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Original Article

The effect of long-term mandibular advancement on the hyoid bone and pharynx as it relates to the treatment of obstructive sleep apnoea

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A cephalometric analysis was carried out to determine the effects of long-term mandibular advancement on the hard and soft tissues of the upper airway and, in particular, the relationship of the hyoid bone to both the cranium and the cervical spine, following mandibular advancement. One hundred consecutively-treated patients (87 males and 13 females; mean age: 49.26 years; SD: 8.56; range: 33–74 years) diagnosed with obstructive sleep apnoea and/or habitual snoring were reviewed at 6-month intervals over 6 to 30 months of treatment with a mandibular advancement splint. Significant changes to both the oropharynx and velopharynx were observed. At 12 months, the posterior airway space had increased from 10.71 mm to 11.99 mm (mean difference: 1.28 mm). At 6 months, significant changes had occurred in the soft palate length and thickness: a mean reduction in length of 1.46 mm ($p < 0.0001$) and in thickness of 0.57 mm. No changes were observed in the hypopharynx: the position of the hyoid bone remained unchanged in relation to both the cranium and cervical spine in all linear and angular measurements.
The author concludes that mandibular advancement with oral appliances should be considered as a treatment for life.

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Introduction

The use of mandibular advancement in the treatment of snoring and obstructive sleep apnoea is well established. Little is known, however, of the long-term effects of mandibular advancement on the structures of the upper airway and, in particular, the relationship of the hyoid bone to both the cranium and cervical spine following such treatment.

The hyoid bone is the bony origin of the root of the tongue and the site of insertion of the muscles of the hyoid bio-dynamic system that regulates respiration, mastication, deglutition and phonation.[1] Described by Durzo and Brodie[2] as a "floating bone", the hyoid bone is suspended posteriorly and bilaterally from the cranial base to an anterior attachment near the midline of the mandible, its horns delimiting the laryngeal part of the pharynx within which the superior opening of the larynx is included.[1]

Developmentally in man, the hyoid bone has assumed additional functions over those demanded in other species.[3] With man's change to an upright position, the larynx and trachea are no longer held away from the upper respiratory tract by gravity. As a consequence, patency of the upper airway can only be maintained by those muscles that lie anterior to the hyoid bone. To enhance breathing efficiency, the suprahyoid and infrahyoid muscle groups pull the hyoid bone forward to maintain oropharyngeal airway patency during the inspiratory phase of respiration.[4,5]

Durzo and Brodie,[2] and Bench[5] have shown that the hyoid bone becomes more inferiorly positioned during growth and that in adulthood it is usually situated at the level of the fourth cervical vertebra.[2,5] Kollias and Krogstad,[6] in a longitudinal cephalometric investigation of the position of the hyoid bone in patients between 22 and 42 years of age, observed that over a 20-year period it assumed a more inferior position in males than in females; however, the horizontal position in relation to the third cervical vertebra was found to be stable for both genders. Tallgren and Solow[7] considered that this stable hyo-cervical relationship was probably due to the close anatomical and functional relationship of the hyoid bone to the laryngeal cartilages. Other investigators have suggested that this stable position reflects the functional demand for maintenance of upper airway patency.[8,9] Tourné[10] considered that the descent of the hyoid bone in older age groups was a functional compensation for an increase in tongue bulk. Tallgren and Solow[7] found that changes in hyoid bone position were related to changes in the position of the mandible and concluded that it was co-ordinated with both facial morphology and head and cervical posture. The relationship of the hyoid bone to natural head position was recently reported by Özbek *et al.*,[11] who found that a lower hyoid bone position in relation to the mandibular plane was statistically related to a cranio-cervical extension.

Cephalometric analyses have been used by many investigators to identify morphological parameters characteristic of obstructive sleep apnoea.[12–17] The position of the hyoid bone in patients with documented obstructive sleep apnoea has been found to be more inferior in relation to the vertical distance to the mandibular plane at a level of C4-C6, than in non-apnoeic controls at a level of C3-C4.[14,18–22]

Aberrations in uvulo-pharyngeal morphology based on cephalometric analyses have also been reported; the typical features in patients with obstructive sleep apnoea including thick and long soft palates, reduced posterior airway space (PAS), and a larger than normal tongue.[23-26] The dimensions of the pharynx are also reported to be considerably reduced, irrespective of whether or not patients were investigated in the upright or supine position.[27–28]

Pracharktan *et al.*,[29] in an assessment of a craniofacial index score (C1S) that was used to differentiate patients with obstructive sleep apnoea from non-apnoeic snorers, found that the following variables had the highest predictive values: hyoid bone to mandibular plane distance, soft palate length and Body Mass Index (kg/m^2). They concluded that a CIS constructed from cephalometric measurements could be used to differentiate patients.

