal and a vertical reference line was drawn perpendicular to the maxillary plane through sella. All calculations were made with this orientation and all measurements were converted to life size. Fifty linear, angular, and proportional measurements were computed, together with the areas of the oropharynx, soft palate and tongue. Twenty-five of these were used in the examination of hyoid and airway behaviour. The differences between the measurements on the first and second films were calculated (Tables 1 and 2).

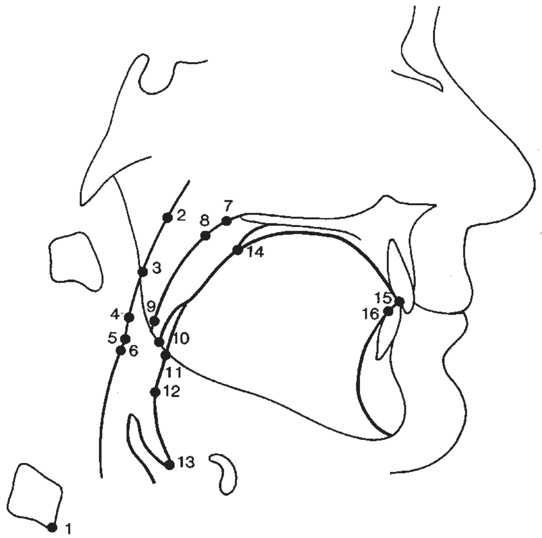

Figure 2 1. The most anterior inferior point on C5. 2. The point on the posterior pharyngeal wall at the same horizontal level as point 7. 3. The point of intersection of the occlusal plane with the posterior pharyngeal wall. 4. The point on the posterior pharyngeal wall where the airway behind the soft palate is at its narrowest. 5. The point on the posterior pharyngeal wall at the same horizontal level as the tip of the soft palate (point 10). 6. The point on the posterior pharyngeal wall where the airway behind the tongue is at its narrowest. 7. The point on the nasal surface of the soft palate at the level of the maxillary plane (opposite point 2). 8. The point on the nasal surface of the soft palate to determine its maximum thickness (in conjunction with point 14). 9. The most posterior point on the contour of the soft palate. 10. The tip of the soft palate (uvula). 11. The point on the posterior surface of the tongue where the post-lingual airway is at its narrowest. 12. The most posterior point on the contour of the tongue. 13. The deepest point of the vallecula. 14. A point on the oral surface of the soft palate where the palatal width is at its maximum. 15. The tip of the tongue. 16. The point of intersection of the occlusal plane with the lingual contour of the lower incisor.

Method error

Duplicate tracings of 20 films were made and random method error assessed as described by Dahlberg (1940). Systematic error and the coefficient of reliability were determined as suggested by Houston (1983). Errors were normally less than one unit, ranging from 0.3 mm, for the width of the oropharynx at the maximum bulbosity of the soft palate, to 2.3 mm, for the hyoid to gonion measurement. Reproducibility of gonion was difficult to achieve because of the disparity between the right and left mandibular shadows on some films. Systematic errors were detected in a few measurements, but these were not in a consistent direction. Coefficients of reliability ranged from 91 per cent, for the hyoid to gonion distance, to 99.5 per cent, for lower anterior face height.

Statistical evaluation

Data were analysed using SPSS PC+ (SPSS Inc., Chicago, IL). Because most variables were based on linear measurements, data for males and females were examined separately. The data were checked for normality and means, standard deviations and ranges were calculated. Differences in hyoid position, oropharyngeal airway dimensions, and other related measurements between the intercuspal and protrusive films were computed by subtraction. Paired *t*-tests examined the differences between measurements on the first and second films for the males; for the smaller group of females, the non-parametric Wilcoxon-paired signed ranks test was used.

Pearson product moment correlation coefficients were sought between changes in airway dimensions and hyoid movement, and both the cephalometric measurements recorded on the intercuspal film and the differences computed between film pairs. Because of the small number of females involved, this analysis was only undertaken on the male subjects. A probability of 0.01 was considered statistically significant.

Results

Demographic data

The mean age for the male subjects was 51 years, with a range of 22.4–81 years, and for the female subjects 50.5 years (range 31–65.3 years).

Cephalometric findings (Tables 1 and 2)

Mean linear and area measurements were larger for males than for females. However, with the exception of the forward movement of the hyoid during mandibular protrusion and measurements

Table 1 Initial cephalometric measurements (in millimetres, except where indicated), changes on protrusion, and their significance: males (n = 45).

