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REVIEW ARTICLES

A consideration of factors affecting palliative oral appliance effectiveness for obstructive sleep apnea: a scoping review

Bruce S. Haskell, DMD, PhD[1,2,3]; Michael J. Voor, PhD[4,5]; Andrew M. Roberts, MS, PhD[2,6]

[1]*Division of Orthodontics, University of Kentucky College of Dentistry, Lexington Kentucky;* [2]*Department of Physiology, School of Medicine, University of Louisville, Louisville, Kentucky;* [3]*Comprehensive Dentistry, School of Dentistry, University of Louisville, Louisville, Kentucky;* [4]*Department of Orthopedics, School of Medicine, University of Louisville, Louisville, Kentucky;* [5]*Department of Biomedical Engineering, School of Medicine, University of Louisville, Louisville, Kentucky;* [6]*Department of Pediatrics, School of Medicine, University of Louisville, Louisville, Kentucky*

Study Objectives: This scoping review allows physicians, researchers, and others interested in obstructive sleep apnea to consider effectiveness of oral appliances (OAs). The intent is to improve understanding of OA effectiveness by considering morphologic interaction in patients with obstructive sleep apnea.

Methods: Morphologic and biomechanical criteria for positional alterations of the mandible assessed success rates of OA appliances. Searches of databases (Medline, PubMed, The Cochrane Library, EBSCO) using terms: OA treatment effectiveness and positive and/or negative outcome predictors. Craniofacial predictors of OAs and obstructive sleep apnea biomechanical factors of anatomical traits associated with OA effectiveness were included. Databases searched radiographic cephalometric imaging for morphology/phenotypes and apnea-hypopnea index responses. Articles were excluded if title or abstract was not relevant or a case report. If the analysis did not report mean or standard deviation for apnea-hypoxia index, it was excluded. No language, age, or sex restrictions were applied.

Results: Analysis of 135 articles included in searched literature indicated alterations in musculature and pharyngeal airway structure through OA use. These alterations were individually unpredictable with wide variability 61.81% ± 12.29 (apnea-hypoxia index mean ± standard deviation). Morphologic variations as predictors were typically weak and idiosyncratic. Biomechanical factors and wide variations in the metrics of appliance application were unclear, identifying gaps in knowledge and practice of OAs.

Conclusions: An integrated basis to identify morphologic and biomechanical elements of phenotypic expressions of sleep-disordered breathing in the design and application of OAs is needed. Current knowledge is heterogeneous and shows high variability. Identification of subgroups of patients with obstructive sleep apnea responding to OAs is needed.

Keywords: obstructive sleep apnea, oral appliances, oral appliance negative effects, morphologic factors

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BRIEF SUMMARY

Current Knowledge/Study Rationale: The efficiency rate of oral appliances for mild to moderate obstructive sleep apnea approaches 50% depending upon the baseline apnea-hypopnea index used for successful treatment. A scoping review indicated the lack of clear rationale for an individualized appropriate application technique for oral appliances.

Study Impact: Anatomical and biophysical attributes presented as criteria for oral appliance application are statistically inconsistent with few exceptions. Selected participants of "responder vs. limited-responder" phenotypes based on morphologic attributes in the searched literature with oral appliance use are presented as examples with superimposed computer tomographic images.

INTRODUCTION

The goals of our scoping review were 1) to provide a perspective of the variable success rate of oral appliance (OA) devices used by dentists to treat obstructive sleep apnea (OSA) and 2) to identify morphologic and biomechanical factors that may lead to better patient preselection and improved fabrication guidelines for OAs.

OSA is a partial or complete collapse of the upper airway caused by relaxation of muscles and tissues controlling the soft palate and tongue. It may be blamed for various maladies, including waking somnolence, impaired mental function, delayed reactions, and loss of concentration.[1–4] Hypertension, heart disease, congestive heart failure, pulmonary hypertension, cardiac arrhythmia, ischemic heart disease, and stroke are also associated with untreated/undiagnosed OSA, as are many industrial accidents due to fatigue.[5–7] OSA is a multifactorial integrated dysfunctional system where simple changes in posture, poor neurophysical properties of muscle activation, airway pressure, muscle tone aging, moderate obesity, or sleep state may cause airway narrowing with nonpatency. The inability to breathe properly during sleep and its correction is the subject of much investigation.[8]

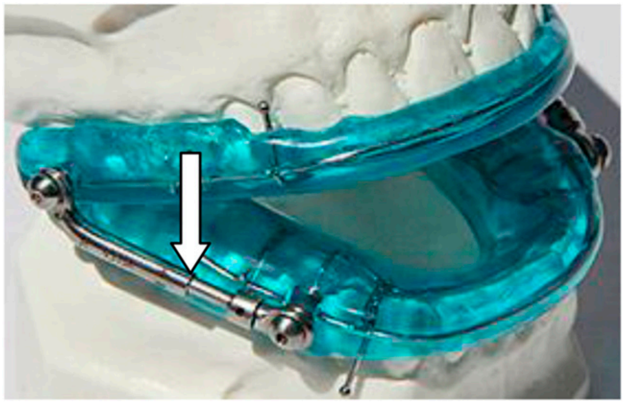
Continuous positive airway pressure (CPAP) is the primary palliative treatment approach.[9] Wearing a facial mask with air pressure applied, the pharynx becomes patent as it is inflated. Due to poor compliance, 25-50% of patients with OSA will either decline CPAP therapy or find it intolerable.[1,10–17] CPAPs are unwieldy, hard to travel with, and loud, with the air containment seal often leaking and blowing or venting air onto a sleeping partner. Therefore, a successful alternative to CPAP is welcome. The relatively simple and straightforward OA palliative therapy may represent a partial solution (**Figure 1**). Appliance use is intended to increase sagittal and coronal width of the pharyngeal airway. This is performed noninvasively (and reversibly) with a mandibular advancing device, a removable OA. A problem with current OA therapy is determining which patients will respond well and which will not. Such knowledge may partially negate the need for CPAP or bilevel positive airway pressure (BPAP) devices or invasive therapies. Sutherland et al[18] reported, "However despite similar health benefits between treatments, approximately one-third of OSA patients will not respond to [mandibular advancing device] (MAS) [an OA]. This is of significant concern in terms of resource wastage and treatment delays. Much attention has been given to understanding patient phenotypes which relate to MAS response such as sex, obesity, craniofacial structure, and type and severity of OSA. However, none of these factors are universal, and hence there is an unresolved need for reliable indicators of MAS treatment response." Treatment with an OA is considered indeterminate (stochastic) with the worse responders having high initial apnea-hypopnea index (AHI) scores.[19,20]

OAs for OSA are used in mild to moderately affected individuals with < 35 AHI events/h. OAs are considered successful if an AHI reduction in moderate cases (AHI = 15 to 30 events/h) is in the realm of 50% from the original baseline but is often less effective in reducing the AHI score.[21,22,51]

The OA brings the mandible forward, enlarging the oral cavity by pulling upon the muscles of the oropharynx to gain improved airway volume.[20,23] The forward position of the mandible with an OA specifically increases velopharyngeal and genioglossal tension, opening the pharynx an unspecified amount.[24–26] The American Academy of Sleep Medicine suggests use of the OA for patients with only mild to moderate OSA and allows use of this oral device in individuals 18 years and older, as well as those who decline to use CPAP/bilevel positive airway pressure or are not able to tolerate one.[27] Patients are counseled to avoid alcohol, smoking, and psycho-sedatives, with an additional directive for weight reduction for those with a high body mass index (BMI).