Mandibular advancement has been established as a recognised method of treating patients presenting with mild to moderate obstructive sleep apnoea.[30–37] Isono *et al.*[38] observed endoscopically that the velopharynx was the most common site of obstruction in patients with obstructive sleep apnoea. Their research found that the anterior movement of the mandible widened the retro-palatal airway, as well as that of the base of the tongue, thereby stabilising the airway. They concluded that, as well as increasing the pharyngeal area, a decrease in the collapsibility of the velopharynx may be also due to an increase in palatoglossal arch tension resulting in an improvement of velopharyngeal airway patency. Various other authors have reported changes to the pharynx and the position of the hyoid bone in patients with mandibular advancement splints in situ.[31,36,39–41] Supine cephalometric investigations by Battagel *et al.*[40] and Johal and Battagel[31] observed an upward movement of the hyoid bone relative to the mandibular plane of 4.3 mm and 4.6 mm, respectively, in patients who had appliances *in situ.* These finding were comparable with a 3.0 mm decrease in the same dimension in upright patients, as reported by Bonham *et al.*[36]

Gale *et al.*,[41] using computerisd tomography, reported significant increases in the minimum pharyngeal cross-sectional area in 32 conscious, supine obstructive sleep apnoea patients with similar mandibular advancement. They concluded, however, that there was a wide individual variation that could not be predicted from the degree of mandibular advancement. Mayer and Meier-Ewart[22] found that the position of the hyoid bone relative to the mandible was the only cephalometric parameter to show a direct correlation with respiration; the closer the hyoid bone was positioned to the mandible with mandibular advancement, the greater the improvement in respiration. In light of these findings, it is not unrealistic to assume that any adaptation of the hyoid apparatus to intermittent mandibular advancement may be of benefit to upper airway patency. No studies to the author's knowledge have been undertaken to investigate the effects of long-term mandibular advancement on the structures of the upper airway.

The present investigation is a cephalometric analysis of the effects of long-term mandibular advancement on the hard and soft tissues of the upper airway and, in particular, the relationship of the hyoid bone to both the cranium and the cervical spine, following mandibular advancement.

Materials and methods

In this study, one hundred consecutively-treated dentate patients, medically referred, were treated using mandibular advancement splints for obstructive sleep apnoea and/or habitual snoring. Patients were required to wear a non-adjustable mandibular advancement splint[42] for a minimum of five to six hours per night. Mandibular advancement was established at 75 per cent of maximum protrusion, measured from incisal edge to incisal edge, as determined by the George-gauge[43] (range 3–14 mm). The sample comprised eighty-seven males and thirteen females (mean age: 49.25 years; SD: 8.56 years; range: 33-74 years).

Cephalograms

A cephalogram was taken for all patients at their initial consultation. Following insertion of mandibular advancement splints, review cephalograms were taken at 6-month intervals, over a period of from 6 to 30 months, without the appliance *in situ.* Only one review cephalogram was taken for each patient. Prior to splint insertion, patients were randomly assigned to a 6-month review period, each sample size consisting of twenty patients. Cephalograms were taken with the subjects seated, with maximal intercuspation of the teeth, the lips in light contact, and in natural head position as described by Moorrees and Kean.[44] Bilateral ear rods were inserted into the external auditory meatus to stabilise the head during exposure. All cephalograms were taken by the same operator. Rare earth intensifying screens were used to obtain maximum detail. Exposure was adjusted for each patient, the average being 85 KVP and 15 MA, with a 1.0 second exposure.

Cephalometric measurements

Reference points and planes (Figure 1) were based on anatomically stable structures in the cranial base, maxilla, mandible, pharynx and cervical spine. These landmarks were identified and transferred to mylar film. The co-ordinates of each point on the tracings were digitised twice with a reflex metrograph, and the mean values converted to linear and angular measurements. The student's *t*-test for paired data was used to compare all measurements before (T1) and after (T2) mandibular advancement. A value of $p < 0.05$ was considered as significant. To determine the investigative error, double determinations were taken of ten randomly-selected cephalograms and compared with Dahlberg's formula.[45] The reliability of the cephlometric measurement in this study was found to be comparable to that reported by others.[46,47] The smallest linear error was 0.25 mm (H-MP) and the greatest error, 0.71 mm (apw_4–ppw_4). This latter measurement determined lower pharyngeal depth and was difficult to obtain because of the soft tissue definition. The error in angular measurement was comparable to other studies,[46,47] the largest error being 0.97 degrees for the angle H axis/vert.