Variable	Mean	SD	Range	Mean change following protrusion	SD of change	Range of change
Overjet	3.9	1.8	–1.4 – 9.3	–5.3***	2.3	–1.6 to –11.5
Overbite	2.9	2.2	–2.5 – 11.9	–6.5***	2.9	–0.1 to –14.3
Point B to S. vert.	57.2	9.3	33.2 – 77.3	4.6***	3.3	–2.2 – 9.8
Point M to S. vert.	50.9	11.5	24.6 – 79.0	4.6***	3.9	–3.0 – 15.0
Point G to S. vert.	–8.2	7.2	–22.8 – 7.4	5.2***	3.2	–2.4 – 12.7
Width of oropharynx: at level of PNS	16.5	5.1	4.2 – 30.3	0.2 NS	4.2	–11.7 – 9.6
Width of oropharynx: minimum distance behind soft palate	3.0	2.3	0.0 – 8.2	1.0**	2.3	–3.2 – 8.7
Width of oropharynx: at tip of uvula	7.5	3.0	0.1 – 13.4	0.3 NS	2.8	–5.5 – 7.4
Width of oropharynx: minimum distance behind tongue	8.3	3.2	0.7 – 15.2	0.8*	2.6	–3.5 – 6.6
Area of oropharynx	6.3	2.4	2.3 – 12.5	0.5 NS	1.7	–3.1 – 5.9
Hyoid to ANS (A–P)	56.0	9.0	40.9 – 81.9	–1.1 NS	4.2	–8.7 – 9.1
Hyoid to point B (A–P)	46.1	6.4	33.7 – 62.4	3.4***	3.3	–3.4 – 11.5
Hyoid to menton (A–P)	42.4	5.9	28.7 – 56.5	3.5***	3.9	–3.3 – 4.5
Hyoid to vallecula (A–P)	23.6	5.2	12.4 – 35.4	0.1 NS	2.9	–9.2 – 4.5
Hyoid to C5 (A–P)	37.2	6.2	21.0 – 46.8	1.6***	2.9	–4.5 – 8.4
Hyoid to maxillary plane (vert.)	74.6	8.5	58.7 – 95.3	–1.3 NS	5.0	–11.5 – 13.5
Hyoid to mandibular plane (vert.)	25.3	7.4	9.8 – 41.2	–4.3***	5.2	–16.6 – 10.3
Hyoid to gonion (vert.)	40.1	9.4	20.7 – 58.7	–6.9***	5.7	–18.4 – 6.9
Intermaxillary space length	72.7	6.0	54.9 – 87.2	6.9***	3.1	2.4 – 15.4
Intermaxillary space area (mm^2)	37.2	4.8	24.2 – 44.6	7.0***	2.9	1.9 – 13.6
Lower anterior face height	68.8	5.6	59.7 – 83.0	6.1***	2.7	0.0 – 12.6
Lower posterior face height	34.4	6.6	16.7 – 47.0	5.8***	2.9	–1.3 – 14.1
Tongue length	77.8	6.0	68.1 – 94.4	–8.2***	5.8	–25.6 – 3.8
Tongue area (mm^2)	51.0	10.7	32.9 – 71.4	–1.8**	4.1	–10.5 – 7.3
Tongue proportion (%)	135.8	27.7	87.3 – 193.6	–25.1***	16.0	–64.8 – 6.8

*$P < 0.05$; **$0.05 < P < 0.01$; ***$0.01 < P < 0.001$.

involving face height, the differences between the intercuspal and protrusive films were larger in the female subgroup. In all cases, mean changes were associated with a wide range of individual variation.

Males (Table 1)

Mandibular movement and tongue behaviour. Maximum comfortable protrusion in males resulted in a mean reduction in overjet of 5.3 mm, together with a 6.5-mm decrease in overbite. At the same time, the mandible moved forwards by 4.6 mm at point B and 5.2 mm at gonion. These changes were highly statistically significant ($P < 0.001$).

This manoeuvre increased lower anterior face height by 6.1 mm and lower posterior face height by 5.8 mm. The distance between the tip of the lower incisor and the posterior pharyngeal wall (the intermaxillary space length) increased by 6.9 mm. The area bounded by the maxillary and mandibular planes, the posterior pharyngeal wall and the lingual gingival aspect of the lower incisor (the intermaxillary space area) was similarly enlarged, thus increasing the space available for the tongue. Once more, these gains were highly significant ($P < 0.001$). As tongue area was slightly smaller on the protrusive films, the proportion of the tongue in relation to its working area was also very significantly reduced.

Hyoid position. The position of the hyoid was recorded in relation to both the mandible and the maxilla, as well as to the cervical spine and vallecula. With respect to the mandible (which itself had moved downwards and forwards), the hyoid became 3.4 mm closer to point B and 4.3 mm nearer to the mandibular plane. In the

Table 2 Initial cephalometric measurements (in millimetres, except where indicated), changes on protrusion and their significance: females (n = 13).