Surgical intervention may be required in patients for whom an OA or CPAP device is inadequate. A maxillo-mandibular surgical advancement of both jaws is conventionally 1 cm.[28–30] This includes those with a high AHI and associated comorbidities (significant bradycardia, hypercapnia, cor pulmonale. and extreme hypersomnolence). Intervention may require both soft and hard tissue corrections. Gaining improved airway patency with less resistance due to a wider airway via tension on the suprahyoid and velopharyngeal musculature can be biomechanically advantageous in that a slight improvement in the radii of the pharyngeal structure is significant (eg, Poiseuille's Law: As the radius is doubled it decreases the resistance by a factor of 16).[7,28,29,31–33]

Figure 1—Example of removable oral appliance.



Note that the upper and lower dental trays for the teeth are connected by sliding sheaths (white arrow) that allow the lower jaw to be advanced to 75% of maximal protrusion in an attempt to open the oro-pharynx for additional airway patency (Image courtesy of Dream Systems, Roseville, CA).

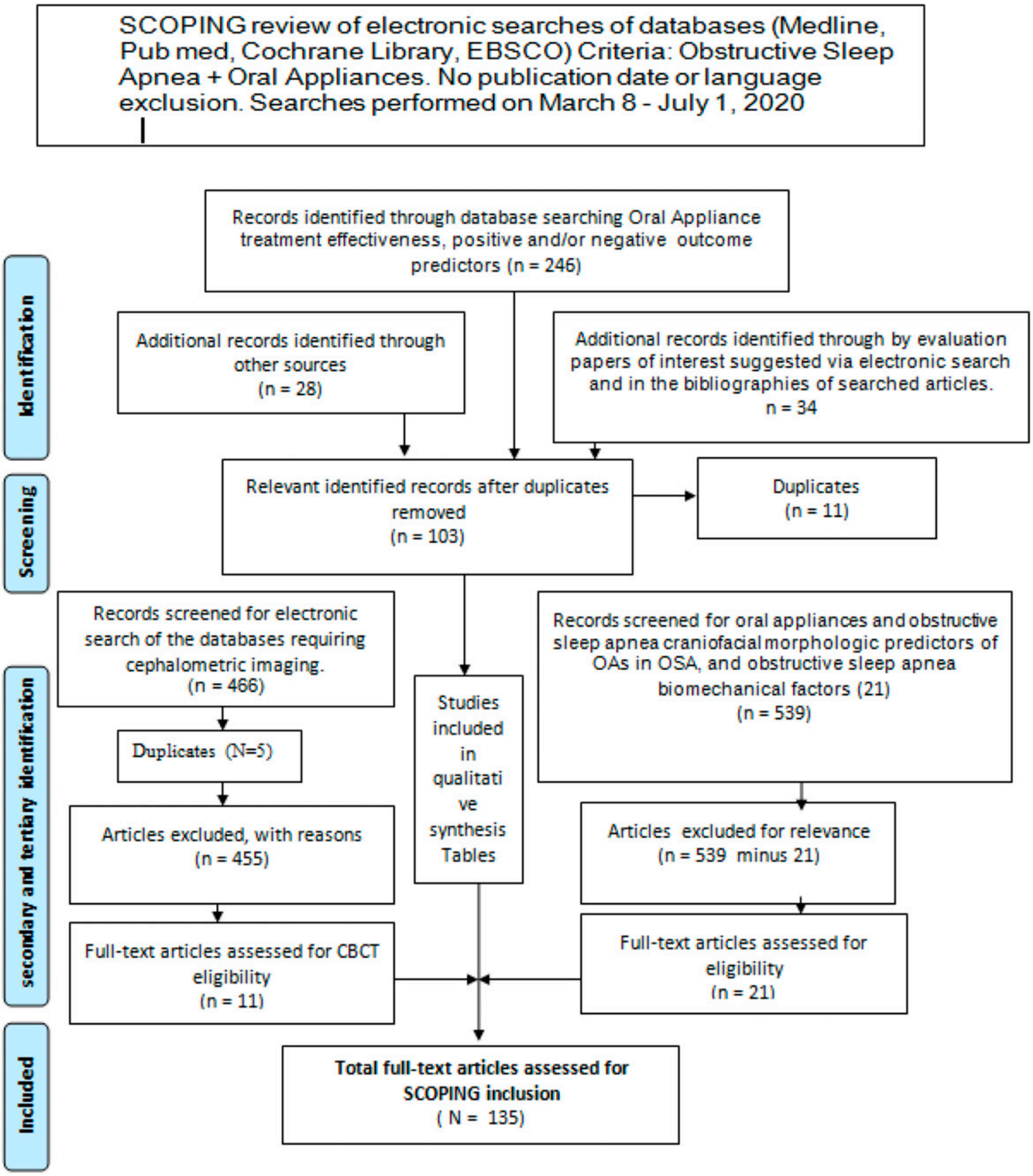
METHODS

The scoping review performed is a broad approach, mapping selected literature and addressing a wide-ranging research question. It is appropriate in this instance as the studies discovered were of different types with distinct population databases, incomparable statistics, lack of quantitative data, and dissimilar results. In contrast to scoping reviews, systematic reviews with meta-analysis answer a specific question with comprehensive data analysis of similar studies of like populations combined into one analyzed grouping. Our scoping review search identified and clarifies key concepts by identifying gaps in research knowledge by overview of the existing base of current practice in the field. Synthesis of the acquired data is necessarily limited due to the broad range and variable nature of the studies and their quality.[34]

Electronic searches of databases for a scoping review (Medline, Pubmed, Cochrane Library, EBSCO) for keywords for OSA were performed using the search terms: oral appliance treatment effectiveness and positive and/or negative outcome predictors. Of 246, 46 identified titles and abstracts were relevant. Eleven duplicates were eliminated. Sixty-two papers suggested via the search and in the bibliographies of searched articles were included (see scoping diagram **Figure 2**) for 108 relevant articles. Articles were excluded if 1) the title or abstract was not helpful or relevant to the review, 2) it was an anecdotal clinical case report, or 3) a quantitative analysis did not report the mean or standard deviation for AHI effectiveness. Only English or translated searches were used with no age or sex restrictions applied. Dates of search were up to July 1, 2020.

To determine a predictive etiology of appliance effectiveness, searches included databases for craniofacial morphologic

Figure 2—Scoping diagram of electronic searches.



A scoping review of electronic searches of databases (Medline, PubMed, Cochrane Library, EBSCO). Criteria: obstructive sleep apnea + oral appliances. Note the number of articles identified in the boxes for the selected searches.

predictors of OAs in OSA and OSA biomechanical factors to construct a listing of 21 articles with recognized anatomical traits associated with OA use. Articles had to include description of morphologic and biomechanical criteria for OAs relating to palliative positional alterations of the mandible, hyoid, and its associated pharynx and assessed for response to OA appliances in patients with OSA. Search date: July 1, 2020.

In addition, the databases were assessed to determine the radiographic cephalometric imaging for the specific morphology/phenotypes describing the AHI responses to OA use for 11 additional articles. The searched numbers are shown in the scoping diagram **Figure 2**. Total references included are 135.

Usage of OAs is demonstrated by de-identified examples with cone beam computer tomography (CBCT) superimpositions selected from the obstructive sleep apnea data bank of the University of Louisville School of Dentistry, Department of Dental Radiology.

Participants self-reported improvements as clinically successful, limited, or unsuccessful.

