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The Mechanics of Mouth-Breathing and Its Role in Nasal and Sleep Disorders

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Abstract

Objective: This study was done to investigate the causal links between malocclusion, tongue tone, and jaw structure and the initiation of apneic/hypopneic events during sleep. Structural causes of strain on the lips and downstream tongue collapse were tested using physical models.

Methods: Distinct models were used to break down the sequence of apneic events. First, the establishment of the lips as a resting closure mechanism of the mouth was tested. Next, a tongue tone model was used to determine the force required to prevent collapse into the pharynx. Finally, a pharyngeal model was used to evaluate differential negative pressure zones during collapse.

Results: The lips may be the primary closure structure of the mouth due to mechanical advantage. The least radial strain placed on the lips permitted better mouth closure. There is a threshold that is required to maintain oral position of the tongue without collapse and resultant buildup of pharyngeal negative pressure.

Conclusions: Apneic/hypopneic events can be simplified to 3 steps: (1) failure of mouth closure due to strain upon the lips, (2) release of tongue restraint by oral compression or intrinsic tongue tone causes collapse, and (3) partial or complete tongue collapse into the pharynx causes a distal negative pressure surge.

Keywords: Airway collapse, apnea, hypopnea, mouth-breathing, obstructive sleep apnea

INTRODUCTION

In a recent original article in this journal,[1] and similar articles,[2,3] the association between mouth-breathing (MB) and certain malocclusion phenotypes was clearly documented. A link between MB and obstructive sleep apnea (OSA) class of disorders has also been determined to exist.[4]

The conventional causality perspective is that MB (from habit) causes malocclusion during development, which causes narrowing of the airway and eventual OSA-type disorders. There are some limitations to this chain of events, in that the origin of the habit remains unclear and there is no clear mechanism to explain how malocclusion specifically narrows the nocturnal but not the daytime airway. Evidence from a recent article sheds some light that even with extensive MB re-training, the presence of malocclusion limits improvement in labial competence.[5] This suggests the possibility that an alternative series of events may occur, in that malocclusion (due to facial immaturity, genetics, or environment) may be the inciting factor, which structurally limits labial competence and subsequently triggers nocturnal MB, which goes on to permit apneic events.

A causal diagram of this proposed chain of events is shown in Figure 1.

Mouth-breathing in this scenario is attributed to a structural failure of the jaw to close during sleep, not to actual functional problems of the nose, as might be assumed.[6] This relaxation-related opening of the mouth subsequently releases a structural clamp: a tongue-restraining mechanism between the hard palate above and the muscular floor of mouth below. Only once the oral tongue-clamping mechanism is released and falls below its intrinsic threshold for self-support, does the tongue collapse posteriorly into the pharynx. This collapse subsequently causes focal buildup of negative pressure, causing barotrauma on the pharyngeal mucosa and generation of inflammation in the pharynx.

This explanation of the relationship requires a re-understanding of the resting forces permitting normal nocturnal mouth closure (while widely assumed to be related to the muscles of mastication) and may actually be maintained by