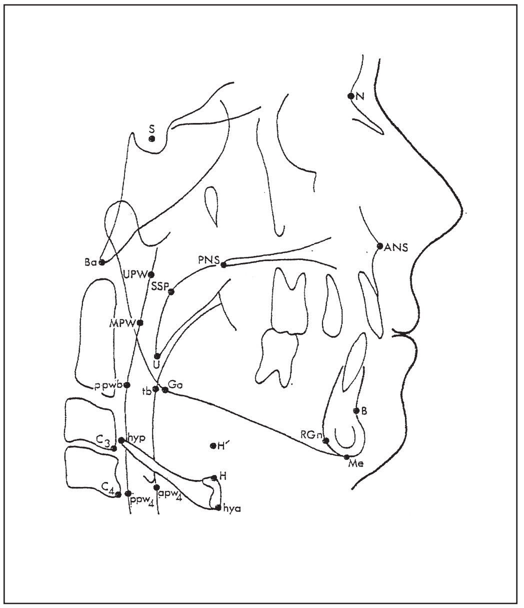

Figure 1. Cephalometric reference points and planes.

Because no lead wire was used during exposure to indicate the true vertical on the cephalogram, the right-hand border of the cephalogram was used as the vertical reference line.[7]

Hyoid measurements vertical (mm)

H–MP	Distance along a perpendicular from H to the mandibular plane (Go-Me)
H–H′	Distance between H and a perpendicular to the line C3-RGn
H–Pal P	Distance along a perpendicular from H to the palatal plane (ANS– PNS)
H–SN	Distance along a perpendicular from H to the anterior cranial base (S–N)

Cephalometric reference points

ANS Anterior nasal spine: the tip of the anterior nasal spine

apw_4 The anterior pharyngeal wall along the line intersecting C4 and H

B B point: the most posterior point on the anterior contour of the lower alveolar process

Ba Basion: the most postero-superior point on the anterior margin of the foramen magnum

C_3 The most inferior anterior point on the third cervical vertebrae

C_4 The most inferior anterior point on the fourth cervical vertebrae

Go The most posterior inferior point on the angle of the mandible

H Hyoidale: the most antero-superior point on the body of the hyoid bone

H′ The intersection point between the perpendicular from H to the line connecting C_3 and RGn

hya The most anterior point of the body of the hyoid bone

hyp The most posterior point of the greater horn of the hyoid bone

Me Menton: the most inferior point on the lower border of the mandibular symphysis

MPW The middle pharyngeal wall. The point on the posterior pharyngeal wall identified by an extension of the functional occlusal plane (FOP)

N Nasion: the most anterior point of the fronto-nasal suture

PAS Posterior airway space. linear distance between tb and ppwb, determined by an extension of the line B through Go to the posterior pharyngeal wall

PNS Posterior nasal spine: the most posterior point of the bony hard palate

ppwb The intersection point of a line from B through Go to the posterior pharyngeal wall

ppw_4 The posterior pharyngeal wall along the line intersecting C_4 and H

RGn Retrognathian: the most inferior posterior point on the mandibular symphysis

S Sella: the centre of sella turcica

SSP The most prominent point on the superior soft palate

tb The intersection point of a line from the point B through Go and the base of the tongue

U The tip of the uvula

UPW The upper pharyngeal wall: the point on the posterior pharyngeal wall identified by an extension of the palatal plane (ANS-PNS) to the upper pharyngeal wall

Reference planes

MP Mandibular plane: the line connecting Go and Me

Pal P Palatal plane: the line connecting ANS-PNS

FOP Functional occlusal plane: the average occlusal plane of the buccal teeth including the canines and first permanent molars.

H axis Long axis of the hyoid bone: the line connecting hya and hyp

True Vert Right border of cephalogram

Angular (°)

H axis/MP The angle between the long axis of the hyoid bone and the mandibular plane

H axis/Pal P The angle between the long axis of the hyoid bone and the palatal plane

H axis/N-Ba The angle between the long axis of the hyoid bone and the line N–Ba

H axis/vert The angle between the long axis of the hyoid bone and the true vertical

Pharyngeal and soft palate measurements (mm)

PAS Posterior airway space: the linear distance between the tongue base (tb) and the posterior pharyngeal wall (ppwb) determined by an extension of the line B through Go to the posterior pharyngeal wall

UPW-PNS Upper pharyngeal depth: the distance between the posterior nasal spine (PNS) and the intersection point between the palatal plane and the posterior wall of the nasopharynx

MPW/U-PNS	Distance between the posterior pharyngeal wall (MPW) and the intersection of a perpendicular to the line U-PNS
$apw_4 - ppw_4$	Lower pharyngeal depth: the linear distance between the pharyngeal anterior and posterior walls defined by the intersection of the line C_4-H
Soft P length	Linear distance between the posterior nasal spine (PNS) and the tip of the uvula (U)
Soft P thickness	The maximum dimension of the soft palate between its oral and nasal surfaces. Linear distance between the point SSP and a perpendicular to the line PNS-U