Variable	Mean	SD	Range	Mean change following protrusion	SD of change	Range of change
Overjet	5.2	3.2	0.4 – 11.3	–6.4**	1.8	–9.1 to –3.4
Overbite	3.3	2.6	–0.1 – 8.9	–6.5**	2.7	–11.5 to –3.2
Point B to S. vert.	50.7	5.2	43.2 – 58.2	5.2**	4.0	–4.1 – 9.9
Point M to S. vert.	43.2	6.4	31.0 – 51.7	4.5*	5.3	–5.6 – 11.5
Point G to S. vert.	–8.4	4.6	–15.7 to –1.0	5.9**	3.4	–1.9 – 9.6
Width of oropharynx: at level of PNS	15.3	3.0	11.7 – 21.1	1.1 NS	2.9	–4.6 – 4.2
Width of oropharynx: minimum distance behind soft palate	3.2	1.1	1.8 – 5.3	1.5*	1.6	–1.3 – 3.9
Width of oropharynx: at tip of uvula	6.2	1.7	3.9 – 8.7	1.1	1.9	–1.5 – 4.5
Width of oropharynx: minimum distance behind tongue	6.0	2.7	0.0 – 10.3	1.2	2.1	–3.2 – 4.4
Area of oropharynx	4.0	1.0	2.5 – 5.7	0.4	0.8	–0.9 – 2.4
Hyoid to ANS (A–P)	57.0	6.2	44.6 – 65.9	–2.1 NS	3.5	–10.6 – 2.6
Hyoid to point B (A–P)	44.9	4.7	34.6 – 50.5	3.2**	2.3	–0.6 – 6.4
Hyoid to menton (A–P)	40.3	3.9	33.4 – 46.6	2.5*	2.8	–1.8 – 8.5
Hyoid to vallecula (A–P)	19.6	4.3	12.5 – 24.2	–0.2 NS	2.8	–5.3 – 3.5
Hyoid to C5 (A–P)	31.9	2.9	24.9 – 35.3	2.5*	1.8	–0.6 – 5.0
Hyoid to maxillary plane (vert)	60.9	7.1	52.7 – 73.4	–3.2*	4.1	–8.1 – 4.6
Hyoid to mandibular plane (vert.)	19.8	6.0	9.8 – 31.6	–4.8*	3.4	–9.2 – 3.0
Hyoid to gonion (vert)	33.8	6.9	20.6 – 44.3	–7.9**	5.3	–15.8 – 4.7
Intermaxillary space length	69.2	5.2	62.4 – 77.6	7.8**	3.3	–0.5 – 12.5
Intermaxillary space area (mm^2)	30.9	3.7	26.1 – 37.3	5.6**	2.3	1.1 – 9.1
Lower anterior face height	63.3	4.0	57.8 – 70.1	5.5**	2.2	2.7 – 9.0
Lower posterior face height	27.1	4.9	20.2 – 35.4	4.7**	3.4	–0.6 – 11.1
Tongue length	72.3	5.6	64.0 – 81.9	–8.4**	5.3	–22.9 to –1.7
Tongue area (mm^2)	40.1	7.2	27.3 – 51.5	–2.6**	2.1	–5.8 – 0.9
Tongue proportion (%)	131.2	29.3	98.4 – 196.9	–27.3**	10.9	–50.7 to –6.9

$*P < 0.05$; $**0.05 < P < 0.01$.

vertical plane, the distance between hyoid and gonion decreased by 6.9 mm. Each of these alterations was significant at the 0.1 per cent level.

With respect to the maxilla, hyoid movement was very much less; vertically, it was elevated by 1.3 mm and anteroposteriorly it moved forwards by 1.1 mm. Neither of these alterations was significant. When compared with its anteroposterior distance from the fifth cervical vertebra, a significant increase of 1.6 mm was recorded. The position of the hyoid in relation to the vallecula was unchanged.

These mean changes masked a wide range of individual variation and gave no indication of the actual direction of hyoid movement in any one person. Whilst, on average, the hyoid moved upwards and backwards in relation to the mandibular plane, the range spanned a 180-degree arc. When related to the maxilla, movement of the hyoid spanned the entire 360 degrees of a circle, explaining why the average changes were relatively small. Individual movements of the hyoid are shown in Figure 3. Figure 3a describes hyoid behaviour in relation to the mandible, whilst Figure 3b depicts this in relation to the maxilla: males are plotted on the left and females on the right in each case.

Oropharynx. Despite the significant alterations in the majority of mandibular and hyoid measurements, linear oropharyngeal dimensions altered very little in response to mandibular protrusion. The minimum distances between the posterior pharyngeal wall, and both the soft palate and tongue increased by 1.0 and 0.8 mm, respectively ($P < 0.05$). In percentage terms, however, these increases were equivalent to those of the lower jaw.

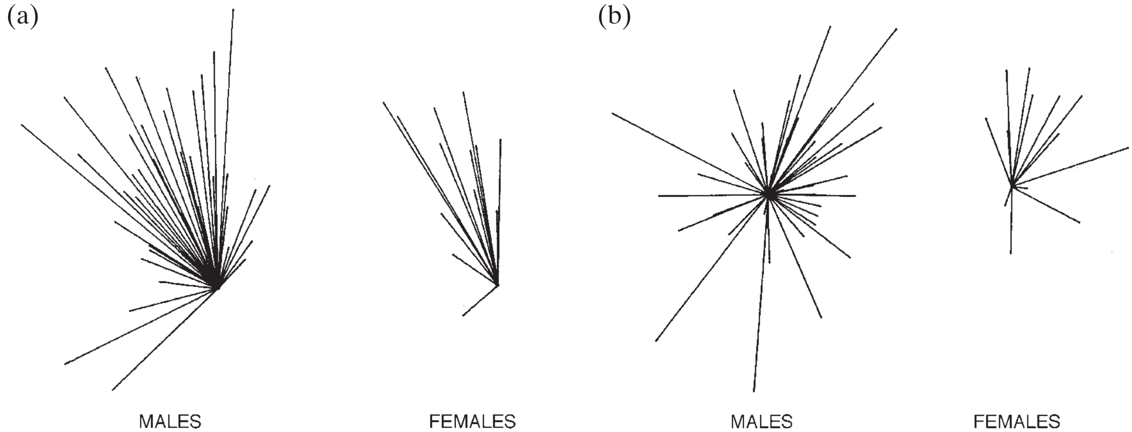

Figure 3 (a) Movement of the hyoid during mandibular protrusion, recorded in relation to the mandibular plane. Left: 45 male subjects; right: 13 female subjects. (b) Movement of the hyoid during mandibular protrusion, recorded in relation to the maxillary plane. Left: 45 male subjects; right: 13 female subjects.