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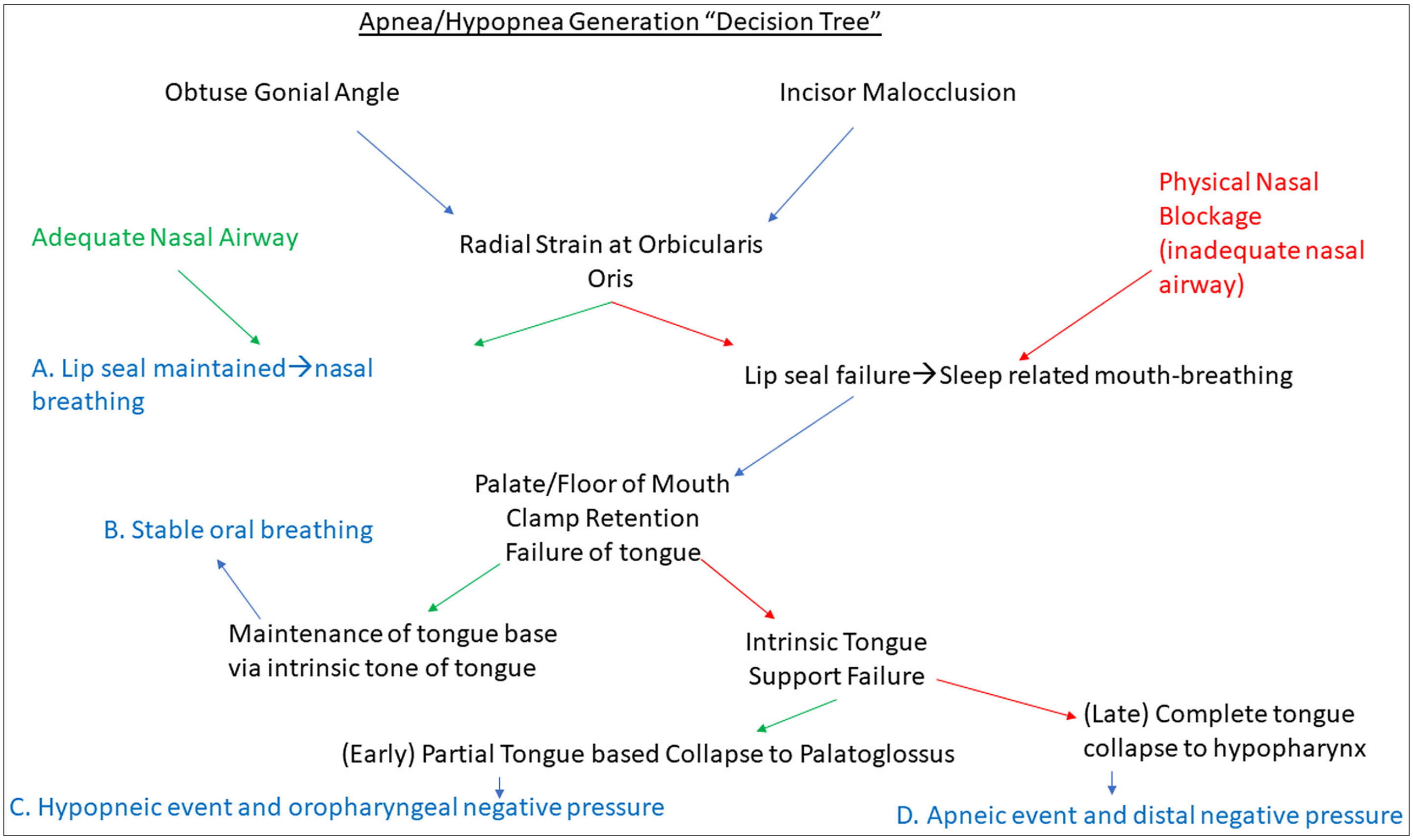

Figure 1. Causal diagram of interaction of malocclusion, mouth-breathing, tongue tone, and sleep disordered breathing. Critically, both mouth-breathing and tongue tone reduction below its self-retaining threshold are required to trigger an apneic or hypopneic event of tongue collapse, and the probabilities of each occurring are increased by malocclusion/radial strain and systemic body tone reduction, respectively.

the tone of the lips and the confluence of the orbicularis muscle with its investing musculature (mentalis) that attaches to the mandible.[7,8] Thus, it is radial strain (prevention of closure) upon the lips that raises the threshold of energy required to prevent MB during sleep and results in intermittent failure of mouth closure. The radial lip strain itself is literally due to mechanical prevention of closure of the elliptical orbicularis closure by 2 factors: (1) occlusive abnormalities (particularly where the maxillary incisors protrude substantially relative to the mandibular incisors, creating an increased distance between the natural draping of the upper and lower lips and (2) unfavorable "center of mass" of the mandible, where the position of the tooth-bearing body of the mandible correlates with excessive obtuseness of the gonial angle and predisposes to a mouth-open resting position that strains the closure of the lip/orbicularis complex[9] (Figure 2).

After failure of the palate/floor of mouth-clamping mechanism, if the now-released muscular tongue tone falls below a threshold to maintain its own oral position, it will become limp and fall posteriorly into the oropharynx[10] and can partially or completely obstruct airflow, resulting in an apneic or hypopneic event[11] and an excess of negative pressure in the airway[12] (Figure 3).

Based on this cascade of proposed events, we used a series of models to test specific causality for the hypothesis that:

1) the lip musculature is of critical importance in maintaining nocturnal mouth-closure and is mechanically/physiologically superior to the masticatory muscles in maintaining this;
2) the orbicularis oris muscle and its confluences (mentalis muscle) maintain a clamp-like retention of the tongue between the hard palate and the muscularly suspended floor of mouth that is suspended from hyoid to lingual-surface of the mandible;
3) once the oral clamp-mechanism is released, if the tongue-tone falls below its own threshold of support to stay within the oral cavity, the tongue may collapse posteriorly into the pharynx, thus generating an apneic event and generating negative airway pressure.