Anteroposterior (mm)

C_3–H	Distance between C_3 and H
H–RGn	Distance between H and the mandibular symphysis (RGn)

Results

The mean values, standard deviations and mean differences of all patients for the hyoid bone, and for the soft tissue and pharyngeal measurements are given in Tables I and II, respectively. A comparison of the vertical position of the hyoid bone relative to the mandible, maxilla and cranial base (Table I) demonstrated no change following long-term mandibular advancement. A change in the antero-posterior position relative to the third cervical vertebra (C_3-H) was statistically significant ($p < 0.019$; mean difference: 0.52 mm); however, no change was found in the variable H–RGn (Table I). Although statistically significant, this minor change was not considered to be clinically relevant. The measurement C_3–H, using the 12-month data, was not statistically significant ($p < 0.467$; mean difference: 0.25 mm).

Analyses of the angular position of the long axis of the hyoid bone (H–axis) to the mandibular plane (H–axis/MP), the palatal plane, H–axis/Pal–P, the cranial base line (H–axis/N–Ba) and the true vertical (H–axis/vert) were made (Table I), and no change was observed relative to the overlying cranial structures.

An analysis of pharyngeal and soft palate dimensions for all patients is given in Table II. Posterior airway space increased from 10.99 mm to 11.79 mm (mean difference: 0.79 mm; $p < 0.002$), which was significant. A significant increase of PAS was present at 12 months (10.71 mm to 11.99 mm; mean difference: 1.28 mm; $p < 0.009$). A 6-month review found that this change was not statistically significant. Therefore, it can be concluded that an increase in PAS occurs, on average, between 6 and 12 months following mandibular advancement.

Changes to both the length and thickness of the soft palate were observed. In a comparison of all patients, soft palate length decreased from 43.49 mm to 42.02 mm (mean difference: 1.46 mm; $p < 0.0001$). The change was significant both at 12 months (mean difference: 1.40 mm; $p < 0.020$) and at six months (mean difference 1.35 mm; $p < 0.033$). Therefore, it can be concluded that a significant reduction in soft palate length occurs within the first six months of mandibular advancement. This occurrence is probably due to a loss of oedema associated with the elimination of habitual snoring. A reduction in soft palate thickness was observed in a comparison of all the patients (mean difference: 0.57 mm; $p < 0.002$). These changes were not statistically significant at the 12-month review. Although other studies have noted difficulties in landmark identification of soft-tissue structures,[48] the error in soft palate length (0.37 mm) and thickness (0.30 mm) was surprisingly low.[45]

The author attributes changes in the posterior airway space and in the length and thickness of the soft palate to the elimination of habitual snoring, and observed no changes in the position of the hyoid bone relative to its surrounding structures, following long-term mandibular advancement.

Discussion

Cephalometry is one of the more accepted techniques used to evaluate upper airway and craniofacial morphology during the awake period in patients with obstructive sleep apnoea.[49] It is inexpensive and correlates with other, less readily available techniques, such as computer tomography[50] or somofluroscopy.[51] Cephalometry allows a static evaluation of the pharynx, soft palate, tongue and the hyoid bone, relative to their surrounding cranio-cervical structures. Although the obvious limitations of any two-dimensional cephalometric study have been clearly recognised, many practitioners consider that gross changes in tongue position can be assessed by analysing changes in the position of the hyoid bone.[52,53] The position of the hyoid bone is,

Table I. Hyoid bone measurements, before (T1) and after (T2) mandibular advancement (6–30 months).

	(T1) Mean	SD	(T2) Mean	SD	Mean Diff	*p*
Linear (mm						
H–MP	24.84	5.27	24.78	5.59	-0.06	0.832
C_3–H	40.33	4.89	40.85	5.05	0.52	**0.019**
H–RGn	42.83	5.99	42.64	5.92	0.19	0.580
H–H′	11.49	5.11	11.46	5.38	0.03	0.925
H–PalP	76.50	6.92	77.15	7.14	0.65	0.079
H–SN	125.05	8.51	125.68	8.65	0.63	0.102
Angular (°)						
H axis/MP	8.96	6.13	9.08	6.07	0.12	0.802
H axis/Pal	32.67	8.37	33.51	7.87	0.84	0.147
H axis/N–Ba	60.72	8.43	61.75	8.32	1.03	0.081
H axis/vert	66.81	7.72	67.08	7.46	0.27	0.675

Table II. Pharyngeal and soft palate measurements before (T1) and after (T2) mandibular advancement.