Females (Table 2)

Mandibular movement and tongue behaviour. In females, maximum comfortable protrusion resulted in a mean reduction in overjet of 6.4 mm, together with a 6.5 mm decrease in overbite. The mandible moved forwards by 5.2 mm at point B and 5.9 mm at gonion. Because of the smaller size of the female group, these numerically larger differences were associated with reduced levels of significance ($P < 0.01$) when compared with the males.

As a result of protrusion, lower anterior face height increased by 5.5 mm and lower posterior face height by 4.7 mm. The intermaxillary space length increased by 7.8 mm and the intermaxillary space area by 5.6 mm^2. All these increments were significant at the 1 per cent level. Tongue area was again slightly reduced on the protrusive film and the 27.3 per cent reduction in tongue proportion was highly significant.

Hyoid position. Movement of the hyoid was less than that of the mandible with hyoid becoming 3.2 mm closer to point B and 4.8 mm nearer to the mandibular plane. In the vertical plane, the distance between hyoid and gonion decreased by 7.9 mm. These alterations were significant, but at a lower level than in males.

With respect to the maxilla, hyoid movement was greater than in males, showing a significant 3.2-mm elevation and a 2.1-mm anteroposterior increment. Again, the direction of hyoid movement spanned a wide range. Movement in relation to the cervical spine was also significant, with the hyoid moving 2.5 mm forwards away from C5. Again, there was no difference in the position of the hyoid in relation to the vallecula.

Oropharynx. In females, oropharyngeal dimensions also altered considerably less than those of the hard tissues as the mandible was protruded. The minimum distances between the posterior pharyngeal wall, and both the soft palate and tongue increased by 1.5 and 1.2 mm, respectively ($P < 0.05$). This was a 50 per cent greater improvement than that registered in males. A significant increment of 1.1 mm occurred at the level of the tip of the uvula and of 0.4 mm^2 in the oropharyngeal area.

Correlations

Hyoid behaviour (Tables 3 and 4). Few correlations were present between the starting cephalometric parameters and the changes in hyoid position (Table 3). In the anteroposterior direction, weak correlations occurred between the movement of the hyoid in relation to ANS, and the initial size of the soft palate ($r = 0.37$) and tongue ($r = 0.42$). The same trend was apparent when the hyoid to C5 distance was considered:

Table 3 Correlation coefficients between hyoid movement and starting cephalometric measurements.

Measurement	Hyoid to ANS	Hyoid to C5	Hyoid to point B	Hyoid to gonion	Hyoid to mandibular plane
Soft palate area	0.37*	–0.51**			
Soft palate thickness	0.36*	–0.38*			
Tongue area	0.42*	–0.42*			
Tongue proportion	0.37*				
Airway at tip of uvula				–0.45*	–0.36*
Minimum airway behind soft palate				–0.37*	–0.37*
BaSN			–0.38*		
Overjet				–0.37*	–0.35*
Gonion to menton		–0.42*			
Hyoid to point B			–0.36*		
Lower posterior face height (%)			–0.35*		

Only significant results are reported.
*Significant correlations at the 1 per cent level.
**Significant correlations at the 0.1 per cent level.

Table 4 Correlation coefficients between hyoid movement and changes in other cephalometric measurements.

Measurement	Hyoid to C5	Hyoid to menton	Hyoid to point B	Hyoid to ANS	Hyoid to gonion	Hyoid to mandibular plane	Hyoid to maxillary plane
Overjet	–0.37*			0.41*	0.51**		
Point B to S. vertical	0.37*			–0.65**	0.50**		
Gonion to menton				–0.39*			
Intermaxillary space length	0.47**				–0.51**	–0.35*	
Soft palate thickness		–0.36*		–0.36*			
Hyoid to point B		0.92**	1.00	0.67**		0.47**	
Hyoid to menton		1.00	0.92**	0.62**		0.53**	
Hyoid to gonion	–0.50**				1.00	0.83**	0.84**
Hyoid to ANS		0.62**	0.66**	1.00	0.44*	0.59**	
Hyoid to mandibular plane	–0.46**	0.53**	0.47**	0.59**	0.83**	1.00	0.82**
Hyoid to maxillary plane	–0.42*				0.84**	0.82**	1.00
Hyoid to C5	1.00				–0.50**	–0.46**	–0.42*
Airway at tip of uvula					0.39*	0.35*	
Minimum airway behind soft palate					0.41*		
Minimum airway behind tongue	0.41*						
Area of oropharynx					0.60**	0.57**	0.65**
Tongue length		–0.46**	–0.42*				
Lower posterior face height					–0.49 **		

Only significant results are reported.
*Significant correlations at the 1 per cent level.
**Significant correlations at the 0.1 per cent level.

the correlations were negative because, as the mandible protruded, the hyoid to ANS distance decreased, whereas the hyoid to C5 length increased. The larger the initial soft tissue dimensions, the more the hyoid came forwards. Greater hyoid movement in relation to point B was seen where the cranial base angle (BaSN) was low ($r = –0.38$).