Main Points

- *The lips may be critical in maintaining resting mouth closure and thus airway support, more than the muscles of mastication as previously believed.*
- *An apneic/hypopneic event may be a 3 step process, beginning with mouth-breathing and unlocking of the oral mouth-closure clamp that restrains the tongue in the mouth, secondly prolapse of the now-released tongue and soft palate into pharynx, and finally, build-up of negative pressure within the pharynx distal to the site of obstruction.*
- *Negative pressure build-up zones distal to obstructive sites in the airway causes secondary barotrauma to pharyngeal walls, with in-drawing of tissue and potential damage.*
- *Immature or deficient skeletal/dental structure can be a phenotype that predisposes specifically to mouth-breathing, while muscle tone deficiencies (elevated age or BMI) can be associated with a phenotype of collapse, including hypopneic or apneic events.*

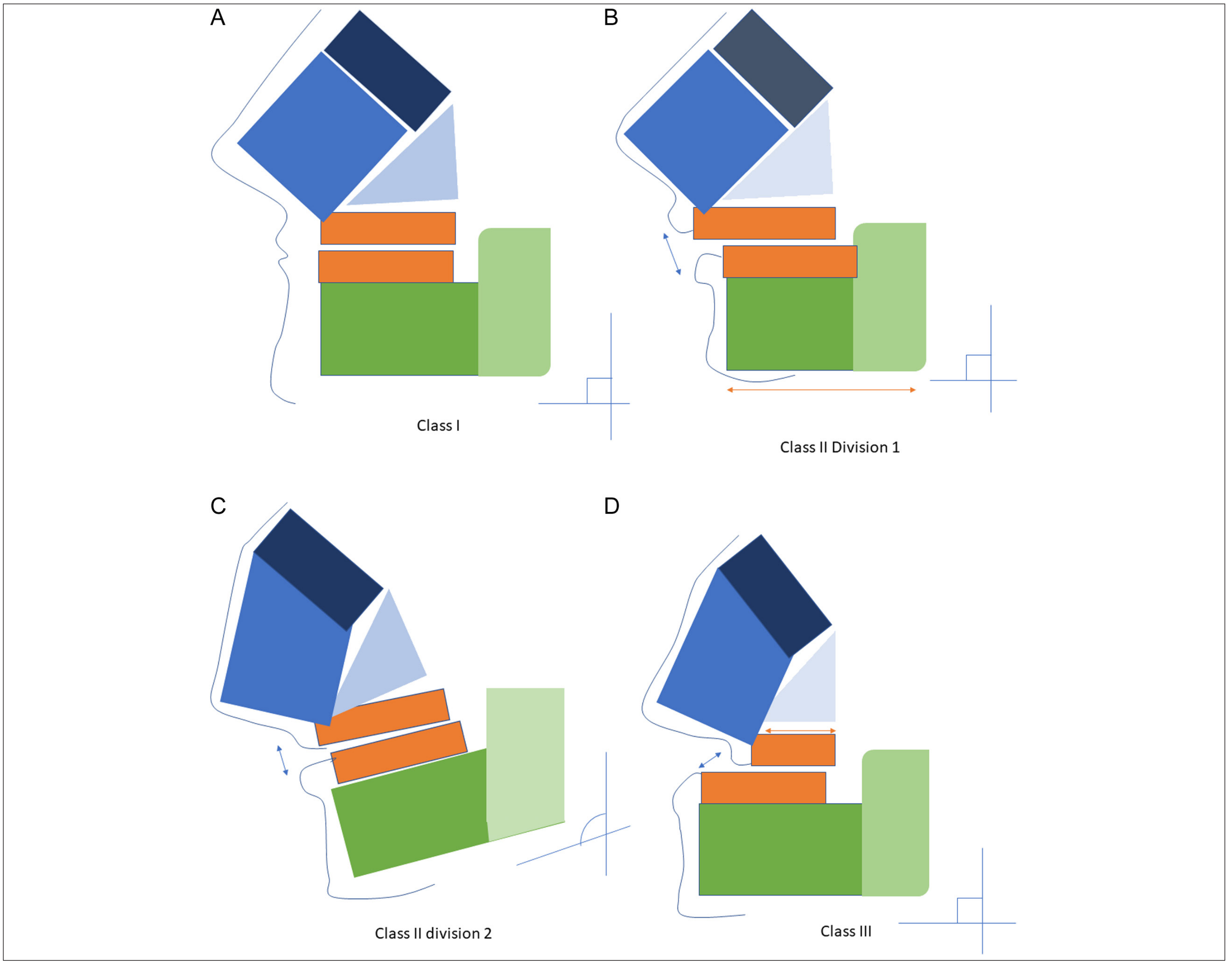

Figure 2. Sagittal view of gonial angle. E, ethmoid perpendicular plate; V, vomer; S, septal cartilage; MB, mandibular body; MR, mandibular ramus. The orange boxes represent the maxillary (upper) and mandibular (lower) dentition. (A) Class I occlusion due to ideal location of skeletal components and tendency toward mouth/lip closure with ideal gonial angle represented by right angle symbol. (B) Ideal gonial angle (represented by right angle symbol) with class II division 1 occlusion due to mandibular diminishment (orange arrow) relative to a protrusive maxilla, creating a radial strain on the orbicularis oris/mentalis musculature complex with subsequent predisposition to mouth-breathing (blue arrow). (C) Excessively obtuse gonial angle (represented by obtuse angle symbol) with class II division 2 occlusion due to under-rotation of the mandibular body (orange arrow) with compensation by the maxilla and upper facial components, altering the equilibrium center of mass with a subsequent predisposition to mouth-breathing (blue arrow). (D) Class III occlusion due to maxillary diminishment (orange arrow) relative to a protrusive mandible, creating a radial strain on the orbicularis oris/mentalis musculature complex with subsequent predisposition to mouth-breathing (blue arrow).

METHODS

Only synthetic models were used to obtain data for this study, and thus no ethical board approval was required or obtained.

We used 3 distinct non-anatomic models to test 3 stages of nocturnal respiratory event generation:

Model 1: Factors predisposing to non-obligate mouth-breathing:

A. mechanical advantage of lip versus masticatory muscles,
B. gonial angle and strain, and
C. quantification of radial strain from malocclusion.

Model 2: Factors in collapse of the tongue-base into the pharyngeal airway

Model 3: Negative pressure generation after tongue-base collapse

Model 1A

In its mastication function, the mandible has been described at length as a "third-degree lever," with the bulk of its force controlled by the large masticatory muscles like the masseter. However, during sleep, the resting tone of the mandible may be more influenced by facial musculature.

The well-described "third-degree lever" mandible description looks at the mandible as if it were a 2-dimensional sagittal plane model, where the