RESULTS

The electronic search described above using the terms "oral appliance treatment effectiveness" and "positive and/or

Table 1—Variability of treatment success rates of palliative OAs for patients with OSA.

n	AHI without OA, events/h	AHI with OA, events/h	Percent Change in AHI	Comments	References
30	64.6	31.3	51.54	Large age range. All participants severe OSA. Post OA AHI SD exceeded the mean	35
22	15.9	3.31	79.18	Large age range. Combined moderate and severe participants. Ideal AHI with OA. SD exceeded the mean	36
47	40.3	17.07	57.64	Adults, age ~24–57 y. Reduction to moderate AHI level. OA less effective in older individuals .	37
14	38.4	10.9	71.61	Large age range. Post OA AHI was in mild range. SD exceeded the mean.	38
53	33.0	10.8	67.27	Participants age ~38–61 y. Post OA AHI SD exceeded the mean. Results in mild OSA range but varied with OSA level.	39
09	31.6	8.3	73.73	Small population. Reduction of AHI to mild range.	50
19	34.7	12.9	62.82	Reduction of AHI to mild range.	40
32	23.0	7.6	66.95	Large age range. AHI reduced to near normal level. SD not reported.	41
57	22.0	10.4	52.72	Large age range. Post OA AHI SD approached mean.	42
14	34.0	10.0	70.58	Small sample, large age range. AHI reduced to mild level.	43
72	27.4	13.3	51.45	Post OA SD exceeded the mean.	44
89	21.0	4.9	76.66	Large age range. Reported results as ranges of AHI to near normal. Nonresponders remained at moderate level.	45
12	53.81	35.99	33.11	AHI reduction remained in the severe range.	46
26	17.8	8.3	53.37	Limited age range (40–50 y). 19% showed deterioration of AHI with OA.	47
1600	22.4	9.3	58.48	Population age ~50 y. Adverse effects developed in 14.7%.	21
Mean ± SD (n=15)	31.99 ± 13.46	12.96 ± 9.07	61.81 ± 12.29		
Range	15.9 to 64.6	3.31 to 35.99	33.11 to 79.18		

Note that the change in the AHI depended upon the degree of OSA and patient characteristics. Means and standard deviations of the AHI before and after placement of an OA, percent changes with the OA, as well as the range of AHI values are shown for the 15 studies. AHI = apnea-hypopnea index, OA = oral appliance, OSA = obstructive sleep apnea, SD = standard deviation.

negative outcome predictors" yielded 246 articles. Of these, 46 were assessed for relationships between polysomnograph, cephalometric, and morphologic variables and success rates for AHI reduction.

A total of 15 articles was found that reported the effect of oral appliances on AHI (**Table 1**). On average, AHI was reduced from 32 ± 13 events/h without an OA to 13 ± 9 events/h with an OA, representing an average AHI reduction of 62 ± 12% (**Table 1**).[21,35–50]

Success rates varied, with clinicians defining successful treatment as a 50% reduction in AHI in more than half of the patients with moderate OSA, defined as an AHI of greater than 15 events/h to a score of 30 events/h. Mild cases reported a higher AHI reduction, while severe cases reported only a modestly improved reduction score and stayed in the same OSA category. The more severe the initial AHI, the less successful a positive response, with no consistency of cure.[21,37,48] Large differences in post-OA use were explained as being due to differing populations and initial severity of OSA.[3] The scoping review illustrates the wide range of evidence in the search studies, with inconsistent numbers of study participants, age, and disease comorbidity factors. For example, one study reported a good response in younger participants and those with smaller upper airways, while in older patients, use of OAs was less effective.[21,45] The change in the AHI percent was related to physiologic age, BMI, cephalometric indicators (overjet, height of the maxillary molars, vertical height of the hyoid bone), and airway variables.[37] It was often unclear as to what an acceptable residual therapeutic AHI would be. AHI variability for the patients with OSA presented for treatment was high (**Table 1**), making it difficult to assess OA capabilities for an individual. Only one of the identified reviews presented post-OA AHIs for each study.[49] Our report for the polysomnographic results for AHI improvement approximated 61%, as shown in **Table 1**.

Table 2—Anatomical variables associated with favorable AHI response to an OA categorized in three major groupings.

	References
Mandible-Hyoid	
Short distance between mandible and hyoid	49,50,51
Greater hyoid vertical movement to mandible with OA	49
Greater hyoid vertical movement to mandible with OA (with a 65% reduction in distance)	52
Forward, downward flexion of the hyoid	50
Retrognathia	53,127
Short mandibular body length	51
Maxillofacial	
Small anterior facial height	50
Dolichofacial (long-faced) phenotype	54
Short anterior facial height	53
Short anterio-posterior face length	51
Larger sella-nasion-subspinale angle	50
Smaller sella-nasion-infradentale angle	50
Increased cranial base angulation	49
Pharynx	
Narrow laryngopharyngeal space	49
Narrow retroglossal airway	49,55
Short distance of posterior pharyngeal wall to lower incisors	51
Long distance between anterior of mandible and second cervical vertebra	50
Short soft palate	50
Overly rostral position of tongue base	50,55
Narrow posterior airway space	50

AHI = apnea-hypopnea index, OA = oral appliance.

However, standard deviations in each study often approached the mean itself and at times exceeded it. The extreme range in resulting AHI scores makes a predicable improvement unlikely. An exception was a predictive success of 74.2% by Iwamoto et al[45] using logistic regression analysis for his responder population, but with a wide range of post-OA AHI for both responders and nonresponders. These results were attributed to low BMI for the Japanese population compared to those from Western countries and inherent craniofacial deformities (retrognathia, steep mandibular angled jaw) in the Japanese population.

The listed electronic databases for oral appliances and OSA, craniofacial morphologic predictors of OAs in OSA, and OSA biomechanical factors included a description of phenotypic criteria for OAs relating to palliative positional alterations of the mandible, hyoid, and its associated pharynx assessed for response to OA appliances in patients with OSA. Twenty-one articles were discovered by electronic search by evaluating those papers of interest and others "suggested" via search and in bibliographies of searched articles (see search diagram **Figure 2**). Anatomical and biophysical criteria for OAs relating to palliative positional alterations of the mandible and hyoid were evaluated and chosen based upon 2-dimensional radiologic interpretation. These criteria for anatomical variables associated with favorable AHI response to an OA are in **Table 2**.[49–55] Cephalometric variables for anatomical variables associated with limited AHI response to an OA are in **Table 3**.[37,49–51,54,56–60] These data indicate sporadic or limited improvement rates in unselected patients with OA use.[61]

No specific AHI changes were reported for each trait. Therefore, the majority of the anatomical features for good vs. limited responders may be considered generalized indicators of AHI reduction success, taken seriously but not necessarily literally. The distance of the hyoid to mandibular plane is an exception, with an R^2 of .688 and .37, respectively, reported in 2 studies.[40,43] The former study had a sample of uniform age, while the later had a large range of ages with a small sample. When longer than normal, the distance of the superior-anterior body of the hyoid to the mandible and perpendicular to the occlusal plane correlated with sleep apnea.[49,50] Several other studies reported a low positioned hyoid is indicative of limited response with OA use (**Table 3**).

While an OSA oral appliance conventionally requires the patient to advance the mandible 67%-75% of maximum forward splinted position, the amount of vertical opening to percentage of AHI improvement was reported in 3 studies.[37,59] The vertical opening was intentionally kept constant, with increments of jaw advancement to determine the least amount of negative OA side effects with mandibular protrusion.[62] Using fluid-dynamic analysis, the minimal bite opening position necessary for

Table 3—Three major anatomical groupings associated with limited AHI response to an OA.