In the vertical plane, changes in the proximity of the hyoid to the mandible and maxilla were

Table 5 Correlation coefficients between alterations in airway size and other cephalometric measurements.

Change in oropharyngeal dimension in response to mandibular protrusion	Level of ANS (start)	Level of ANS (change)	Minimum airway behind soft palate (start)	Minimum airway behind soft palate (change)	Tip of uvula (start)	Tip of uvula (change)	Oropharyngeal area (change)	PNS to uvula (A–P dist.) (change)	Hyoid to mandibular plane (change)
At level of ANS	–0.43*	1.00		0.40*			0.51**		0.35*
Minimum distance behind soft palate		0.40*	–0.46**	1.00		0.78**	0.57**	–0.56**	0.45*
At tip of uvula				0.78**	–0.44**	1.00	0.47**	–0.81**	0.35*
Minimum distance behind tongue							0.47**		

Only significant results are reported.
*Significant correlations at the 1 per cent level.
**Significant correlations at the 0.1 per cent level.

weakly negatively correlated with the minimum post-palatal airway (r = –0.37). Thus hyoid moved more when the starting upper airway was small, occasioned by larger areas of palatal and lingual tissue described above. A similar correlation was found between vertical hyoid movement and the patient's overjet (r = –0.37). Normal occlusions with relatively small overjets were associated with more vertical hyoid repositioning as the mandible came forwards. Hyoid movements were naturally highly correlated with one another: r = 0.83 for the alterations in hyoid position in relation to gonion and to the lower border of the mandible (Table 4).

Weak correlations occurred between changes in the hyoid to C5 and hyoid to gonion measurements, and the narrowest airway dimensions (r = 0.41). The soft palate became thinner, the further forwards the mandible moved, but this association was very weak (r = –0.36 between soft palate thickness and hyoid to ANS). Increased hyoid movement in the vertical dimension was highly significantly correlated with increases in the oropharyngeal area (r = 0.65 for hyoid to maxillary plane, r = 0.60 for hyoid to gonion, and r = 0.57 for hyoid to mandibular plane, $P < 0.01$).

The airway (Table 5). At all levels, the increase in airway size behind the soft palate was negatively correlated with its starting value. That is, the smaller the initial airway space, the more it increased in response to protrusion. All correlations were weak: r = –0.43, –0.46, and –0.44.

Changes in one airway dimension were, as expected, significantly related to those in the remainder of the oropharynx. Highly significant negative associations were found between the change in airway size behind the soft palate and the alteration in the horizontal distance PNS to uvula. Thus, as the airway opened, the soft palate repositioned itself more vertically. The correlations between airway dimensions and alterations in hyoid position have already been noted.

Discussion

Radiographic technique

Although radiographs were taken according to a standardized protocol, head position could not be controlled as precisely as when the ear rods of a cephalostat are available. Subjects were asked to adopt a position that they felt resembled that which they adopted during supine sleep. Head extension would therefore vary considerably between patients. Subjects were asked not to move between the first and second exposures, but when the wax wafer was inserted, some alteration in head posture inevitably occurred. In the sagittal plane, alignment of the head was checked by the radiographer, but left/right superimposition was poorer than when a cephalostat is used, compounding the possible errors in measuring the films.

Differences between the sexes

Obstructive sleep apnoea is more common in males and, therefore, there was a preponderance of men in this study. There were too few females to allow parametric evaluation of the data and, for many measurements, the data were not normally distributed. Despite their smaller size, the increments of change in response to mandibular protrusion in females equalled or exceeded those found in their male counterparts.

Tongue behaviour

For any mandibular advancement device to be effective at preventing pharyngeal occlusion, the tongue and soft palate must be accommodated further forwards in the mouth, increasing the functioning space available for the tongue. Alterations in intermaxillary space length and area, and in tongue proportion provided a measure of this change. Intermaxillary space length increased by approximately 10 per cent and the space available for the tongue, the intermaxillary space area, by about twice this amount. The proportional relationship of the tongue to its functioning space was thus reduced by the same degree. This is only a two dimensional and therefore very simplistic representation of effect of mandibular protrusion, but it would appear that considerable space is made available by this manoeuvre.

However, this improvement may be slightly exaggerated. When the protrusive radiographs were taken, an inter-occlusal wafer was present in the mouth and, despite instructions to hold the tongue normally, the wafer tended to affect tongue posture. Thus, the tongue tended to be held in a more upward and backward position, and measurements of its length, area, and thickness were all smaller on the second film.

Initial airway dimensions

Radiographs in this study were taken with the subjects lying supine. Although studies have reported the changes in airway dimensions between the upright and supine positions (Yildirim *et al.*, 1991; Pae *et al.*, 1994; Pracharktam *et al.*, 1994; Lowe *et al.*, 1996; Ono *et al.*, 1996) and the response to mandibular protrusion in the erect subject (Bonham *et al.*, 1988; Schmidt-Nowara *et al.*, 1991; Johnson *et al.*, 1992; Eveloff *et al.*, 1994), there are no reports of protrusion when the subject is supine. Any comparisons with previous work will therefore be indirect only. Dimensions involving soft tissues recorded in the supine position may differ from measurements made when the subject is upright. Reductions in the airway behind the bulk of the soft palate of between 1.5 and 2.7 mm have been reported as the soft palate alters in shape, when subjects move from the upright to the supine position (Yildirim *et al.*, 1991; Pae *et al.*, 1994; Pracharktam *et al.*, 1994; Lowe *et al.*, 1996). In the upright subject, the soft palate is vertically dependent, and therefore longer and thinner: when the supine position is assumed, gravity acts across the bulk of the tissue, thus increasing its thickness. At the tip of the uvula no differences were found.

