

Invited Review Paper
Orthognathic Surgery

Biomechanics of the upper airway: Changing concepts in the pathogenesis of obstructive sleep apnea

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Abstract. Obstructive sleep apnea (OSA) is a disorder characterized by repetitive, episodic collapse of the pharyngeal airway. Over the last two decades, understanding of the pathophysiology of sleep disordered breathing, which includes OSA, has improved. Once thought to be predominately related to anatomic constriction of the maxillomandibular complex, central nervous system regulation of breathing is now recognized as a significant contributor to the pathogenesis of OSA. Ventilator control, the central response to chemoreceptor phenomena, has important implications for oral and maxillofacial surgeons who treat OSA, particularly for patients who appear refractory to treatment with maxillomandibular advancement (MMA). The purpose of this article is to review the biomechanics of the upper airway as it relates to the pathophysiology of OSA, to discuss emerging concepts of ventilator control mechanisms in normal sleep versus sleep-disordered breathing and to discuss the concept of complex sleep apnea, a new category of sleep disordered breathing with both obstructive and central features.

Keywords: obstructive sleep apnea; airway dynamics; maxillomandibular advancement; orthognathic surgery.

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Obstructive sleep apnea (OSA) is a well-recognized disorder that affects at least 4% of the population in the USA^{36,99}. It is characterized by repetitive collapse of the upper airway, commonly defined as the soft tissue region bounded by the nasopharynx superiorly, the epiglottis inferiorly, the maxillomandibular complex anteriorly and the spinal column posteriorly. Collapse of the upper airway decreases its intra-luminal diameter and increases airway resistance, in accordance with Poiseuille's Law (Fig. 1). This

increased resistance to flow results in reductions in ventilation (hypopneas) or complete cessation of ventilation (apneas), with corresponding metabolic disturbances (respiratory acidosis due to hypoventilation) and sleep fragmentation. Compensation for metabolic disturbances occurs primarily in the form of alterations in respiratory effort, which is the primary determinant of arousals from sleep. While brief transitions to the wake state provide ventilator compensation to correct blood gas abnormalities, this comes at the cost of

further destabilizing respiratory control at the sleep-wake interface. Concomitant activation of the sympathetic nervous system results in increases in blood pressure, which, over the long term, have been linked to increased risk for sudden death, stroke and myocardial infarction^{5,12,19,49,58,59,95}. Sleep-event related arousals produce fragmentation of sleep patterns, resulting in excessive daytime somnolence, neurocognitive impairment and increased risk for accidents related to sleep deprivation^{36,38,61,98}.

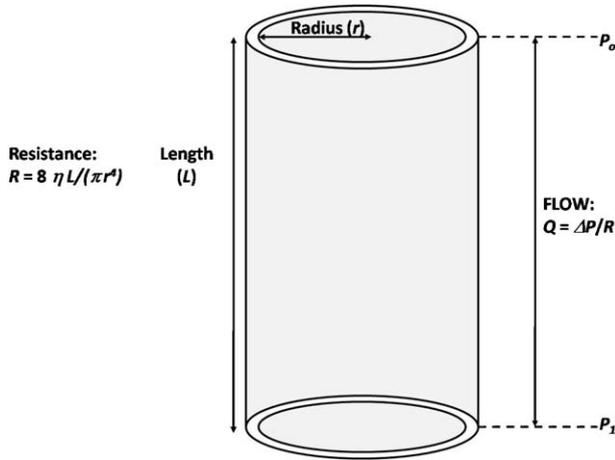


Fig. 1. Resistance to air flow as related to airway diameter and length (Poiseuille’s Law). Model of a cylinder, demonstrating that resistance to airflow (R) is proportional to the length of the cylinder (L) and inversely proportional to the fourth-power of the radius (r). Thus, in patients with OSA, increases in cross-sectional area as a result of intervention (e.g. MMA), can decrease airway resistance. Given that flow (Q) is inversely proportional to resistance (R), decreasing resistance will increase flow.

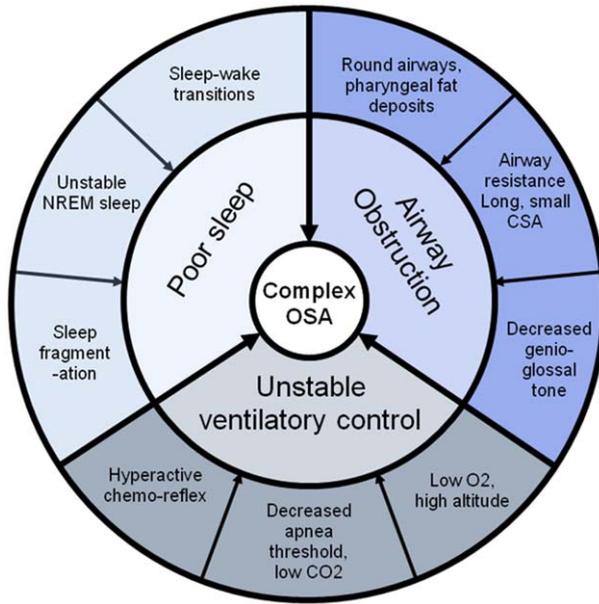


Fig. 2. Anatomic, sleep-related and central nervous system factors in the development of OSA. OSA develops as result of a complex interaction between anatomic factors, sleep-related factors and central nervous system control over ventilation. CSA, cross-sectional area; NREM, non-REM. Adapted from reference 2.