	References
Mandible-Hyoid	
Long distance of anterior/superior of hyoid to mandibular plane	56,57
Posteriorly positioned maxilla and mandible	50
Steep mandibular plane to Frankfurt Horizontal	49,50,56,128
Long mandibular body measurement (Gnathion-Gonion).	57
Obtuse mandibular corpus-ramus angle	50
Short distance of mandible to cervical spine	49
Vertical and back rotation vector of mandible	37
Steep dental occlusal plane to Frankfurt Horizontal	50
Proclined and over-erupted maxillary and mandibular teeth	50
Maxillofacial	
Retrognathia	56,58
Cranio-cervical extension, forward head posture	56
Increased facial height	50,56
Excessive anterior vertical development of the skull (Leptoprosopic)	49,59
Insufficient anterior skull base development	49,59
"Square-jawed" (Brachyfacial)	54
Pharynx	
Excessive pharyngeal fat pads	60
Posteriorly placed pharyngeal wall	50
Small hypopharyngeal airway	37
Larger and longer soft palate	51,56,57
Upright tongue posture	56
Large tongue size	51
Small oropharynx depth	51
Large middle and inferior airway spaces	49
Long distance posterior nasal spine to the velum tip of soft palate	57

AHI = apnea-hypopnea index, OA = oral appliance.

mandibular protrusion was effective in increasing airway volume compared to a larger degree of bite raising.[63]

Of the 11 papers selected for review in a final search for 3-dimensional CBCT anatomical relevance, only 3 of these used this imagery to assess effects of OA wear.[64,65] These 3 studied anatomical regions of the upper airway. In 8 other articles discovered for CBCT evaluation of OA appliances, minimal axial airway of the pharyngeal space was not reported; this is the point of most resistance and commonly believed to be the most significant factor of obstructed airway flow.[28,33,64,66–70] Thus, the literature does not indicate a clear rationale for OA functional design factors.

DISCUSSION

A scoping review assessing relationships between polysomnographic, cephalometric, morphologic variables, and success rates with OAs for AHI reduction showed the reported success varied widely. This rate varied in proportion to the severity of OSA (**Table 1**). It was not always clear what a therapeutically successful OA would be (eg, lowered AHI, increased oxygenation, etc.) in moderate to severe cases with OA use. Not all studies used AHI as an indicator of success, instead defining it as a reduction of related symptoms.[18] Due to variability of OSA etiology in the overall population and variable range in resulting AHI reductions with an OA, it is difficult to be categorical in regard to OA capabilities.[49]

A substantial AHI reduction in moderately severe OSA may not necessarily be a successful therapeutic outcome for treatment. A successful reduction from a high AHI score of > 50 events/h was reduced to a "moderate" AHI index > 20 events/h in 1 study.[37] However, it was not indicated if this level was sufficient to address OSA as viable treatment for these patients with OSA. The extreme variability in AHI improvement, when its standard deviation meets or exceeds the mean, indicates difficulty achieving success with OA devices. The range of standard deviations observed in the search for resulting AHI with OAs makes a predicable or practicable improvement currently indeterminate. Given that etiological factors are markedly diverse is reason for recommending an OA in fairly mild OSA situations and not attempting to treat those in the high moderate to severe range. Reducing the AHI by approximately 50%, even with high variability, is likely an acceptable treatment level for mild OSA categories, as a resulting low AHI is acceptable. Conversely, reduction of a high AHI score to lower values may not be individually therapeutic or necessarily considered efficacious. It is thus inappropriate for clinicians to accept a general "improvement" of AHI of 50% for all levels of OSA conditions. Implementation for successful use of OAs is highly variable and may be "hit or miss" due to the range of etiologic factors of anatomy and comorbidity. Thus, OAs are intended for moderate OSA situations only or in combination with CPAP/bilevel positive airway pressure devices for the patients with the most severe OSA.[18,66]

None of the studies analyzed could relate the reduction of AHI to a specific anatomical feature, with the exception of low hyoid placement to the mandibular plane.[49,50,57] The variation in findings suggests a need for integrating the multiple factors of OSA to improve application of OAs for individuals and their unique phenotypes. It was not determined how individual OSA anatomy responded to OA use, nor was it attributed to differences in musculature or ethnic variations except in 1 article reviewed. Increased age was usually a factor for poor response as reported in a study of 1,300 participants, as airway volume decreases steadily after age 50 to a size comparable to that of an early teen.[33,37,71]

Identification of an OA design and airway biomechanics research gap

The scoping search identified a gap in the knowledge base due to the uninvestigated nature of OA action in individual skeletomuscular patterns. The exception was hyoid distance to the mandible: a complex interaction of suprahyoid musculature and skeletal structure. This lack likely affects performance of clinical practice in the field with OAs (**Table 1**). A description of OA anatomical interactions is indicated to direct future studies for improved application. Previous modeling attempts used many arbitrary factors that reduce accuracy and predictability and failed to reproduce adequate biomechanical behavior of airway tissues.[8,72–74] Current computational techniques are based on 2-dimensional and 3-dimensional imaging using finite-element methods. A drawback of these studies is that they lack kinematic integration of mechanical linkages between muscles and hard structures.[75]

OA anatomical alteration and muscle vectors

OAs with sliding jigs (**Figure 1**) are designed to protrude the mandible anteriorly, resulting in tension of the muscles of the oropharynx. OA therapy usually produces significant changes in the upper airway volume that correlate with a decrease in the AHI (**Table 1**).[76] CPAP/bilevel positive airway pressure devices operate by pneumatically splinting the airway with a reduction in airway muscle activation, whereas OAs work by enhancing muscle splinting/activation with tension, bringing the mandible forward, enlarging the oral cavity.[20,23] OA appliances function by employing mandibular muscular attachments to the tongue, pharyngeal, and dilator muscles. They include an indirect soft tissue relationship to the soft palate to increase velopharyngeal and genioglossal tension to open the oropharynx.[26,76] A direct soft tissue connection from the ramus of the mandible and the hyoid bone and pharyngeal walls was observed to enlarge airway dimensions laterally.[11–17] Moving the mandible anteriorly allows these associated structures to move as well, increasing the airway space by an unknown extent. The minimal axial section is increased with the OA, but its location in the pharynx is changed (**Figure 3**).[66] Some OAs advance the jaw a calculated amount, while other types permit self-titration by the patient to what is "felt" to be a self-perceptible improvement by a jaw protrusion of approximately 75% (**Table 1**). In contrast to other OSA treatments, effectiveness of OAs depends on muscular distention of tissues to improve airway patency. This variable process is subject to idiosyncrasies of individual anatomical differences and muscle physiology.