Behind the tongue, expectations are contradictory. The airway is variously described as being reduced (Pae *et al.*, 1994; Pracharktam *et al.*, 1994), maintained (Miyamoto *et al.*, 1997) or increased (Yildirim *et al.*, 1991). Eveloff *et al.* (1994) report a 2.3-mm increase in their text, but the accompanying table does not appear to support this. Some of these findings may be explained by the fact that few authors have controlled the phase of respiration during which the films were taken, and that the exact level at which measurements are taken depends heavily upon the horizontal plane used to orientate the film.

Pharyngeal opening

At first sight, the improvements in oropharyngeal airway dimensions appear rather small. However, if these are considered as a proportion of their starting values, rather than in absolute terms, the increments reflect those of mandibular advancement.

Where the soft palate was at its thickest, the airway opened by 1 mm (33 per cent) in males and 1.5 mm (or 47 per cent) in females. At the tip of the uvula there was negligible alteration in males, but an 18 per cent improvement in females: non-significant because of the small sample size. The data for males are in broad agreement with Bonham *et al.* (1988), who reported increments of 2.4 and 0.0 mm for similar recordings in the upright position. The initial airway dimensions are smaller than described by these authors, but are in keeping with the supine values quoted above (Yildirim *et al.*, 1991; Pae *et al.*, 1994; Pracharktam *et al.*, 1994; Lowe *et al.*, 1996).

Behind the tongue, the airway increased from 8.3 to 9.1 mm in males and from 6.0 to 7.2 mm in females, despite a more posterior position taken by the tongue to accommodate the inter-occlusal record. This is a 10 per cent improvement for males, but a 20 per cent increase for females. This is greater than the increment described by Bonham *et al.* (1988) in the upright stance, but these authors found that mandibular protrusion was only 50 per cent of that in the present study.

Correlations between alterations in airway dimensions and other parameters were sparse and weak, although alterations in the airway space at one level did relate significantly with changes at the other three levels. The ability of the entire oropharyngeal region to respond to mandibular protrusion was assisted by larger increments of hyoid movement, especially in the vertical dimension. Behind the tongue, the response to protrusion was more direct: the airway widened as the intermaxillary space length increased and where the hyoid moved further forwards. However, despite their statistical significance, these correlations are weak and may not be clinically helpful.

The clinical significance of these findings has yet to be determined. Although physical improvements in tongue space and airway have been demonstrated in the awake state (Schmidt-Nowara *et al.*, 1991), and in anaesthetized and paralysed subjects (Isono *et al.*, 1995), the aetiology of OSA includes pathophysiological components. Abnormalities in muscle tone and activity play an important part (Brown *et al.*, 1985; Adachi *et al.*, 1993; Miyamoto *et al.*, 1997). Furthermore, Horner *et al.* (1989) confirmed that the size of the oropharyngeal airway space during wakefulness did not predict the presence of airway occlusion during sleep, and it would be inappropriate to assume that the findings in this paper would directly translate into clinical outcomes.

Hyoid behaviour

With respect to the mandibular plane, mean hyoid movement was upwards and backwards, indicating that the mandibular protrusion and opening exceeded the concomitant upward and forward repositioning of the hyoid. The reduction in the hyoid to mandibular plane distance of 4.3 mm in males and 4.8 mm in females compares with the 3.0-mm decrease reported by Bonham *et al.* (1988) in the erect subject. However, one of the interesting outcomes of this study was the wide variation in both the amount and direction of hyoid movement as the mandible was protruded.

When hyoid behaviour is examined in relation to the maxilla, the range of hyoid movement appears more diverse. The expected upward and forward movement of the hyoid predominated, but this was not a universal finding. It seems unlikely that mandibular protrusion would be associated with downward and backward hyoid drift, but this cannot be ruled out. An analysis of consecutive films taken from fluoroscopic studies, whilst the hyoid was in motion might help to elucidate this and such work is currently being undertaken. Any posterior repositioning of the tongue, adopted to accommodate the inter-occlusal record, may have been responsible for some of this anomalous movement. Furthermore, hyoid position is sensitive to changes in the respiratory cycle and, perhaps in the atypical individuals, films were not exposed at end expiration despite the radiographer's instructions.

The hyoid and its musculature occupy a key role in the regulation of the pharyngeal airway (van Lunterern *et al.*, 1987), and its position is affected by the location of both the mandible and tongue. Laterally, the middle constrictor attaches the hyoid to the walls of the pharynx and, therefore, hyoid position (and its changes), as well as constrictor muscle tone, will influence the volume of the oropharynx.