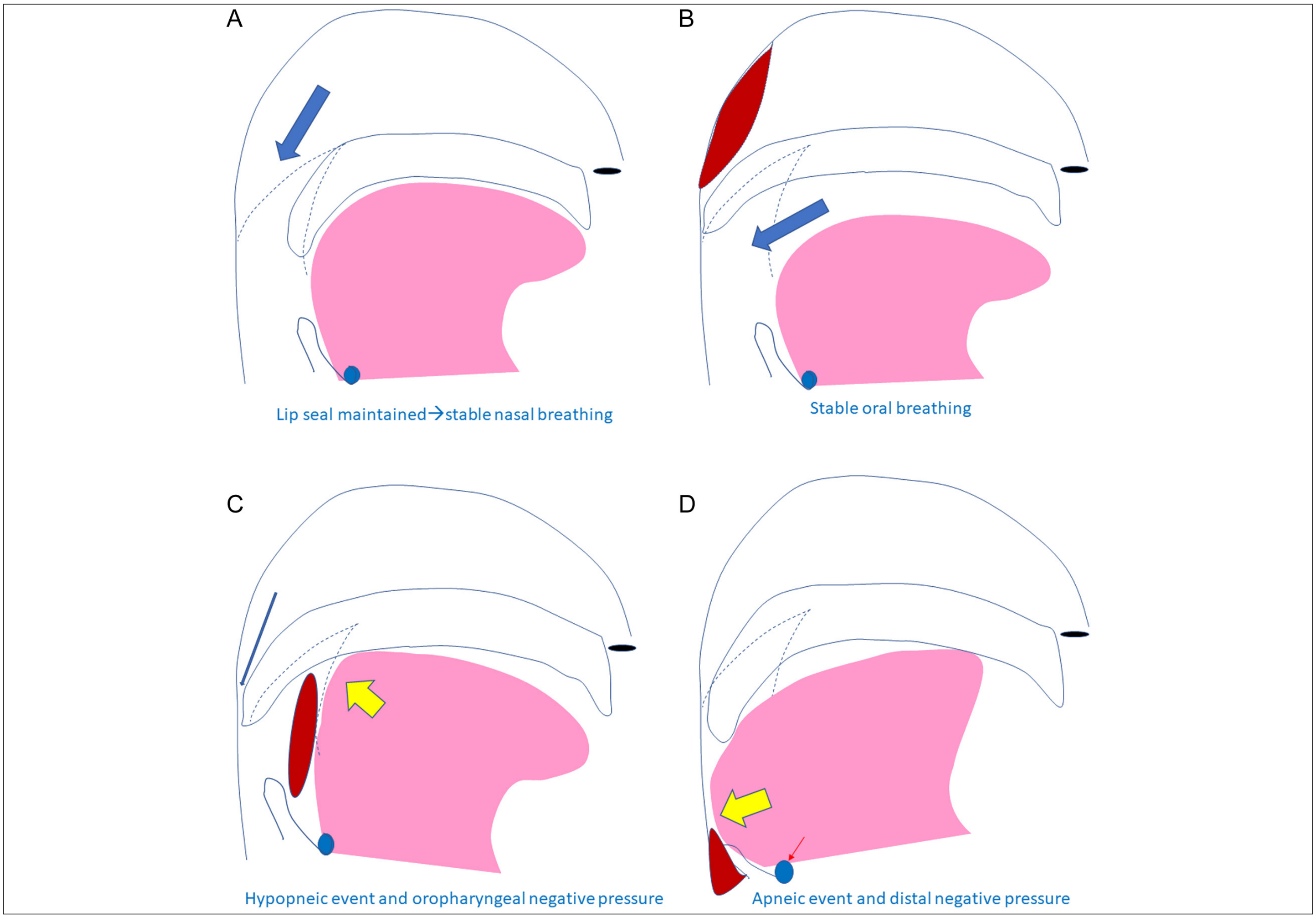

Figure 3. Sagittal view of the upper airway. Pink body = tongue, Blue arrow = breathing route, dotted lines = anterior and posterior tonsillar pillars, blue vertical oval = hyoid, blue horizontal oval= nostril, yellow arrow = maximal collapse point, red = negative pressure build-up zone. (A) Tongue, in a resting mouth-closed position in the oral cavity locked against the hard and soft palate, which with adequate nasal breathing, palate is in line with the anterior tonsil pillar or palatoglossus muscle. There is no negative pressure build-up zone, because on inspiration atmospheric air passes without restriction through the nasopharynx. (B) Tongue, in a mouth-open position, where the tongue remains stable in the oral cavity , supported via intrinsic tongue tone, but the soft-palate has closed off the nasopharynx and is in line with the posterior tonsil pillar or palatopharyngeus muscle due to oral airflow. There is a negative pressure zone in the nasopharynx, where there is exposure to negative pressure from the thorax/pharynx, but lack of airflow from the nasal cavity.[12] (C) Tongue, in a mouth-open position, has partially collapsed into the oro-pharynx against the palatoglossus or anterior tonsil pillar, after failure of intrinsic tone, while the soft palate remains in the mouth-open position in line with the palatopharyngeus muscle, resulting in a partial reduction in airflow (hypopnea) and a negative pressure build-up in the oral pharynx between the tonsil pillars. (D) Tongue in a mouth-open position, where the tongue has complete collapsed into the hypo-pharynx against the posterior pharyngeal wall, due to long-term tone reduction, and descent of the hyoid inferiorly as the tongue collapses below the restraining tonsillar pillars. There is a negative pressure buildup in the distal airway.

temporomandibular joint (TMJ) serves as the lever fulcrum, the effort is mainly distributed at the mandibular angle at the location of the primary attachment of the masticator and pterygoid muscles, while the load bearing segment is the occlusal surface.[13]

The third-degree lever has a mechanical advantage less than 1, which means that the effort required by the masticatory muscles is actually higher than the bite force, implying energy inefficiency, the only advantage being that the distance moved by the muscular effort arm is small, saving space.[14]