The review suggested 3 mechanisms of OA operation with respect to the tongue due to soft tissue contiguous associations with the airway.[18,50,53,62] They include 1) the musculature of the tongue is pulled forward with jaw advancement to open the oropharyngeal airway; 2) the inferior portion of the tongue also travels forward; 3) the whole tongue becomes elongated during the advancement process. An upper airway size circa 40 to 67 mm^2 at the smallest cross-sectional area in adults is associated with sleep apnea. A size of circa 149 mm^2 is considered normal for adults.[77]

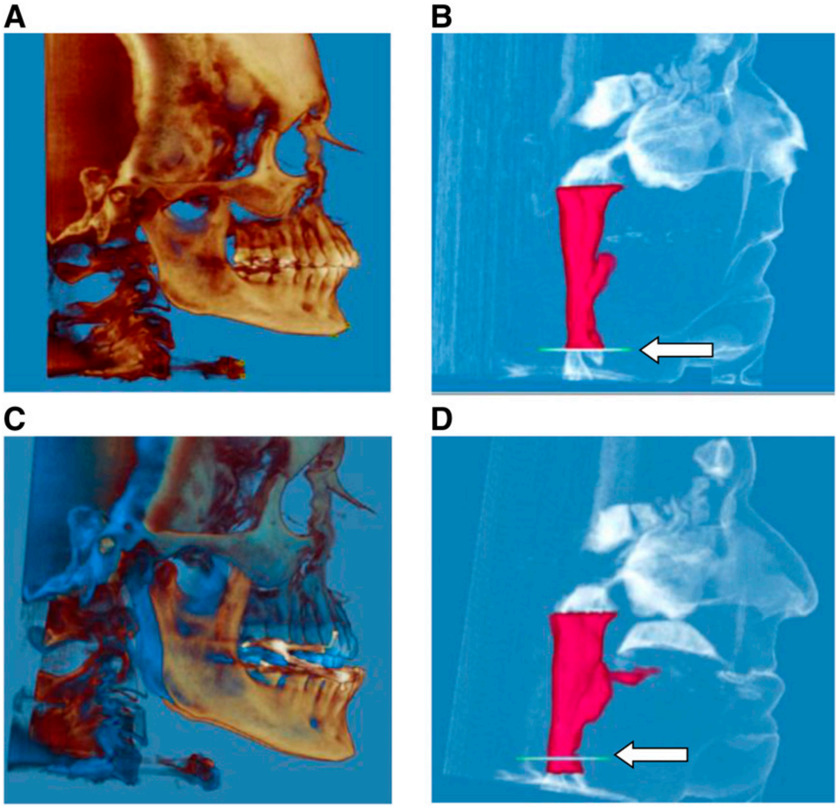
Muscles preserving airway patency such as the geniohyoid may be placed at an anatomical disadvantage in individuals with OSA. The structure and function of the genioglossus were reported abnormal in patients with OSA.[78] Variations in other suprahyoid musculature and its angulation in relation to hard structures are documented.[67]

Due to muscle and tendon viscoelasticity, we speculate a constant displacement induced with an OA may predispose to a gradual time-dependent reduction in associated skeletal airway muscle effectiveness (eg, the geniohyoid) in maintaining oropharynx airway patency during sleep. Different vectors of the geniohyoid and associated skeletal musculature are likely to exhibit varying degrees of biomechanical efficiency in different phenotypes due to marked vector differences and are illustrated in **Figure 4**.

OSA individuals may activate associated airway musculature to compensate for increased airway loads while sleeping. Electromyographic activity may be activated fully while awake but is unable to exceed the required level of activation necessary for patency when the airway is loaded during sleep.[66,79,80] Advancing the jaw with an OA alters compliance of the muscles, changing the tone of the pharyngeal dilators.[49] We speculate muscle fatigue could affect efficiency if an oblique action vector of the geniohyoid muscle reflects a low hyoid position (**Figure 4**). This configuration is reported to yield a poor response to an OA (**Table 3**).[30,56]

In patients with OSA, nonideal anatomical muscle orientation may aggravate muscle sag and creep due to prolonged nocturnal activation and gravity in a supine position when combined with negative airway pressure with inspiration. The search suggested why senior individuals with decreasing

Figure 3—Differences in airway volume in individuals with and without OA.



Mandible advancement: 7.5 mm *x*-axis, 9 mm *y*-axis. **(A)** CBCT of jaws without OA in place. **(B)** CBCT of airway without OA. Red area shows airway volume with minimal axial cross-section of airway space of pharynx indicated by arrow (airway volume 27,636 mm^3, minimal axial area 130 mm^2). **(C)** CBCT superimposition with OA in place. **(D)** Airway volume with OA in place showing that the minimal axial-section increased, but its location changed. Note that the oropharynx increased substantially for an improvement in total airway volume (airway volume 43,813 mm^3, minimal axial area 237 mm^2). CBCT = cone beam computed tomography, OA = oral appliance.

muscle tone are more susceptible to sleep apnea and why they fared so poorly in OAs reducing the AHI.[81,82]

Radiographic studies

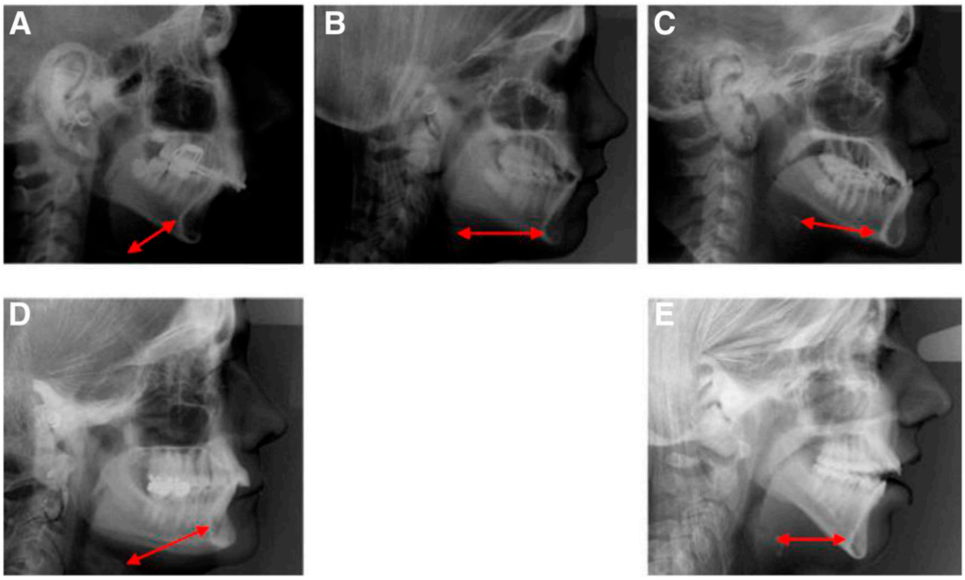
Disagreement exists about suitability of CBCT to assess treatment outcomes for patients with OSA, except for those with extreme blockage.[13,50,66,71,79,80,83–106] However, CBCT can discriminate borders of soft tissue as well as void spaces to diagnose static airway structures.[4,107,108] The search indicated airway volume is altered with OA use and often enhanced with corresponding change in the position/location of the narrowest airway lumen.[9,66,100] A relationship was found between airway volume and pharyngeal cross-section measurements in individuals with and without OSA (**Figure 5**) that may alter pharyngeal resistance and restrict or enhance airway flow.[6,109,110] Airway size is not likely a sole determinant of breathing disorder severity, nor can waking measurements of airway resistance be used. Individuals with OSA often display normal resistance values.[66,79,83–87] EMG activity, pharyngeal size, and pharyngeal resistance may be normal in patients with OSA. As the scoping data reveal, a lack of data for a combination of anatomic, physiologic, and comorbidity factors exists. These factors may contribute to the relative success of OAs for improving sleep-apnea indices and have not been fully considered.[66,67,79,80]

Morphologic patterns and OA use

"When one considers the complex multifactorial nature of the disease, assigning the cause of OSA to any one minor dental factor [ie, mandibular advancement only] or change in dento-facial morphology is not logical."[111] **Figure 6** and **Figure 7** show typical phenotypes superimposed with and without their OAs. These phenotypes are associated with favorable and less favorable airway volume and axial cross-section sequelae as discovered in the search. Neither of these clinical examples show all responder features (**Table 2** and **Table 3**). The patients with OSA in **Figure 6** and **Figure 7** show varied positions of the hyoid and mandible, implying a differing line of action for the suprahyoid musculature as shown in an assortment of genio-hyoid vectors of different phenotypes (**Figure 4**). A 2015 comprehensive review of cephalometric indicators with OA use reported evidence for successful prediction of OA advancement based upon imaging is insufficient. The cephalometric data were "relatively weak and inconsistent," suggesting that one cannot make clinical decisions based on only these morphologic indicators. Other risk factors must be integrated into any anatomical or radiological analysis, such as age, sex, and BMI, and be considered in context.[49]

Our scoping search illustrated a paucity of investigative modeling of synergistic action between airway morphology and

Figure 4—Examples of how widely varying vertical orientations and positions of the hyoid bone change the relative line of action of associated musculature.