	(T1) Mean	SD	(T2) Mean	SD	Mean Diff	*p*
Linear (mm)						
6 months						
Soft palate length	43.57	4.42	42.22	4.61	-1.35	**0.033**
PAS	10.77	3.67	11.64	3.70	0.87	0.188
12 months						
Soft palate length	43.75	5.06	42.35	4.48	-1.40	**0.020**
Soft palate thickness	8.56	2.34	7.98	2.39	-0.58	0.063
PAS	10.71	3.18	11.99	3.29	1.28	**0.009**
6–30 months						
PAS	10.99	3.15	11.79	3.19	0.79	**0.002**
UPW–PNS	26.12	3.47	25.93	3.28	-0.19	0.370
MPW/U–PNS	13.33	2.95	13.54	2.55	0.21	0.233
apw_4–ppw_4	16.87	4.09	17.42	3.74	0.54	0.091
Soft palate length	43.49	5.15	42.02	5.14	-1.46	**<0.0001**
Soft palate thickness	8.55	2.21	7.98	2.38	-0.57	**0.002**

therefore, of great clinical interest, as favourable changes to its position may lead to improved airway patency and function.[4,22,36,38]

Changes in the linear and angular measurements of the position of the hyoid bone in this study were similar to other studies, and demonstrated a lower hyoid-to-mandibular-plane distance (MP-H) in apnoeic patients (mean: 24.8 mm) than in non-apnoeic patients (mean: 15.4 mm).[13-19] No change was found relative to the facial structures, following long-term mandibular advancement. The only statistically significant change occurred in the distance C_3-H (mean difference: 0.52 mm); however, Stepovich[54] has stated that measurements of the hyoid bone of less than 2.0 mm may be considered within the realm of individual physiological variation between sequential cephalograms.

Previous studies of the relationship of the hyoid bone to the facial skeleton and cervical column have indicated that the relationship of the hyoid bone to the cervical column is more stable than its relationship to the cranium and mandible.[7,52] In this study, the long axis of the hyoid bone was closely aligned to the mandibular plane, which is in accordance with the findings of Adamidis and Spyropoulos.[55]

Haralabakis *et al.*[9] found that the hyoid axis formed significantly higher angles with the basion-nasion plane (Ba-N), as well as with the palatal plane (ANS-PNS), when their patients with anterior open bites were compared with those with normal occlusions. No difference was found when a comparison was made of the angle between the long axis of the hyoid bone and the mandibular plane. These authors concluded that the hyoid bone moved in close correlation with the pharynx, cervical spine and mandibular plane in patients with entirely different skeletal patterns.[9] The relative position of the hyoid bone appeared to be unchanged even after orthognathic surgery. Takagi *et al.*[56] found little change in the antero-posterior relation of the hyoid bone relative to the cervical vertebrae, following bilateral oesteotomy of the mandible. LaBanc and Epker[57] investigated the relationship between the tongue and the position of the hyoid bone following surgical mandibular advancement and, although changes in tongue posture were observed two years post-operatively, the hyoid bone had returned to its original pre-operative position.

Similar adaptive changes in the position of the hyoid bone were reported by Graber,[58] who observed a greater than normal descent of the hyoid bone after three years of chin-cup therapy for the correction of a Class III malocclusion. Graber concluded that both stability and patency of the pharyngeal airway were primary factors in hyoid bone positioning. Recent longitudinal normative growth studies of the hyoid bone and the pharynx have led to a better understanding of the prevalence of obstructive sleep with increasing age[59] and its gender predisposition.[60] Kollias and Krogstad[6] cephalometrically evaluated the position of the hyoid bone and related structures in patients between 22 and 42 years of age and noted that, although the antero-posterior position remained unchanged during this period, in both genders it assumed a more inferior position with age. The descent was significantly more pronounced in males than in females.

Uvulo-glossopharyngeal changes with age were also reported by Kollias and Krogstad.[61] The overall significant gender differences over a 20-year period were that males showed a more caudally extended tongue mass, with a greater reduction in the sagittal dimension of the minimal pharyngeal airway space. These changes were coupled with a greater increase in the sagittal area of both the soft palate and the tongue. Johnston and Richardson,[62] over a 32-year period also observed an increase in soft palate length and a narrowing of the oropharynx with increasing age. According to Tourné,[10] this latent descent of the hyoid bone, especially in males with increasing age, is a compensatory mechanism to maintain upper airway patency as a result of an increase in tongue bulk. In the light of these findings, soft tissue morphology and maturation changes are the most likely factors in the increasing prevalence of obstructive sleep apnoea with age.[62]

Although an upward elevation of the hyoid bone occurs, on average, with mandibular advancement,[31,36] with associated increases in pharyngeal width,[39-41] these changes are transitory in nature and exist only when an oral appliance is *in situ.* The findings of this present study indicate that long term intermittent mandibular advancement does not have any adaptive effect on either the position of the hyoid bone or the hypopharynx.