A significant focus in the oral and maxillofacial surgical literature has been to identify anatomic parameters related to OSA and to determine the effect of surgical intervention (e.g. maxillomandibular advancement, MMA) on airway anatomy^{2,7,13,23,28,43–46,72,87,89,90,92,94}. The success of MMA in patients with purely obstructive disease has been well documented^{11,23,28,43,44,46,60,90,89}. The small percentage (10–20%) of patients who fail to respond to MMA are often presumed to

have a component of central apnea or are labelled as ‘refractory’ to treatment if the anatomic goals of MMA have been achieved^{11,24,29,30,45,97}.

Recent advances in understanding the pathophysiology of sleep apnea are incon-

sistent with the classical notion of OSA as an anatomic disorder^{21,36,42,73,87,92,96}. The complex interplay between anatomic, sleep-related and central nervous system factors may explain the variable results seen after MMA (Fig. 2). Specifically, a subset of patients with sleep apnea have been found who challenge two commonly held beliefs: that (1) central and obstructive apneas are independent processes and (2) poor sleep is a secondary result of OSA rather than a primary cause. The study of these patients considered to have ‘complex sleep apnea’, has shed light on the variable pathophysiology of sleep apnea.

The purpose of this article is to review the factors that contribute to upper airway collapse, to introduce the role of ventilator control on the pathogenesis of OSA and to describe the phenomenon of complex sleep apnea.

Upper airway patency and collapse

Patency of the upper airway is insured by a balance between collapsing forces and dilating forces (Table 1, Fig. 3)⁹². Akin to Starling’s Law for fluid flow within capillaries, the upper airway can be described as a Starling resistor, the caliber of which is determined by the pressure differential between the collapsing forces and dilating forces, P_{crit} (Fig. 4)⁵⁷. Collapsing forces are related to intra-luminal upper airway pressures during inspiration and the composition of the pharyngeal wall. Dilating forces are predominantly related to pharyngeal dilator muscle tone, with contributions from airway traction during inspiration, and increases in lung volume increases^{34,35}.

Collapsing factors

Collapsing forces on the airway can be broadly classified as those acting within the airway (intra-luminal) and those that act on the airway wall itself (extra-luminal). These factors result in decreased intra-luminal diameter and obstruction due to increased resistance to airflow. Conceptually, the threshold pressure required for airway collapse can be determined using pressure-flow curves^{67,68}. Nasal airway pressure required to maintain airway patency is defined as the critical closing pressure (P_{crit}). Numerous studies have demonstrated that P_{crit} is

Table 1. Dilating and collapsing forces on the pharyngeal airway.

Dilating forces	Collapsing forces
Pharyngeal dilator muscle activity	Negative intra-luminal pressure during inspiration
Airway traction from lung expansion	Pressure from parapharyngeal tissue

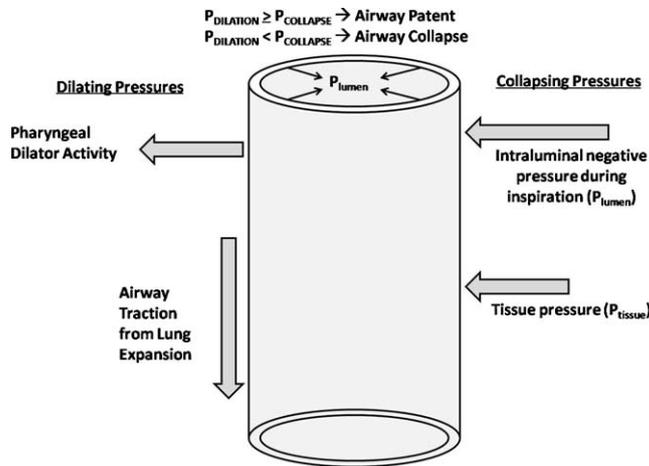


Fig. 3. Factors influencing pharyngeal collapsibility. The dynamic forces influencing airway caliber are shown. Airway patency is promoted by pharyngeal dilator activity and, to a lesser extent, caudal traction on the airway due to lung expansion. Airway collapse is due to negative intra-luminal pressure during inspiration and inward pressure from extra-luminal factors, such as adipose tissue within the pharyngeal walls. To the extent that collapsing pressures exceed dilating pressures, the airway collapses and obstruction ensues. Adapted from reference 92.