(A) Retrognathic, steeply inclined mandible with very low hyoid position. **(B)** Normal mandible and hyoid position. **(C)** High relative orientation of hyoid to prognathic mandible. **(D)** Robust mandible with low hyoid relative orientation. **(E)** Vertically steep mandible with a low hyoid orientation and dental open bite. Double arrows indicate the length and path of the origin and insertion of the geniohyoid muscle in the various phenotypes. From the left, each arrow shows the anterior body of the hyoid extending to the right indicating the genial tubercles of the mandible. These relative orientations are likely to indirectly influence opening the oro-pharynx with OA usage. Modified and adapted with permission from Drauer et al. Pharyngeal airway volume and shape from cone-beam computed tomography: relationship to facial morphology. *Am J Orthod Dentofacial Ortho*. 2009;136(6):805-814. doi:10.1016/j.ajodo.2008.01.020. OA = oral appliance.

varying suprahyoid muscle vectors in different phenotypes. This may contribute to the lack of predictability for selection of participants for palliative OA treatment and account for differences between responders and limited responders.[66] AHI reduction may be attributed to functional interaction of the anatomy rather than the static anatomy accounting for the weak anatomical correlation for good and limited responders in the search.

Reduced airway muscle tone in combination with a supine position may exacerbate a negative effect on airway patency, as extreme electromyographic activity would presumably be necessary to maintain an open airway. The hyoid drops inferiorly with normal aging and populations who are leptoprosopic (long-faced), suggesting less mechanical efficiency together with increased incidence of OSA (**Table 3**).[76,90]

In one reviewed study, an OA raised the hyoid an average of 3.9 mm toward the mandible with its advancement, reducing the AHI.[112] When an OA advances the mandible, the hyoid bone is intended to “swing” upwards and anteriorly (**Figure 8**), opening the pharyngeal airway. The hyoid’s key role together with the tongue and mandibular position helps regulate pharyngeal airway dimensions. The genioglossus and geniohyoid musculature hold the tongue forward and anteriorly from the back of the pharynx, preventing airway occlusion.[112]

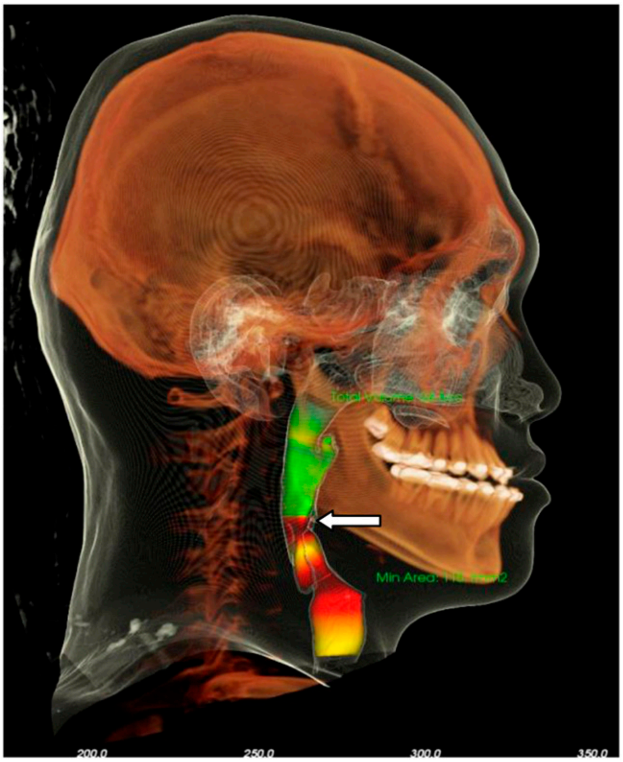
A high hyoid positioned toward the mandible with the geniohyoid muscle orientated horizontally is likely in an efficient position to assist opening of the pharyngeal airway. Individuals with flat (nearly parallel) mandibular plane angles (plane of the inferior border of the mandible crossing with Frankfurt horizontal) who have low-positioned hyoids are reportedly the most likely nonobese people to have OSA.[90]

A low hyoid indicates an oblique action of the geniohyoid, resulting in loss of biomechanical efficiency and adding an additional component to the myriad factors contributing to OSA. This could explain why patients with flat mandibular plane angles and low-positioned hyoids are not considered good candidates for an oral palliative device (**Table 3**).[67,90] A patient without OSA with inefficient suprahyoid abduction vectors likely has robust musculature to assure airway patency. As discovered in the search, only 1 reference concerned position and angulation of the geniohyoid in OSA patients with and without the use of an OA.[90]

Bite opening and adverse airway restriction

In addition to advancement, OA placement requires a slight opening of the jaws. The search discovered no reference concerning OA use and bite opening effects. Individuals with OSA may experience worsened changes when the mouth is held open for long periods.[67,113,114] A conundrum exists in that it is difficult if not impossible to place an OA to advance the mandible and increase airway patency without also opening the jaw. Excessive open-mouthed breathing due to overly thick appliance construction may increase severity of OSA during sleep. Over opening results in translation/rotation of the mandible, potentially obstructing the airway.[113,115]

Figure 5—Airway volume and minimal axial-section visualized (arrow) by cone beam computerized tomography.



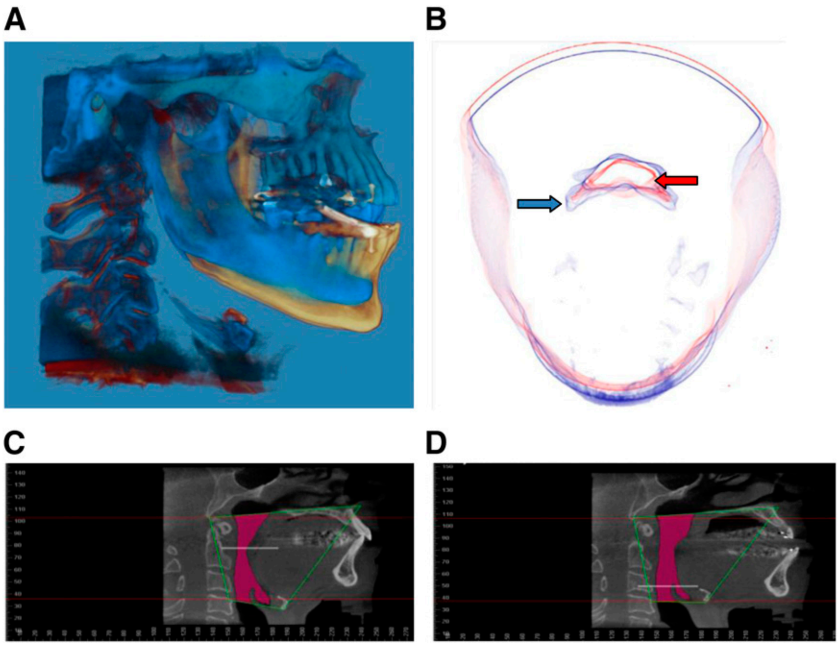
Alterations in size/shape/position of the narrowest point that may alter pharyngeal resistance and decrease airway flow during sleep cannot be currently predicted.