In contrast, the confluence of the orbicularis oris muscle of the lips with the mentalis muscle that contacts the mental protuberance at the chin may be the key muscle unit in providing resting tone of mouth closure during sleep.[15] While the masticatory muscles (masseter, etc.) are large muscles that are implicated in massive bite forces, the trigeminal nerve (cranial nerve X) that innervates these has poor or no resting tone according to facial reanimation sources, compared to the resting tone of the facial nerve (cranial nerve VII).[16] Further, because this orbicularis/mentalis muscle confluence is located further from the fulcrum of the mandible (temporomandibular joint) than the load (occlusive surface), it means that for non-masticatory resting jaw closure, the mandible is actually a second-degree lever with a mechanical advantage greater than 1, meaning the amount of effort force required is less than that of the load, implying efficiency and conservation of energy. Thus, a lower resting tone is required to maintain jaw closure during low-tone activity like sleep, requiring less force to maintain. The problem then lies with amaloccusion phenotypes that involve increased overjet (spacing between the upper and lower incisors) as the orbicularis requires more energy to overcome this radial strain (triggering labial incompetence) this making MB more likely.[6,17]

In order to compare the efficiency of muscular attachments of the masticatory muscles versus the facial musculature (lip and associated muscles), we used a force meter to measure force required to achieve jaw closure in a synthetic skull model at the insertion of the mentalis/orbicularis in the symphysis of the model compared to the force required to achieve jaw closure at the insertion of the masseter at the angle of the mandible. Supporting the mechanical advantage of the muscles of the lip as the maintainers of resting jaw closure compared to the muscles of mastication, it was hypothesized that substantially lower force would be required at the mentalis insertion than the masseter insertion because of the difference in lever class and mechanical advantage.