related to anatomical features and lung volumes. Anatomically, P_{crit} has been shown to correlate with soft palate length in obese patients and airway length and hyoid-mandibular distance in non-obese patients^{8,48,87}. These findings correlate with those reported in the surgical literature, which demonstrate that patients with OSA have longer soft-palates and longer airways^{47,68,69,76,77}. Since pressure is the force applied over a given cross-sectional

area, an increase in the critical closing pressure (i.e. an increased propensity for collapse) is seen in individuals with narrower and longer airways^{55,87}. Since P_{crit} is influenced by a number of anatomic factors, it is likely that P_{crit} varies with individual patient characteristics as noted above. This may explain the observation that some patients with large diameter airways have severe OSA, while patients without OSA can have relatively small

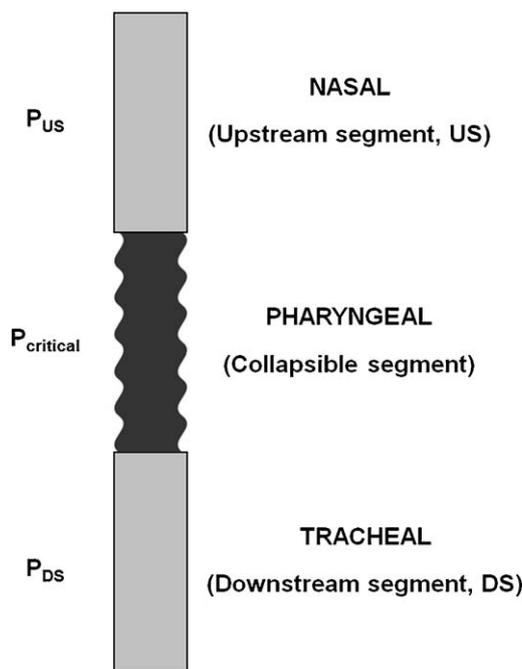


Fig. 4. Starling resistor model of the pharyngeal airway. The pressure required to keep the airway patent (P_{crit}) is a function of the pressure upstream to the collapsing segment (P_{US}).

airways. Thus, it is plausible that the magnitude of MMA required to improve or eliminate OSA may be related to these individual anatomic characteristics rather than to a fixed number of millimeters.

Intra-luminal forces acting to collapse the airway are related to pressure changes during respiration and vary by respiratory patterns. In the upper airway, pressure is generated during inspiration and expiration, even though the direction of airflow is different. The caliber of the upper airway is therefore dependent on pressure within the airway lumen (P_{lumen}). During inspiration, the volume of the thorax increases, and the pressure decreases, allowing for airflow into the lungs, but the decrease in pressure results in a relative negative intra-luminal pressure within the upper airway, predisposing toward collapse. Collapse is generally prevented in these patients due to reflex activation of dilator muscles, as discussed below.

During expiration, intra-luminal pressure initially increases, which acts to dilate the upper airway. At the end of expiration, intra-luminal pressure begins to fall to a point at which the airway can collapse. Such collapse occurs in the setting of extra-luminal factors, discussed below, which affect the elastance of the pharyngeal airway. Airway cross-sectional area is lowest at the end of expiration. Expiratory narrowing is more significant in patients with OSA than in normal controls^{54,66,87}.

The second set of factors responsible for upper airway collapsibility is related to extra-luminal pressure or pressure from the tissues that comprise and support the pharyngeal airway. The upper airway is a flexible structure composed of varying amounts of muscular and adipose tissue. Though some of the pharyngeal musculature is attached to the facial skeleton or vertebral column, the upper airway is, for the most part, only passively supported by bony structures. This relative lack of rigid support causes the upper airway to behave like a collapsible cylinder with well-defined anatomic factors that predispose to upper airway collapse. These factors can be broadly classified as soft tissue, myoneural and skeletal.

Soft tissue factors include fat deposition within the parapharyngeal structures, pharyngeal edema/inflammation, adenotonsillar hypertrophy and macroglossia^{87,92}. Imaging studies of obese patients with OSA have demonstrated increased adipose tissue in the lateral pharyngeal fat pads, tongue and soft palate. This has been hypothesized to increase tissue pressure on the pharyngeal wall, predisposing toward collapse^{32,70,71,76}. In addition,

deposition of fat within the airway wall has been shown to increase overall mass within these tissues, which may also increase tissue pressure, resulting in airway collapse and decreased airway volume^{26,31,88}. Pharyngeal edema likewise results in decreased airway caliber and has been shown to be increased in patients who snore and those with apnea^{3,9,65}. Fluid secretions on the airway surface have been shown to contribute to collapse in OSA patients by increasing wall tension^{30,32,40}.