Unfortunately, alterations in hyoid position showed very few correlations with any of the original measurements and no conclusions could be drawn as to the likely behaviour of the hyoid from the initial radiograph. It might be expected that a low hyoid would be associated with a tongue which had an extensive vertical component and which would be much more difficult to move forwards (as opposed to upwards) in response to protrusion. A low position of the hyoid is one of the distinguishing cephalometric features of OSA (Jamieson *et al.*, 1986; de Berry-Borowiecki *et al.*, 1988; Tsuchiya *et al.*, 1992) and this has been considered to be a poor prognostic indicator for the successful use of mandibular advancement splints (Eveloff *et al.*, 1994; Mayer and Meier-Ewert, 1995). However, to describe hyoid position in relation to the mandibular plane, when the mandible itself frequently exhibits a short ramus and body, is not particularly helpful. Hyoid location could remain unchanged in relation to the cervical spine, but vary considerably in relation to the mandible, as a result of discrepancies in the lower jaw configuration alone. Thus, it could well be the mandibular configuration, rather than the hyoid position that is responsible for the less than ideal response observed.

Conclusions

1. Mandibular advancement is associated with a proportionate increase in oropharyngeal dimensions.
2. The original cephalometric measurements appear unhelpful in predicting the response of the airway to mandibular advancement. However, nasendoscopic assessment during midazolam-induced sleep may help, as the oropharynx and hypopharynx are visualized with and without mandibular advancement.
3. There is a wide variation in both the amount and direction of the response of the hyoid to mandibular protrusion.

Further work

This survey has not attempted to equate the observed cephalometric changes with the clinical success (or otherwise) of a mandibular repositioning device. Other factors, such as general obesity, neck circumference, and the severity of the OSA, are likely to play an important part and this matter is currently under investigation.

Address for correspondence

Joanna M. Battagel
Department of Orthodontics
St Bartholomew's and the Royal London School of Medicine and Dentistry
Stepney Way
London E1 2AD, UK

Acknowledgements

The authors would like to thank Mr A. M. Ferman of the London Hospital Medical College Biometrics Laboratory, who modified the computer software to enable it to be used in this investigation.

References

Adachi S, Lowe A A,Tsuchiya M, Ryan C F, Fleetham J A 1993 Genioglossus muscle activity and inspiratory timing in obstructive sleep apnea. American Journal of Orthodontics and Dentofacial Orthopedics 104: 138–145

Anch A M, Remmers J E, Bunce H III 1982 Supraglottic airway resistance in normal subjects and patients with occlusive sleep apnea. Journal of Applied Physiology 53: 1158–1163

Battagel J M, L'Estrange P R 1996 The cephalometric morphology of patients with obstructive sleep apnoea (OSA). European Journal of Orthodontics 18: 557–569

Bonham P E, Currier G F, Orr W C, Othman J, Nanda R S 1988 The effect of a modified functional appliance on obstructive sleep apnea. American Journal of Orthodontics and Dentofacial Orthopedics 94: 384–392

British Standards Institution 1983 British standard glossary of dental terms, BS 4492. HMSO, London

Brown I G, Bradley T D, Phillipson E A 1985 Pharyngeal compliance in snoring subjects with and without obstructive sleep apnea. American Review of Respiratory Diseases 132: 211–215

Dahlberg G 1940 Statistical methods for medical and biological students. Interscience Publications, New York de Berry-Borowiecki B, Kukwa A, Blanks R H I, Irvine C A 1988 Cephalometric analysis for diagnosis and treatment of obstructive sleep apnea. Laryngoscope 98: 226–234

Eveloff S E, Rosenberg C L, Carlisle C C, Millman R P 1994 Efficacy of a Herbst mandibular advancement device in obstructive apnea. American Journal of Respiratory and Critical Care Medicine 149: 905–909

Gleadhill I C *et al.* 1991 Upper airway collapsibility in snorers and in patients with obstructive sleep apnea. American Review of Respiratory Diseases 143: 1300–1303

Haponik E F *et al.* 1983 Computerized tomography in obstructive sleep apnea. American Review of Respiratory Diseases 127: 221–226

Horner R L, Shea S A, McIvor J, Guz A 1989 Pharyngeal size and shape during wakefulness and sleep in patients with obstructive sleep apnoea. Quarterly Journal of Medicine, New Series 72: 719–735

Houston W J B 1983 The analysis of errors in orthodontic measurements. American Journal of Orthodontics 83: 382–390

Ingrams D R, Spraggs P D, Pringle M B, Croft C B 1996 CO_2 laser palatoplasty: early results. Journal of Laryngology and Otology 110: 754–756

Isono S, Tanaka A, Sho Y, Konno A, Nishono T 1995 Advancement of the mandible improves velopharyngeal patency. Journal of Applied Physiology 79: 2132–2138

Issa F G, Sullivan C E 1984 Upper airway closing pressures in obstructive sleep apnea. Journal of Applied Physiology 57: 520–527

Jamieson A, Guilleminault C, Partinen M, Quera-Salva M A 1986 Obstructive sleep apneic patients have craniomandibular abnormalities. Sleep 9: 469–477

Johnson L M, Arnett G W, Tamborello J A, Binder A 1992 Airway changes in relationship to mandibular posturing. Otolaryngology Head and Neck Surgery 106: 143–148

Kryger M H 1994 Management of obstructive sleep apnea: overview. In Kryger M, Roth T, Dement W (eds) Principals and practice of sleep medicine, 2nd edn. W B Saunders, Philadelphia, pp. 736–747