In a 2-dimensional hinged model made of stainless steel, with the model temporomandibular joint resistance kept constant with the skull in supine position, the ramus of the mandible was set at 90° relative to the Frankfort plane. Force (Newtons [N]) was measured first using an analog force meter (Beslands NK-500, Zhejiang, China) set in both "push" and "pull" mode position, attaching the device's hook to the approximate mentalis attachment at the symphysis and then comparing this measurement to the hook attachment at the masticatory muscle attachment approximation at the angle of the mandible. Statistical comparison was made with Student's t-test.

Model 1B

One of the most variable regions of the facial skeleton occurs at the gonial angle, also known as the angle of the jaw. Some have suggested that obtuseness of the angle can be associated with OSA/SDB.[18]

The gonial angle may alter the center of gravity and "static equilibrium position" of the mandible relative to the upper skeleton during low-tone resting states like sleep.

The static equilibrium position of an object is determined by its rotation around a suspension point. In the case of the mandible, the TMJ is the "suspension point" in the glenoid fossa of the skull.

In a mandible with a larger or more obtuse gonial angle, the static equilibrium position of the mandibular occlusive surface would be predicted to rest further from the maxillary occlusive surface, than a more acute gonial angle, and thus will also be a source of orbicularis oris radial strain and labial incompetence (compare Figures 2A and 2C).

We tested this concept using physical models of bilaterally hinged synthetic mandibles, comparing gonial angles of 70° (excessively acute), 90°, and 125° (obtuse). Each of the 3 gonial angle variation mandible models was suspended in an upright and supine posture to determine the equilibrium position with gravity, a vertical line from the hinge or joint representing the equilibrium center of mass. The distance of the occlusive plane of the mandible was subsequently measured on each of the 3 models relative to the horizontal Frankfurt plane, as a surrogate for radial strain on the lips.

Model 1C

A model of the orbicularis oris and its interaction with anteriorly protruding teeth/malocclusion was evaluated. In this simple model, we measured the amount of force required to close a draw-string style model of lips with extensive protrusion, limited protrusion, or no protrusion incisor teeth. An analog force meter was used to measure closure force to complete radial lip closure with completely protruding incisors, partially protruding incisors, and no protrusion. The least force necessary to obtain complete closure was tested and recorded for each state, representing the threshold of mouth-closure.

Model 2

In order to test the mechanics of tongue-base collapse during inspiration from the oral cavity into the oral pharynx, a model was created of the oral cavity and oral pharynx. This model included a 100 g elliptical body representing the tongue, hinged postero-inferiorly at the intersection of the oral cavity, and pharynx in the supine position. The pharynx consisted of a posterior opening to a cylindrical chamber, while the oral cavity contained a "floor of mouth" component. In the absence of any forces, simulating a zero-tone state, the elliptical tongue rolled or fell backward, as expected with gravitational forces into the oral pharynx with the weight of its mass (100 g).

Model 2A

To test how resting mouth-closure muscular forces (hard palate compressing tongue against the floor of the mouth) can prevent tongue collapse, the analog force meter was set in the "push" mode position, with a flat surface that represents the hard palate was placed against the supero-posterior quadrant of the "tongue."

Model 2B

To test the intrinsic tone of the tongue to support itself from collapsing into the pharynx, the analog force meter was set in the "pull" mode position and was used to "pull" the tongue in an antero-inferior direction to prevent tongue-base collapse into the pharynx.

In both 2A and 2B, the threshold for the least amount of force required to keep the "tongue" inside the oral cavity was measured, with decreasing force applied from 10 N, until a threshold was passed and collapse occurred.

Model 3

After failure of mouth-closure tongue retaining and intrinsic tongue tone to self-support, the tongue base becomes susceptible to partial or complete collapse into the pharynx, (generating a hypopnea or apnea respectively).[19] Model 3 examines the generation of negative pressure in the pharynx after complete or partial tongue-based collapse. In this model, a cylindrical oropharynx is lined with a thin and pliable latex mucosa, superiorly covered by a transparent, clear plastic, hinged "soft palate" that opens and closes to the patent nasal cavity, and to represent inspiratory activity, the base of the cylinder or the "hypopharynx" is set to −10 mmHg.