There has been increasing interest in the role of 'myoneural factors' (i.e. changes in the sensory and neural structures influencing function of the upper airway)¹⁰. These include increased sensory thresholds and two-point discrimination, evidence of injury to intra-epithelial nerve endings, and myopathic changes^{30,39}.

Such changes may contribute to disease progression. Direct effects of snoring vibrations have also been proposed to play a role⁷⁴.

Skeletal factors that influence upper airway caliber are those most often corrected by the oral and maxillofacial surgeon and include maxillary, mandibular and hyoid bone position. Patients with OSA typically have mandibular or bimaxillary retrognathism and a low-lying hyoid⁸⁷. Skeletal size can also play an indirect role in maintaining the airway. Among patients without OSA, there is a relative concordance between the size of the skeletal airway enclosure (maxillo-mandibular complex and spinal column) and the soft tissue airway (Fig. 5)⁹¹. In patients with OSA, a narrow airway can result from excessive soft tissue on a

normal skeleton or from normal amounts of soft tissue on a deficient skeleton⁹².

Upper airway patency – dilating factors

Collapsing forces related to soft tissue and skeletal abnormalities are typically offset by pharyngeal dilator muscle activity. Though there are a number of pharyngeal muscles that act to dilate the airway, the genioglossus is the largest airway dilator and the most extensively studied^{36,41}. The genioglossus is an extrinsic muscle of the tongue that attaches to the lingual aspect of the mandible. When it contracts, the tongue moves anteriorly and the pharyngeal airway dilates at the retroglossal level⁶⁴. The motor nerve of the genioglossus is the hypoglossal nerve and its activ-

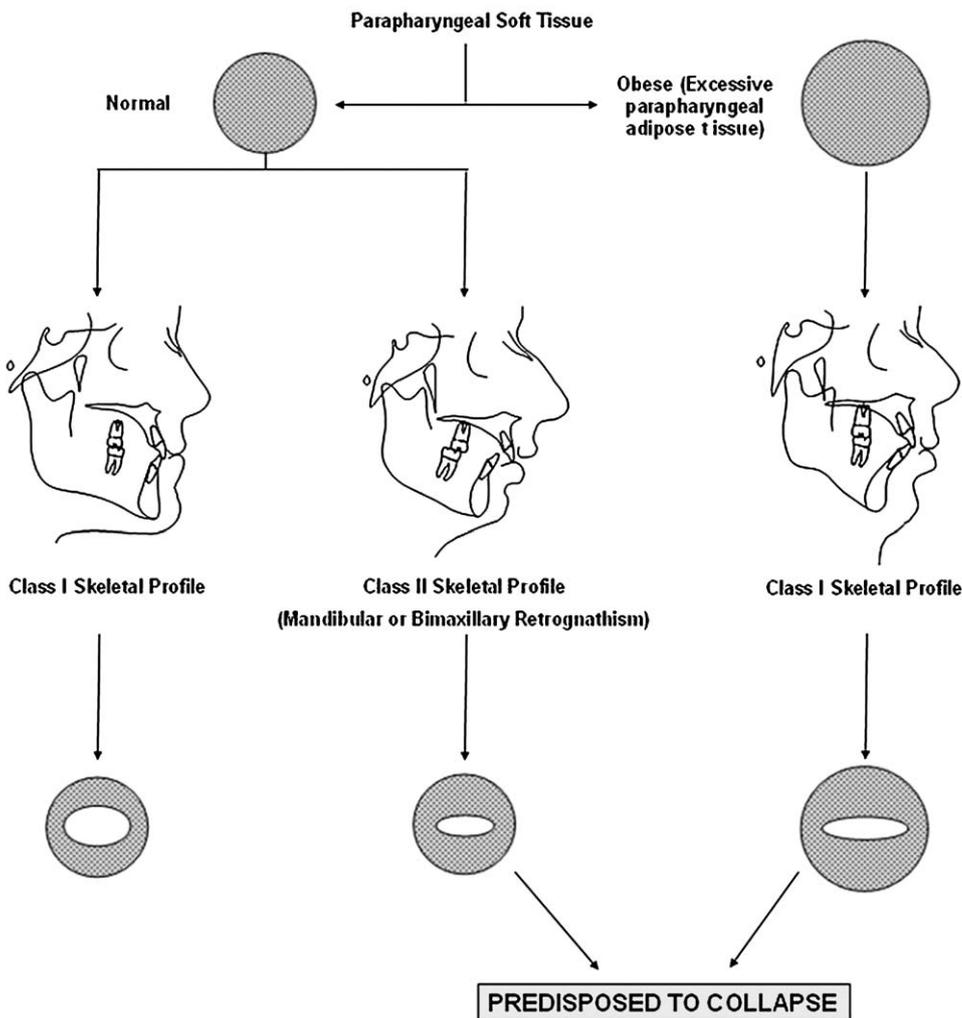


Fig. 5. Combinations of soft tissue architecture and skeletal scaffold predisposing towards obstruction. Airway collapse can occur as a result of excessive soft tissue architecture on an ostensibly normal skeleton (e.g. in an obese patient with a Class I skeletal profile). Conversely, a normal amount of soft tissue laid over a constricted skeleton can result in collapse (e.g. a thin patient with a significant Class II skeletal profile). Adapted from reference 92.