L'Estrange P R *et al.* 1996 A method of studying adaptive changes of the oropharynx to variation in mandibular position in patients with obstructive sleep apnoea. Journal of Oral Rehabilitation 23: 699–711

Lowe A A 1994 Dental appliances for the treatment of snoring and obstructive sleep apnea. In Kryger M, Roth T, Dement W (eds) Principals and practice of sleep medicine, 2nd edn. W B Saunders, Philadelphia, pp. 722–735

Lowe A, Fleetham J A 1991 Two- and three-dimensional analyses of tongue, airway, and soft palate size. In: Norton M L, Brown A C D (eds) Atlas of the difficult airway. Mosby Year Book, St Louis, pp. 74–82

Lowe A A, Santamaria J D, Fleetham J A, Price C 1986 Facial morphology and obstructive sleep apnea. American Journal of Orthodontics and Dentofacial Orthopedics 90: 484–491

Lowe A A *et al.* 1996 Cephalometric comparisons of craniofacial and upper airway structure by skeletal subtype and gender in patients with obstructive sleep apnea. American Journal of Orthodontics and Dentofacial Orthopedics 110: 653–664

Lyberg T, Krogstad O, Djupesland G 1989 Cephalometric analysis in patients with obstructive sleep apnoea syndrome. Journal of Laryngology and Otology 103: 293–297

Mayer G, Meier-Ewert K 1995 Cephalometric predictors for orthopaedic mandibular advancement in obstructive sleep apnoea. European Journal of Orthodontics 17: 35–43

Miyamoto K, Özbek M M, Lowe A A, Fleetham J A 1997 Effect of body position on tongue posture in awake patients with obstructive sleep apnea. Thorax 52: 255–259

Mohammed A J, Marshall I, Douglas N J 1994 Effect of posture on upper airway dimensions in normal human. American Journal of Respiratory and Critical Care Medicine 49: 145–148

Ono T, Lowe A A, Ferguson K A, Fleetham J A 1996 Associations between upper airway structure, body position, and obesity in skeletal Class I male patients with obstructive apnea. American Journal of Orthodontics and Dentofacial Orthopedics 109: 625–634

Pae E-K *et al.* 1994 A cephalometric and electromyographic study of upper airway structures in the upright and supine positions. American Journal of Orthodontics and Dentofacial Orthopedics 106: 52–59

Pae E-K, Lowe A A, Fleetham J A 1997 A role of pharyngeal length in obstructive sleep apnea patients. American Journal of Orthodontics and Dentofacial Orthopedics 111: 12–17

Pracharktam N, Hans M G, Strohl K P, Redline S 1994 Upright and supine cephalometric evaluation of obstructive sleep apnea syndrome and snoring subjects. Angle Orthodontist 64: 63–72

Pringle M B, Croft C B 1993 A grading system for patients with obstructive sleep apnoea—based on sleep nasendoscopy. Clinical Otolaryngology 18: 480–484

Rapoport D M 1994 Treatment of sleep apnea syndromes. Mount Sinai Journal of Medicine 61: 123–130

Remmers J E, de Groot W J, Sauerland E K, Anch A M 1978 Pathogenesis of upper airway occlusion during sleep. Journal of Applied Physiology 44: 931–938

Riley R W, Powell N B, Guilleminault C 1990 Maxillary, mandibular, and hyoid advancement for treatment of obstructive sleep apnea: a review of 40 patients. Journal of Oral and Maxillofacial Surgery 48: 20–26

Rivlin J *et al.* 1984 Upper airway morphology in patients with idiopathic obstructive sleep apnea. American Journal of Respiratory Diseases 129: 355–360

Rodenstein D O *et al.* 1990 Pharyngeal shape and dimensions in healthy subjects, snorers, and patients with obstructive sleep apnoea. Thorax 45: 722–727

Schmidt-Nowara W W, Meade T E, Hays M B 1991 Treatment of snoring and obstructive sleep apnea with a dental orthosis. Chest 99: 1378–1385

Schmidt-Nowara W *et al.* 1995 Oral appliances for treatment of snoring and obstructive sleep apnea: a review. Sleep 18: 501–510

Sullivan C E, Berthon-Jones M, Issa F G 1981 Reversal of obstructive sleep apnea by continuous positive airway pressure applied through the nares. Lancet 1: 862–865

Tsuchiya M, Lowe A A, Pae E-K, Fleetham J A 1992 Obstructive sleep apnea subtypes by cluster analysis. American Journal of Orthodontics and Dentofacial Orthopedics 101: 533–542

van Lunteren E, Haxhiu M A, Cherniak N S 1987 Relation between upper airway volume and hyoid muscle length. Journal of Applied Physiology 63: 1443–1449

Wright J, Johns R, Watt I, Melville A, Sheldon, T 1997 Health effects of obstructive sleep apnoea and the effect of continuous positive airway pressure: a systematic review of the research evidence. British Medical Journal 314: 851–860

Yildirim M *et al.* 1991 The effect of posture on upper airway dimensions in normal subjects and in patients with the sleep apnea/hypopnea syndrome. American Review of Respiratory Diseases 144: 845–847

Yoshida K 1994 Prosthetic therapy for sleep apnea syndrome. Journal of Prosthetic Dentistry 72: 296–302