In this study, changes were evident when the upper pharyngeal dimensions were considered. Like the findings of Isono *et al.,*[38] mandibular advancement with oral appliances appeared to have the most notable effect on the velopharynx and oropharynx. It should be noted that posterior airway space (a measurement of lower oropharyngeal width), increased significantly from a mean width of 10.71 mm to 11.99 mm (mean difference: 1.28 mm). These findings are of considerable clinical importance as evidence suggests that any increase in pharyngeal width denotes a significant change in upper airway patency.[36,63,64] This increase in width was thought to be related to a loss of pharyngeal oedema following the elimination of habitual snoring, and possibly due to an increased tonus of the pharyngeal musculature.

Pressure measurement studies have shown that the soft palate region is an obstruction site of central importance in apnoeic patients. Shepard and Thawley[65] found that 56 per cent of apnoeic patients had collapse confined to the velopharynx and retro-palatal segment of the upper airway. Skatvedt[66] found that 70 per cent of apnoeic patients had varying degrees of residual obstruction in the nasopharynx at the level of the soft palate, even after uvulopalatopharynoplasty. Change in the length of the soft palate following long-term use of mandibular advancement is, therefore, of considerable clinical importance. These changes were statistically significant at six months following appliance insertion, and were thought to be attributed to a loss of oedema following elimination of habitual snoring.

Conclusion

This study revealed that long-term mandibular advancement had no adaptive effect on the hypopharynx, whereas, as indicated by significant changes that occurred in both the posterior airway space and the length and thickness of the soft palate, it did have a demonstrable effect on the oropharyngeal and velopharyngeal regions of the upper airway. These findings confirm the author's agreement with Lowe;[64] namely, that mandibular advancement with oral appliances should be considered as a treatment for life as, to date, no treatment appears to be effective in inducing a permanent change in the hypopharynx.

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References

1. Papadopoulos N, Lykaki-Anastopoulou G, Alvanidou E. The shape and size of the human hyoid bone and a proposal for an alternate classification. J Anat 1989; 163: 249–60.
2. Durzo C, Brodie A. Growth behaviour of the hyoid bone. Angle Orthod 1962; 32: 193–204.
3. Negus V. Comparative anatomy and physiology of the larynx. New York: Grune and Stratton Inc, 1949: 26–7.
4. Van de Graff W, Gottfried S, Mitra J, Van Luteren E, Cherniack N, Strohl K. Respiratory function of hyoid muscles and hyoid arch. J Appl Physiol 1984; 57: 197–204.
5. Pae E-K, Kuhlberg A, Nanda R. Role of pharyngeal length in patients with a lack of overbite. Am J Orthod Dentofac Orthop 1997; 112: 179–86.
6. Kollias I, Krogstad O. Adult craniocervical and pharyngeal changes: a longitudinal cephalometric study between 22 and 42 years of age. Part I: morphological craniocervical and hyoid bone changes. Eur J Orthod 1999; 21: 333–44.
7. Tallgren A, Solow B. Hyoid bone position, facial morphology and head posture in adults. Eur J Orthod 1987; 9: 1–8.
8. Bibby R, Preston C. The hyoid triangle. Am J Orthod 1981; 80: 92–7.
9. Haralabakis N, Toutountzakis N, Yiaptzis S. The hyoid bone position in adult individuals with open bite and normal occlusion. Eur J Orthod 1993; 15: 265-71.
10. Tourné L. Growth of the pharynx and its physiologic implications. Am J Orthod Dentofac Orthop 1991; 99: 129–39.
11. Özbek M, Miyamoto K, Lowe A, Fleetham J. Natural head posture, upper airway morphology and obstructive sleep apnoea severity in adults. Eur J Orthod 1998; 20: 133–43.
12. Solow B, Ovesen J, Nielsen P, Wildschiødtz G, Tallgren A. Head posure in obstructive sleep apnoea. Eur J Orthod 1993; 15: 107–14.