In the partial collapse model, representing the milder form of collapse, especially found in youth and lower BMI states, the tongue base has collapsed only to the anterior tonsillar pillar, or is restrained from complete collapse by the anterior tonsillar pillar, or palatoglossus muscle (Figure 3C). In the complete collapse model, especially found with age and advanced body mass index (BMI), the tongue base collapses against the posterior pharyngeal wall and completely obstructs the hypopharynx (Figure 3D).

In both models, degree of excursion of the oropharyngeal mucosa and degree of excess hypopharyngeal pressure after obstruction were observed and recorded during soft palatal opening versus closure.

RESULTS

Model 1A Results

During "push" mode, measurements were 8.75 N, 7.5 N, and 8.75 N (mean 8.33 N, standard deviation 0.72) at the angle, while at the mentum, measurements were 3.75 N, 3.75 N, and 5 N, (mean 4.17 N, standard deviation 0.72), showing a substantial reduction ($P < .01$) of closure force required at the anterior jaw and consistent with the possibility that the labial muscles could be more efficient at resting tone than the masticatory muscles. Similarly, during "pull" mode, using the hook attachment, measurements were 5 N, 6.5 N, 6.5 N (mean 6.0, standard deviation 0.86) at the angle, while at the mentum, measurements were 2.5 N, 2.5 N, and 2.0 N (mean 2.33 N, standard deviation 0.29), showing a similar substantial reduction ($P < .05$) of closure force required at the anterior part of the mandible.

Model 1B Results

In the upright state, the gonial angle of 125°, which represents the aesthetically challenged obtuse gonial angle, the equilibrium center of mass is drawn nearly parallel to the occlusive plane (mandibular body), which lies 70° from the horizontal, denoting a very wide-open mouth without corrective muscular force in its equilibrium state. For the gonial model of 90° in the upright state, which represents a more robust (less obtuse) gonial angle, the equilibrium center of mass is drawn obliquely to the mandibular body and occlusive plane, which, at rest, lays 30° from the horizontal plane, a more favorable position for maintaining mouth closure. Finally, in the 70° gonial angle model, the equilibrium center of mass is nearly perpendicular to the occlusive plane/mandibular body, which lies parallel or 0° to the Frankfurt plane, signifying a closed upper and lower jaw even without muscle force correction.

Model 1C Results

The mean thresholds for the least amount of force required to radially close the orbicularis lip "drawstring" are:

protruding incisors: 37.5 N, 45 N, 52.5 N (mean: 45 N);
partially protruding incisors: 25 N,27.5 N, 26 N (mean: 26.2 N); and
non-protrusion: 17.5 N, 18 N, 15 N (mean: 16.8 N).

As expected, the least strain provided by protruding teeth has the lowest threshold to cross to complete lip closure.

Model 2 Results

The mean thresholds for the least amount of force required to keep the "tongue" inside the oral cavity, is as follows (see model 2A and 2B):

Model 2A

For compression of the tongue against the floor of mouth by the hard palate is 1.5 N (1.0, 1.5, 2 N)

Model 2B

Measuring the intrinsic self-supporting force of the tongue is 1.5 N (1.5, 1.5, 1.5 N)

The equivalence of these measurements is not surprising as the force required to support 100 g mass upright (on Earth) is roughly equivalent to 1 N of force.

MODEL 3 RESULTS

In the partial collapse model (3A), where the tongue base collapses to only the palatoglossus muscle or anterior pillar, with the anterior-hinged soft palate set to "open naso-pharynx," the "mucosa" remains in place against the lateral oro-pharyngeal walls, and there is no post-obstructive increase in the −10 mmHg inspiratory pressure. However, when the hinged soft palate is set to "closed naso-pharynx," the oro-pharyngeal mucosal is drawn intra-luminally, with mucosa bulging medially from the lateral oropharyngeal walls between the palatoglossus and palatopharyngeus regions, approximating the location of the palatine tonsils. In addition, the hypopharyngeal pressure decreased to –15 mmHg from the obstruction of the oropharynx (50% increase in negative pressure) (Figure 2C).

In the complete collapse model (3B), where the tongue base completely obstructs the opening to the hypopharynx, even with the anterior-hinged soft palate set to "open naso-pharynx" or "closed naso-pharynx," the "mucosa" remains in place against the lateral oro-pharyngeal walls, because inspiratory negative pressure fails to reach the oropharynx from the hypopharynx. In this model, however, the hypopharyngeal pressure decreased from −10 to −22 mmHg (120% increase in negative pressure), displaying the more severe negative pressure buildup in the hypopharynx and lower airway in this model (Figure 2D).