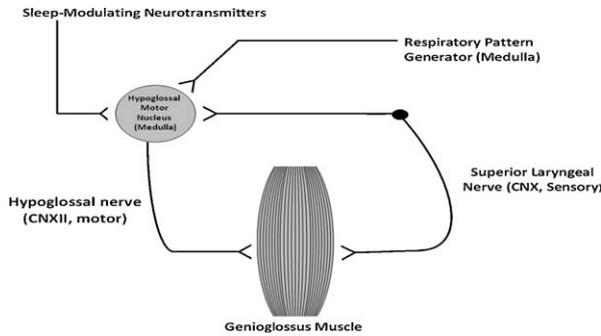


Fig. 6. Factors influencing pharyngeal dilator muscular activity. Genioglossus activity is modulated locally by input from mechanoreceptors in the airway. Negative intra-luminal pressure during inspiration results in activation of these mechanoreceptors and reflex activation of the genioglossus muscle for compensatory airway dilatation (afferent signal in the reflex arc is via the superior laryngeal branch of the vagus nerve, the efferent signal is via the hypoglossal nerve). Central nervous system control via the respiratory pattern generator in the medulla and chemoreceptor control will influence the tonic behavior of the genioglossus and thus have some contribution to airway collapsibility. Sleep-modulating neurotransmitters (e.g. serotonin, orexin, acetylcholine, histamine and norepinephrine) also influence dilator muscle activity. Adapted from reference 92.

ity is modulated by: respiratory pattern generation; pressure receptors within the pharyngeal wall; and central and peripheral chemoreceptors (Fig. 6)^{23,34,36,85,87,92}.

Medullary neurons associated with respiratory control regulate the action of the genioglossus muscles. On inspiration and the generation of negative intra-luminal pressure, mechanoreceptors within the pharyngeal wall transmit afferent information via the superior branch of the internal laryngeal nerve, which acts via a reflex pathway to cause genioglossus contraction^{24,33,85}. This provides a counteracting force to prevent airway collapse^{50,51}. Application of topical local anesthetics can induce airway collapse supporting the concept that airway patency is also maintained by baseline genioglossus muscle tone¹⁴. Neurons responsible for modulating arousal^{25,35} generally increase genioglossus activity, linking pharyngeal dilation with the arousal state⁹².

It has been demonstrated that pharyngeal muscle dilator activity, as a reflex response to negative intra-luminal pressure, is normal or slightly elevated among awake patients with OSA. This is presumably due to the increased inward collapsing force resulting from anatomic factors^{24,53}. However, during sleep, particularly non-rapid eye movement (NREM) sleep, this reflex activity is significantly diminished or lost¹⁶. This may result in inspiratory narrowing of the airway in patients with OSA during NREM sleep.

In addition to pharyngeal dilator muscle activity, pharyngeal patency is influenced by caudal traction on the airway due to lung expansion⁷⁵. Expansion of the thoracic cavity during inspiration applies an

inferior stretching force on the airway walls, creating tension within the wall that opposes the negative intra-luminal pressure and prevents collapse. Thus, decreases in lung volumes, which can be associated with parenchymal disease or obesity, as well as with supine posture and the transition to sleep, generally reduce tension on the airway and promote collapse^{75,83,84,92}.

Ventilator control: loop gain

While the coordination between collapsing and dilating forces is an important concept in the pathogenesis of OSA, there is increasing evidence that the quantity and pattern of ventilation plays a substantial role in airway collapse (Fig. 7)^{15,34,36,52,92,96}. Though patients with OSA generally have narrower and longer airways that are more prone to collapse, not all individuals with such features have OSA. Conversely, not all

patients with OSA have narrow airways. For example, some patients with OSA may have larger airways, which are less prone to collapse. Airway narrowing occurs due to negative intra-luminal pressures generated during inspiration. Airway collapse occurs at the end of expiration, with noted increased collapsibility in patients with longer expiratory times. Thus, ventilator control plays an important role in the pathogenesis of OSA.