13. Tangugsorn V, Skatvedt O, Krogstad O, Lyberg T. Obstructive sleep apnea: Part I. Cervico-craniofacial skeletal morphology. Eur J Orthod 1995; 17: 45–56.
14. Riley R, Guilleminault C, Herran J, Powell N. Cephalometric analyses and flow-volume loops in obstructive apnea patients. Sleep 1983; 6: 303–11.
15. Guilleminault C, Riley R, Powell N. Obstructive sleep apnea and abnormal cephalometric measurement. Implications for treatment. Chest 1984; 90: 793–4.
16. Bacon W, Kriegar J, Turlot J, Stierle J. Craniofacial characteristics in patients with obstructive sleep apnoea syndrome. Cleft Palate J 1988; 25: 374–8.
17. Johns F, Strollo P, Buckley M, Constantino J. The influence of craniofacial structure on obstructive sleep apnoea in young adults. J Oral Maxillofacial Surg 1998; 56: 596–602.
18. Jamieson A, Guilleminault C, Partinen M, Quera-Salva M. Obstructive sleep apnoeic patients have craniomandibular abnormalities. Sleep 1986; 9: 469–77.
19. Partinen M, Guilleminault C, Quera-Salva M, Jamieson A. Obstructive sleep apnea and cephalometric roentgenograms. The role of anatomic upper airway abnormalities in definition of abnormal breathing during sleep. Chest 1988; 93: 1199–205.
20. Tsuchiya M, Lowe A, Pae E-K, Fleetham J. Obstructive sleep apnea subtypes by cluster analysis. Am J Orthod and Dentofacial Orthop 1992; 101: 533–42.
21. Battagel J, L'Estrange P. The cephalometric morphology of patients with obstructive sleep apnoea (OSA). Eur J Orthod 1996; 18: 557–69.
22. Mayer G, Meier-Ewart K. Cephalometric predictors for orthopaedic mandibular advancement in obstructive sleep apnoea. Eur J Orthod 1995;17: 35–43.
23. Lowe A, Santamaria J, Fleetham J, Price C. Facial morphology and obstructive sleep apnea. Am J Orthod and Dentofacial Orthop 1986; 90: 484–91.
24. Lyberg T, Krogstad O, Djupesland S. Cephalometric analysis in patients with obstructive sleep apnoea syndrome: I: Skeletal morphology. J Laryngology and Otology. 1989a; 103: 287–92.
25. Bacon W, Turlot J, Krieger J, Stierle J. Cephalometric evaluation of pharyngeal obstructive factors in patients with sleep apnea syndrome. Angle Orthod 1990; 60: 115–22.
26. Tangugsorn V, Skatvedt O, Krogstad O, Lyberg T. Obstructive sleep apnea: a cephalometric study. Part II. Uvulo-glossopharyngeal morphology. Eur J Orthod 1995; 17: 57–67.
27. Pracharktam N, Hans M, Strohl K, Redline S. Upright and supine cephalometric evaluation of obstructive sleep apnea syndrome and snoring subjects. Angle Orthod 1994; 64: 63–74.
28. Pae E-K, Lowe A, Fleetham J. The role of pharyngeal length in obstructive sleep apnea patients. Am J Orthod and Dentofacial Orthop 1997; 111: 12–17.
29. Pracharktam N, Nelson S, Hans M, Broadbend B, Redline S, Rosenberg C, Strohl K. Cephalometric assessment in obstructive sleep apnea. Am J Orthod and Dentofacial Orthop 1996; 109: 410–19.
30. Schmidt-Nowara W, Lowe A, Wiegand L, Cartwright R, Perez-Guerra F, Menn S. Oral appliances for the treatment of snoring and obstructive sleep apnea: a review. Sleep 1995; 18: 501–10.
31. Johal A, Battagel J. An investigation into the changes in airway dimension and the efficacy of mandibular advancement appliances in subjects with obstructive sleep apnoea. Br J Orthod 1999; 26:205–10.
32. Pancer J, Al-Faifi S, Al-Faifi M, Hoffstein V. Evaluation of variable mandibular advancement appliance for treatment of snoring and sleep apnea. Chest 1999; 116:1511–18.
33. Thorton W, Roberts D. Non-surgical management of the obstructive sleep apnea patient. J Oral Maxillofac Surg 1996; 54:1103–108.
34. Ferguson K, Ono T, Lowe A, al-Mejed S, Love L, Fleetham J. A short term controlled trial of an adjustable oral appliance for the treatment of mild to moderate obstructive sleep apnea. Thorax 1997; 52: 362–8.
35. Cohen R. Obstructive sleep apnea: oral appliance therapy and severity of condition. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 1998; 85: 388–92.
36. Bonham P, Currier G, Orr W, Otham J, Nanda R. The effect of a modified functional appliance on obstructive sleep apnea. Am J Orthod and Dentofacial Orthop 1988; 94: 384–92.
37. Marklund M, Franklin K, Sahlin C, Lundgren R. The effect of a mandibular advancement device on apneas and sleep in patients with obstructive sleep apnea. Chest 1998; 113: 707–13.
38. Isono S, Tanaka A, Sho Y, Konno A, Nishino T. Advancement of the mandible improves velopharyngeal airway patency. J Appl Physiol 1995; 79: 2132–138.
39. Athanasiou A, Papdopoulos M, Mazaheri M, Lagoudakis M. Cephalometric evaluation of pharynx, soft palate, adenoid tissue, tongue, and hyoid bone following the use of a mandibular repositioning appliance in obstructive sleep apnea patients. Int J Adult Orthod Orthognath Surg 1994; 9: 273–83.
40. Battagel J, Johal A. L'Estrange P, Croft C, Kotecha B. Changes in airway and hyoid position in response to mandibular protrusion in subjects with obstructive sleep apnoea (OSA). Eur J Orthod 1999; 21:363–76.
41. Gale D, Sawyer R, Woodcock A, Stone P, Thompson R, O'Brien K. Do oral appliances enlarge the airway in patients with obstructive sleep apnea? A prospective computerized tomographic study. Eur J Orthod 2000; 22:159–68.
42. Robertson C. Obstructive sleep apnea. Part II. Treatment with a customised dental appliance. NZ Dent J 1997; 83: 4–9.
43. George P. A new instrument for functional appliance bite registration. J Clin Orthod 1992; 26:721–23.
44. Moorrees C, Kean M. Natural head position: a basic consideration in the interpretation of cephalometric radiographs. Am J Phys Anthro 1958; 16:213–34.
45. Dahlberg G. Statistical methods for medical and biological students. New York: Interscience Publications, 1940.
46. Nelson C, Harkness M, Herbison P. Mandibular change during functional appliance treatment. Am J Orthod and Dentofacial Orthop 1993; 104: 153–61.
47. Courtney M, Harkness M, Herbison P. Maxillary and cranial base changes during treatment with functional appliances. Am J Orthod and Dentofacial Orthop 1996; 109: 616–24.
48. Miles P, O'Reilly M, Close J. The reliability of upper airway landmark identification. Aust Orthod J 1995; 14: 3–6.
49. Andersson L, Brattström V. Cephalometric analyses of permanently snoring patients with and without obstructive sleep apnea syndrome. Int J Oral Maxillofac Surgery. 1991; 20:159–62.