DISCUSSION

The 3 models evaluated in this study support the possibility that the mechanism of an apneic or hypopneic event during human sleep can be generalized to a 3-step process: (1) mechanical disadvantage that creates radial strain at the lips can determine the likelihood of an MB event, even with normal nasal function. (2) Once jaw opening occurs to the degree that pressure applied by the hard palate, securing the tongue against the floor of mouth in the oral cavity falls below the threshold that supports the intrinsic weight of the tongue, the tongue base becomes *susceptible* to collapse (presence of a narrow-shaped hard palate that prevents tongue "grasp" can also contribute as well).[20] (3) However, once the intrinsic tone of the tongue itself falls below that which is required to self-support the tongue base in the oral cavity, the tongue base collapses toward the oral pharynx, either completely obstructing the opening to the hypopharynx and creating a negative pressure surge in the lower airway and an "apnea" event, or collapsing only partially with milder/temporary tone reductions, creating negative pressure-induced wall stress in the oropharynx and only partially obstructing the airway, in the form of a hypopnea.

The pivotal role of tongue tone is supported by a recent study that shows that fat content of the tongue relative to its muscle tone is most highly consistent with severity of SDB, and low muscle content correlates with obesity and age.[21] Descent of the muscular "sling" of the floor of the mouth, supported by a descended hyoid bone, may contribute to this tonal failure via incapacity to retain the tongue in the oral cavity.[22]

Thus, individuals will have a specific threshold of the muscular tone of lip closure and tongue support that must be met in order to prevent first mouth-breathing and second pharyngeal collapse. Then, moment to moment during sleep, actual tone of the lips, tongue, and palate, whether above or below these thresholds, will determine whether the person is in a state of comfortable nasal breathing, simple mouth-breathing, hypopnea, or apnea (Figure 3A-3D).

Further, current tone is determined by: the sleep level of the individual (i.e., REM, etc.), overall muscle tone (age and BMI and presence or absence of other muscular factors like sedatives, muscular disorders, etc. The threshold of tone that must be surpassed by the current tone is determined by factors like occlusion class, mandibular, and maxillary structure (palate width, gonial angle, mental projection) as well as sleep position relative to gravitational forces.

This concept is further supported by a recent study that showed that the quantitative *depth* of the apnea or hypopnea more strongly correlates with OSA severity and oxygen desaturation nadir than the count of apneas Apnea Hypopnea Index (AHI) and reflects the degree of tone of the tongue after MB release and the degree of its collapse and obstruction of the airway.[23]

Thus, OSA may be of 2 different anatomic phenotypes, in that hypopnea-heavy disease may be a disorder of craniofacial skeletal immaturity/defi ciency with mostly a predisposition to MB with minimal tone-related tongue collapse, mainly manifesting with regional nasal/pharyngeal symptoms, while OSA with complete apneas may be more a disorder of tone (elevated age and Body Mass Index [BMI]) creating total or near-total subsequent collapse of the tongue (after MB) and resulting in hypoxia and systemic symptoms of severe sleep disruption and fatigue.

The importance of specifically stopping MB in the prevention of apneic/hypopneic events has also been shown clinically as well, both in sleep endoscopy[24] and polysomnography.,[25] Limitations of this study are that the models are by design not anatomically accurate in order to isolate specific physical principles and can include investigator bias.

CONCLUSION

Based upon tests of multiple physical models of the jaws, tongue, and lips, a description of the order of events in an apneic/hypopneic event can be potentially described. Like the loading of a firearm is required prior to its firing, first mouth-breathing must be initiated by a failure of lip closure of the mouth, which permits *potential* release of the tongue from its captive position in the oral cavity, potentially resulting in an apneic or hypopneic event if tone thresholds are crossed.

Ethics Committee Approval: Only synthetic models were used to obtain data for this study, and thus no ethical board approval was required or obtained.

Peer-review: Externally peer-reviewed.

Author Contributions: Concept – H.S.; Design – H.S.; Supervision – H.S.; Materials – H.S.; Data Collection and or Processing – H.S.; Analysis or Interpretation – H.S.; Literature Review – H.S.; Writing – H.S.; Critical Review – H.S.

Declaration of Interests: Dr. Stupak holds intellectual property and receives royalties for a Medtronic ENT nasal surgery device and from Stryker CMF for an mandible fracture device unrelated to this paper and is the author of a textbook published by Springer "Rethinking rhinoplasty and facial surgery".

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