The feedback loop that links respiratory control to airway collapsibility can be described in terms of an engineering concept known as loop-gain^{15,34,37,52}. Loop-gain describes the relative strength and speed of response to disturbance in a system that is regulated by feedback loops. Loop-gain can be conceptualized as the magnitude of the system response relative to the magnitude of the disturbance. Thus, a high gain system (loop-gain > 1) will respond to any perturbation with disproportionately high vigor and rate (a destabilizing response), whereas a low-gain system (loop gain << 1) will respond proportionally in a stabilizing manner. Loop-gain has been suggested to increase during NREM Stages 1–2 of sleep and decrease during NREM Stages 3 and 4^{82,92}.

With regard to the pathogenesis of OSA, ventilator responses to obstruction need to be efficient but well-controlled, so as not to cause disruption from sleep. Arousals contribute to ventilator instability and promote upper airway collapsibility⁹⁷. Airway obstruction leads to hypercarbia, which is sensed via peripheral and central chemoreceptors. This elicits a central response to hypoventilation. During sleep, the threshold partial pressure of carbon dioxide (PCO₂) which results in ventilator response is increased relative to the threshold during wakefulness^{20,93}. The rate and magnitude of this response is the loop-gain of the system. A high-gain system generates a robust

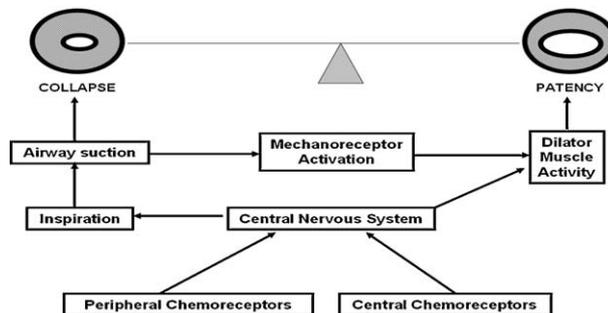


Fig. 7. Overall pathogenic model for airway collapse in OSA showing the balance of forces that determine airway patency. Local reflex factors include the negative intra-luminal pressure generated during inspiration and the resulting reflex activity of the pharyngeal dilator muscles. These local mechanisms are both under central nervous system control. Adapted from reference 92.

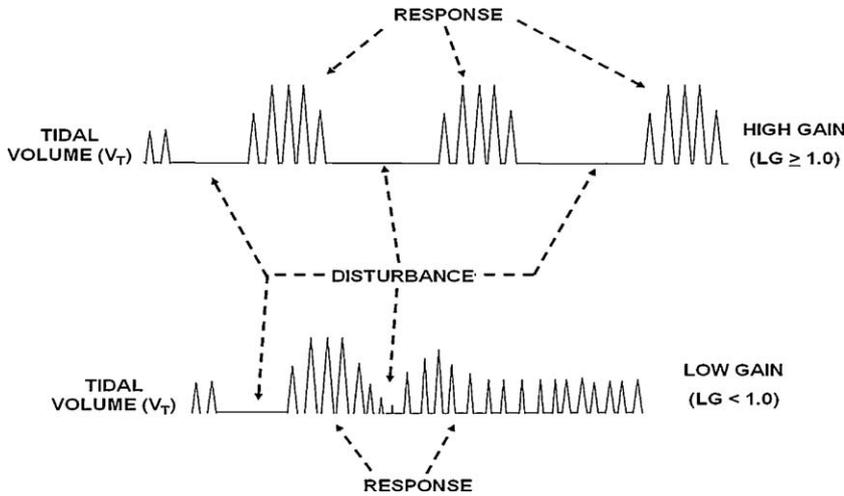


Fig. 8. Loop-gain and ventilation instability in OSA. The ventilator response to an apneic episode is illustrated above to both high gain (top) and low gain (bottom) systems. In the high gain system ($LG \geq 1$), the ventilator pattern remains destabilized for a prolonged period of time following the disturbance. In the low gain system (loop gain, $LG \ll 1$), the ventilator pattern stabilizes relatively quickly after the disturbance (apnea). Adapted from reference 92.

response which, though rapid in generation, takes a long time to produce ventilator stability and periodic breathing occurs (Fig. 8). A low-gain system responds to increased PCO_2 to produce ventilator stability quickly.

High-gain systems, which are detrimental to ventilation during awake and sleep periods, are the result of: brisk chemo- and ventilator-responsiveness to metabolic disturbances (hypoxia/hypercarbia); and increased effectiveness of ventilation (i.e. small ventilator changes result in large PCO_2 changes)^{20,64,81,87,92,93,97}.

Thus, the apnea threshold, or the PCO_2 level at which breathing ceases during sleep, is functionally dependent on the response to hypercapnia and the effectiveness of such a response on the PCO_2 level. Individuals with high-gain systems will have eupneic partial pressure of carbon dioxide in alveolar gas ($P_A CO_2$) levels that approach the apnea threshold, resulting in significant ventilation instability⁹².