50. Haponik E, Smith P, Bohlman M, Allen R, Goldman S, Bleecker G. Computerized tomography in obstructive sleep apnea correlation of airway size with physiology during sleep and wakefulness. Am Rev Respir Dis 1983; 127: 221–26.
51. Suratt P, Dee P, Atkinson R, Armstrong P, Wilhoot S. Fluoroscopic and computer tomographic features of the pharyngeal airway in obstructive sleep apnea. Am Rev Resp Dis 1983; 127:487–92.
52. Fromm B, Lundberg M. Postural behaviour of the hyoid bone in normal occlusion before and after surgical correction of mandibular protrusion. Swed Dent J 1970; 63: 425–33.
53. Gustazvsson U, Hansson G, Holmqvist A, Lundberg M. Hyoid bone position in relation to head posture. Swed Dent J 1972; 65: 423–30.
54. Stepovich M. A cephalometric positional study of hyoid bone. Am J Orthod 1965; 51: 882–900.
55. Adamidis I, Spyropoulos M. The effects of lymphadenoid hypertrophy on the position of the tongue, the mandible and the hyoid bone. Eur J Orthod 1983; 5:287–94.
56. Takagi Y, Gamble J, Proffit W, Christiansen R. Postural change of the hyoid bone following osteotomy of the mandible. Oral Surg, Oral Med and Oral Path 1967;23: 688–92.
57. LaBanc J, Epker B. Changes of the hyoid bone and tongue following advancement of the mandible. Oral Surg, Oral Med and Oral Path 1994; 57: 351–6.
58. Graber L. Hyoid changes following orthopedic treatment of mandibular prognathism. Angle Orthod 1978; 48:33–8.
59. Douglas N. The sleep apnoea/hypopnoea syndrome. Eur J Clin Invest 1995; 25: 285–90.
60. Bresnitz E, Goldberg R, Kosinski R. Epidemiology of obstructive sleep apnoea. Epidem Rev 1994; 16: 210–7.
61. Kollias I, Krogstad O. Adult craniocervical and pharyngeal changes: a longitudinal cephalometric study between 22 and 42 years of age. Part II: morphological uvulo-glossopharyngeal changes. Eur J Orthod 1999; 21: 345–55.
62. Johnston C, Richardson A. Cephalometric changes in adult pharyngeal morphology. Eur J Orthod 1999; 21: 357–62.
63. Clark G, Arand D, Chung E, Tong D. Effect of anterior repositioning on obstructive sleep apnea. Am Rev Resp Dis 1993; 147: 624–29.
64. Lowe A. Dental appliances for the treatment of snoring and obstructive sleep apnea. In Kryger M, Roth T and Derment W, eds. Principles and Practice of Sleep Medicine. Philadelphia: Saunders, second edition. 1994: 722–35.
65. Shepard J, Thawley S. Localization of upper airway collapse during sleep in patients with obstructive sleep apnea. Am Review Resp Dis 1990; 141: 1350–55.
66. Skatvedt D. Continuous pressure measurements in the pharynx and esophagus during sleep in patients with obstructive sleep apnea syndrome. Laryngoscope 1992; 102: 1275–79.