Narrowed airway disorders of the oropharyngeal and hypopharyngeal areas reduce airflow in apneic conditions.[113] A mouth open position causes oropharyngeal airway volume to be significantly reduced when requiring those opening dimensions typical of restorative dental treatment.[116] Glupker et al[113] showed substantially reduced oropharyngeal volumes of the oropharynx with mouth opening and condyles translating downward and forward in an opening motion.[37] When the jaw is widely opened, the tongue falls posteriorly with an anterior component, reducing the space available in the oropharynx and hypopharyngeal areas.[117] Over opening can be due to required appliance mass-for-strength in fabrication of some appliance types as well as vertical/rotational displacement in others with acutely angled distention sheaths or jigs (**Figure 1**). OA jaw over opening/extension required for a "deep-bite" or over closed occlusions and in retrognathias may thus limit airway patency. The degree of mandibular advancement required to be incorporated in such situations also affects the opening pattern.[39,118] The resulting vertical movements may actually reduce the airway volume achieved with different phenotypes (**Table 3**).[47,67,118] An example of this "reversal effect" is shown by a superimposition of a patient with OSA whose jaw was advanced 5 mm with an OA but also opened vertically almost 9 mm obstructing the oropharyngeal airway (**Figure 9**). New research supports the existence of this phenomena.[63]

Additional adverse OA effects

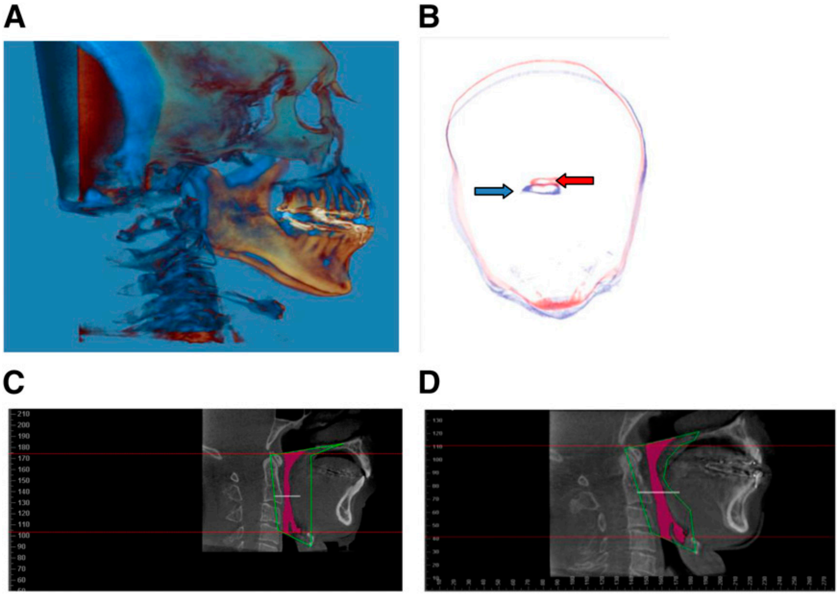
Several OA devices have elastic bands or other hinges (Herbst removable, TAP [Thornton Adjustable Positioner], etc) to limit jaw rotation/opening and prevent airway obstruction. Airway

Figure 6—Phenotype of "good responder" superimposed with oral appliance.



(A) Hyoid height normal, "square" jaw, normal anterior facial height, normal cranial base, good raising of hyoid position with advancement. Mandible advanced: 7 mm *x*-axis, 11 mm *y*-axis. **(B)** Axial minimal cross-section superimposition: no OA (red), OA inserted (blue). **(C)** No-OA (volume: 24,783 mm^3). White line indicates minimal axial cross-section: 229 mm^2. **(D)** With-OA volume: 36,894 mm^3. White line indicates minimal axial cross-section position change (322 mm^2). OA = oral appliance.

Figure 7—Phenotype of a "limited responder" superimposed with oral appliance.



(A) Low hyoid, steep mandibular plane angle, long-faced, short anterior cranial base, clockwise mandibular rotation vector. Mandible advanced (7.5 mm *x*-axis, 9 mm *y*-axis). **(B)** Axial minimal cross-section superimposition: no OA (red), OA inserted (blue). **(C)** No-OA: (volume 14,159 mm^3). White line indicates minimal axial cross-section (94 mm^2). **(D)** With-OA: (volume 16, 963 mm^3). White line indicates minimal axial cross-section position change: 151 mm. OA = oral appliance.

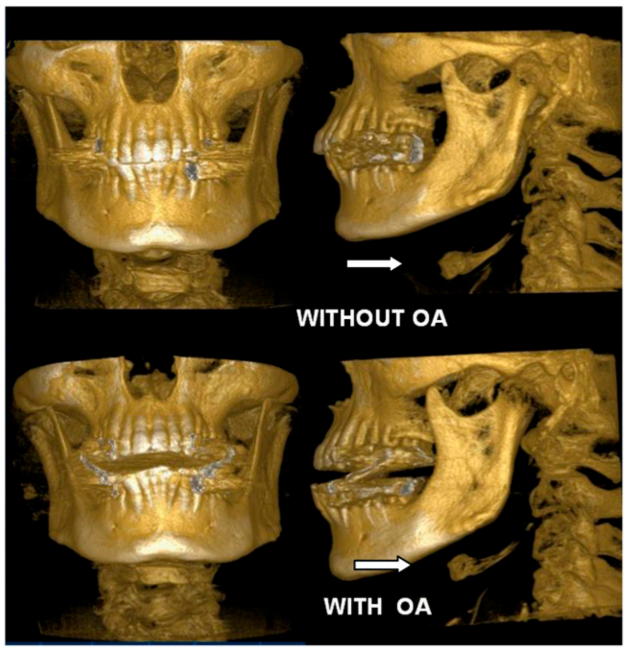
restriction associated with jaw opening through inadvertent appliance design or without a physical vertical impediment may also help explain mixed benefits from use of OAs to reduce the AHI. Multiple reports of adverse orofacial reactions to long -term OA use exist.[21,50,119–122] The searched references include temporary lower jaw protrusion with an incorrect anteriorly positioned occlusion, dental drifting, as well as temporomandibular joint functional impairment with pain, limiting effective usefulness of this palliative therapy.

Mandibular movements, hyoid angulation, and position

Pharyngeal spaces related to mandibular and hyoid dimensions showed the lowest pharyngeal volumes in retrusive jaws and larger volumes in prognathic types.[123] Limited pharyngeal space also occurs in children with a mandibular retrusive "Class II pattern," with those with similar retrusive types showing a higher level of OSA (Table 2 and Table 3).[124,125] The search indicated retrusive jaw skeletal morphology associated with small airways are those most improved in polysomnographic testing with OA jaw advancement (Table 2). Patients with OSA with soft tissue obstructions with high BMI and excessive parapharyngeal fat pads were reported as the least successful candidates for OA therapy (Table 3).[60,126]

The scoping search found another gap as to how differing jaw phenotypes alter pharyngeal airway volume/constriction during OA jaw opening rotations. Normal occlusions have a distinctive Posselt's envelope shape representative of ideal jaw/condylar movement and dental occlusion. Posselt's envelope of mandibular movement refers to the range of movements of the lower jaw. It includes envelope points from maximum dental intercuspation, jaw opening with condyle rotation then translation,