It has been recently demonstrated that individuals with severe OSA have higher loop-gain than those with milder OSA^{64,96}. OSA patients may have a higher

ventilator responsiveness to hypercapnia. In these patients, the PCO_2 drop below the apnea threshold occurs with greater frequency, with possible prolongation of expiratory time, resulting in increased probability of airway obstruction, due to decreased activation of pharyngeal dilator muscles. In addition, among patients with the same risk factors for pharyngeal collapsibility, the severity of disease is determined by the individual response to obstruction (i.e. loop-gain). Thus, loop-gain may help to explain why patients with certain anatomic predispositions to OSA have relatively mild disease, whereas other patients with more subtle anatomical discrepancies may often have severe disease. Some of these changes are reversible, as continuous positive airway pressure (CPAP) treatment has been shown to increase the CO_2 reserve (the difference between the eupneic sleep end-tidal CO_2 and the apnea-threshold CO_2) thus, effective surgical treatment of OSA may have long-term benefits for sleep-breathing beyond improvement in anatomical factors.

Complex sleep apnea

Complex sleep apnea is a newly recognized category in the spectrum of sleep apnea syndromes (Fig. 9)^{27,81}. This form of sleep disordered breathing has been pathophysiologically related to obstruction of the upper airway with concomitant respiratory control dysfunction^{26,77}. Like mixed sleep apnea (a category dropped

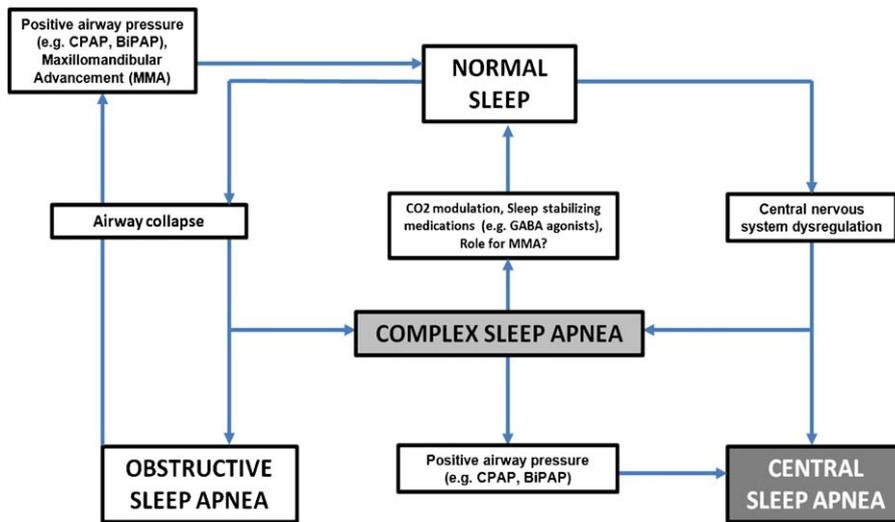


Fig. 9. Spectrum of apnea. The spectrum of apnea-related disease encompasses disease that is related to airway collapsibility (obstructive disease), disease related to central nervous system dysregulation (central disease) and that related to both collapsibility and central nervous system factors (complex disease). It has been shown that patients with complex disease develop central sleep apnea when given positive pressure ventilation, because the obstructive component of their disease is minimized. These patients will respond to CO_2 modulation, which accounts for the central nervous system contributions to the disease process. It is possible that, since complex apnea is obstructive, orthognathic surgery (i.e. MMA) may have a role in the treatment of these patients.