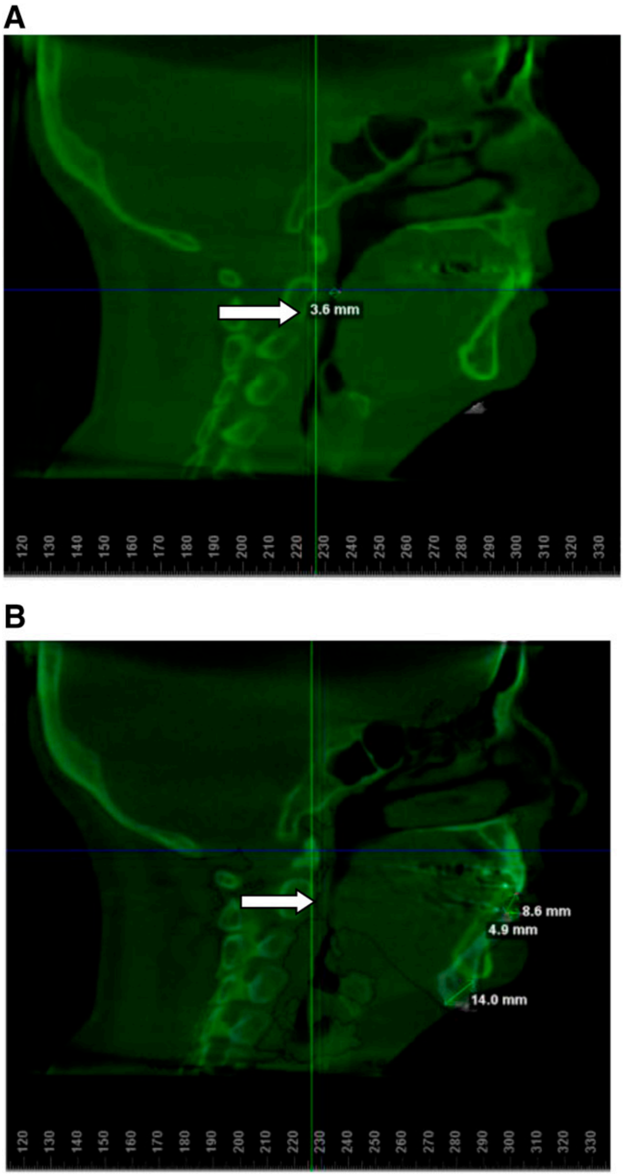
Figure 8—Raising the hyoid with placement and advancement by a "Herbst-type" OA in a patient with obstructive sleep apnea.



Upper panels show patient without the OA. Lower panels with OA in place show advancement of jaw with raised hyoid. Arrows indicate altered position of the jaw and hyoid. OA = oral appliance.

closing with maximum protrusion, closing movement back to an edge-to-edge incisal position, and then returning to the original intercuspation.[118] Patients with mandibular retrognathism, who

Figure 9—Cone beam computer tomography images of an unintended "reversal effect" of an oral appliance reducing the airway.



(A) Patient with obstructive sleep apnea with narrow 3.6 mm oropharynx sagittal airway width. **(B)** Cone beam computer tomography superimposition of the patient with an oral appliance in place and jaw advanced 4.9 mm and opened vertically nearly 9 mm. Arrows show a narrow pharynx subsequently worsened by obstruction when the oral appliance was employed.

often show a high rate of OSA, exhibit a shortened condylar path as expressed in the Posselt's envelope.[124,125] A different rotational and translational pattern of jaw movement of this morphology is seen during opening with backward and posterior movements in short-jawed phenotypes, which may relate to increased oropharyngeal obstruction and limited OA response (**Table 3**).[37,113]

The distance of the anterior hyoid to the chin was less in individuals with retrusive jaws, with a significant bodily downward pitch angulation compared to those with orthognathic (normal) jaw (**Table 2**).[127] Positive correlation of hyoid angulation in relation to steep mandibular planes is shown in the limited responder (**Figure 7** and **Table 3**).[128] This positioning is atypical compared to normal jaw/hyoid morphology (**Figure 6** and **Figure 8**). A forwardly positioned, prognathic jaw hyoid bone position with larger pharyngeal volumes is both anterior and opposite in inclination relative to the mandibular plane in normal individuals (**Table 2**).[129]

Anesthesiologists anecdotally suggest that difficult or problematic intubation is common in patients with OSA. A low hyoid, hyoid flexion, and variable angulation of the jaw are reported to influence intubation difficulty.[130] This implies that a tipped, rotated hyoid/pharyngeal and low hyoid structure are contributing factors in OSA (**Table 3**).[57,70] Only 1 scoping article speculated the position of the hyoid bone on the level of the genial tubercle (ie, a horizontal position) will increase the efficiency of the muscle in pulling the tongue anteriorly and maintaining a patent airway.[131] The hyoid bone reportedly moves in a variable pattern in close conjunction with the pharynx, cervical spine, and mandibular plane in people with differing skeletal morphologies.[132]

Thus, the stomatognathic system, including the airway, should be treated as an integrated system rather than compartmentalized in small components of measurement or action (ie, simply moving the jaw forward with an OA).[123,132] Identifying how the hyoid must move in response to the complexities of mandibular motion to predict the effects on airway patency with OA construction is lacking.

CONCLUSIONS

A scoping review revealed OA applications are individually unpredictable with idiosyncratic anatomical variations in patients with OSA with unclear biomechanical factors, providing no appliance construction rules for improved AHI reduction.[49] While an experienced practitioner may grasp elements of anatomical and muscle interaction with OA placement, more comprehensive study is required.

The data retrieved indicated a circa 62% AHI reduction when employing OAs in moderate conditions of OSA (**Table 1**). There has been a lack of interpretation of palliative biomechanical airway alterations with the use of OAs. Current application appears based on unknown or possibly incorrect assumptions of anatomy, interactive kinematics, and muscle physiology.[19,20,30,64,133]

There is wide variation in the metrics, size, and age ranges of populations that different studies use to report treatment effectiveness in clinical studies. The field has not progressed sufficiently to encompass goals to improve success rates, except for minor variations of appliance application.[37,46,62,85,134,135] Preselection of participants amenable to OA use is still undefined, except for isolated traits yielding insufficient information for OA design for variant phenotypes.

Development of an integrated biometric index distinguishing individuals with OSA who will respond best to OA treatment of OSA is overdue. Age, sex, BMI, and comorbidities should be taken into account. Documentation of cephalometric data as predictors of OA success are inconsistent, with 3-dimensional CBCT imaging recommended to reveal specific phenotypic expressions.[45]

Our review recommends investigation of AHI reduction for OAs, incorporating such factors as differing phenotypic muscle vectors, displacement of the mandible inferiorly and posteriorly, hyoid location/angulation, and the shape and arc of jaw opening. These may be key in understanding sporadic success rates of OAs for development of a preselection process for choosing "good responders." The indirect method of OA function using jaw advancement via muscle tension for patent pharyngeal airway requires development of an index for improved factors in their design and deployment.

ABBREVIATIONS

AHI, apnea-hypopnea index
BMI, body mass index
CBCT, cone beam computed tomographic imaging
CPAP, continuous positive airway pressure
OSA, obstructive sleep apnea
OA, oral appliance

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Address correspondence to: Bruce S. Haskell, Department of Orthodontics, University of Kentucky College of Dentistry, Dental Science Building 4th Floor, 800 Rose Street, Lexington, KY 40536; Tel: (502) 558-7819; Email: dr.bruce.haskell@gmail.com and Andrew M. Roberts, Department of Physiology, University of Louisville School of Medicine, Lousiville, KY; Email: andrew.roberts@louisville.edu

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