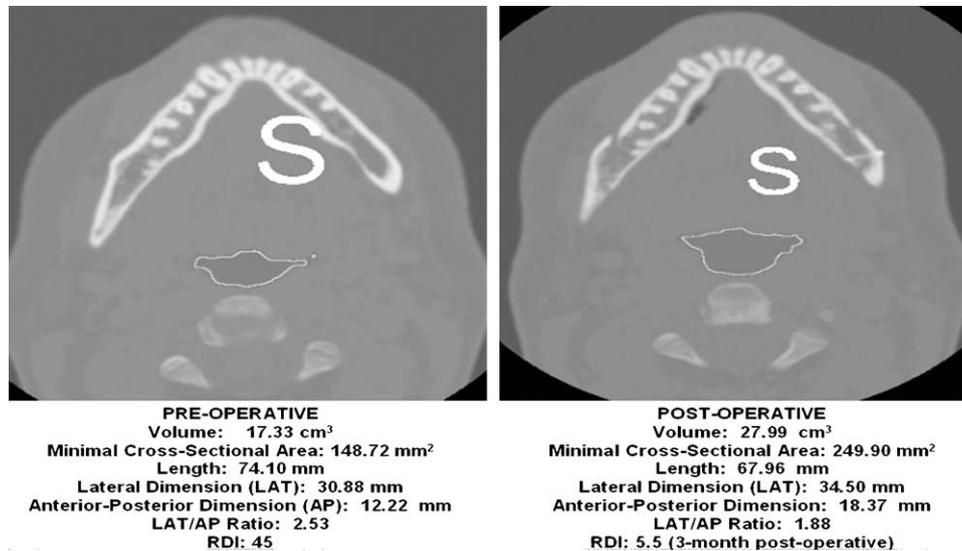


Fig. 10. Changes in retroglottal airway cross-sectional area as a result of MMA. Demonstrable changes in the retroglottal cross-sectional area in a patient who underwent MMA and genial tubercle advancement for treatment of severe OSA. The preoperative image (left) demonstrates a relatively constricted retroglottal airway. The postoperative image (right) shows a 68% increase in cross-sectional area, corresponding to a 62% increase in airway volume. The airway length also decreased following MMA.

from the International Classification of Sleep Disorders because of difficulties with phenotype specification and definition), complex sleep apnea has features of typical obstructive disease (morphologically obstructive events) and polysomnographic evidence of strong chemoreflex modulation of sleep-breathing, including, but not limited to, central apneas. The word 'complex' is used to denote suggestive evidence of strong chemoreflex effects on sleep-breathing. Complex sleep apnea can be distinguished from OSA (and what was called mixed sleep apnea in the past) by the following: NREM sleep dominance of obstructive disease; oscillations of respiration, with or without flow-limitation, with a similarly timed frequency reminiscent of high-altitude periodic breathing; and induction of central apneas or periodic breathing on application of positive airway pressure therapy.

Worsening of disease with treatments directed to anatomical abnormalities may occur because the obstructive component of disease is effectively eliminated, but the ventilator control disturbance remains or is amplified. These worsening conditions are likely due to hypocarbia and sensitivity to CO₂ levels, as manipulation of inspired CO₂ can convert these patients into a more purely obstructive pattern^{79,80}. Given that standard positive pressure treatment is not appropriate for these patients, but that some of their disease patterns are nevertheless related to airway collapsibility, this population presents another group of sleep apnea patients

who may benefit from maxillofacial surgical interventions, recognizing that further management of the central component may be required, including use of nasal O₂, dead space alone, pharmacologic treatment (e.g. carbonic anhydrase inhibitors), or positive pressure-based adaptive ventilation⁴. The same principles apply to persistent post-tracheostomy residual sleep apnea, which is strongly related to chemoreflex effects^{79,80}.

Relevance for the oral and maxillofacial surgeon

The concept of loop-gain as it relates to OSA is important for the oral and maxillofacial surgeon. Patients with OSA, who have abnormal anatomy and high loop-gain, are predisposed to obstruction due to both anatomy and deficient control mechanisms. Though loop-gain is a factor that cannot be modified surgically, anatomic modification of the airway can result in decreased collapsibility.

MMA may be used to expand a normal skeleton (e.g. Class I skeletal profile) to adapt it to excessive soft tissue or to expand a deficient facial skeleton (e.g. Class II skeletal profile) to fit a normal soft tissue distribution. Expansion of the cross-sectional upper airway diameter, which has been documented to occur as a result of MMA (Figs 10 and 11)^{1,22} acts to decrease P_{crit} . This decrease in P_{crit} will increase the threshold pressure required for airway collapse and thus, may be

beneficial, even in patients with high loop-gain.

Conversely, patients who fail to respond to MMA (Fig. 12) may be a subset of high-loop gain individuals or those with complex disease, in whom the response to perturbations from even minimal obstruction results in ventilation instability and disease. One potential explanation for the residual disease following MMA is a chemoreceptive reflex (hypoxia- or hypercarbia-driven apnea) that remains at the pre-MMA activation threshold (i.e. the chemoreflex set point in a patient with recurrent airway collapse and apnea). In these patients, continued management by a sleep physician is imperative. Recent studies suggest that these patients may benefit from modulation of inspired CO₂ during sleep or pharmacologic treatment with carbonic anhydrase inhibitors (e.g. acetazolamide), which have been shown to lower the CO₂ thresholds in patients with central sleep apnea^{17,18,27,56,82,86}. A further strategy for patients with residual sleep apnea post-MMA is the judicious use of sedative-hypnotics ('sleep-stabilizers'). By reducing the 'arousal amplification factor' (i.e. loop-gain) and enhancing periods of stable breathing, there may be important improvements in sleep and breathing quality⁷⁸. The newer non-benzodiazepine gamma-aminobutyric acid (GABA) receptor modulators seem to be safe in those with sleep apnea, and have been shown to improve sleep and breathing in central sleep apnea, and at high altitude^{6,62,63}.

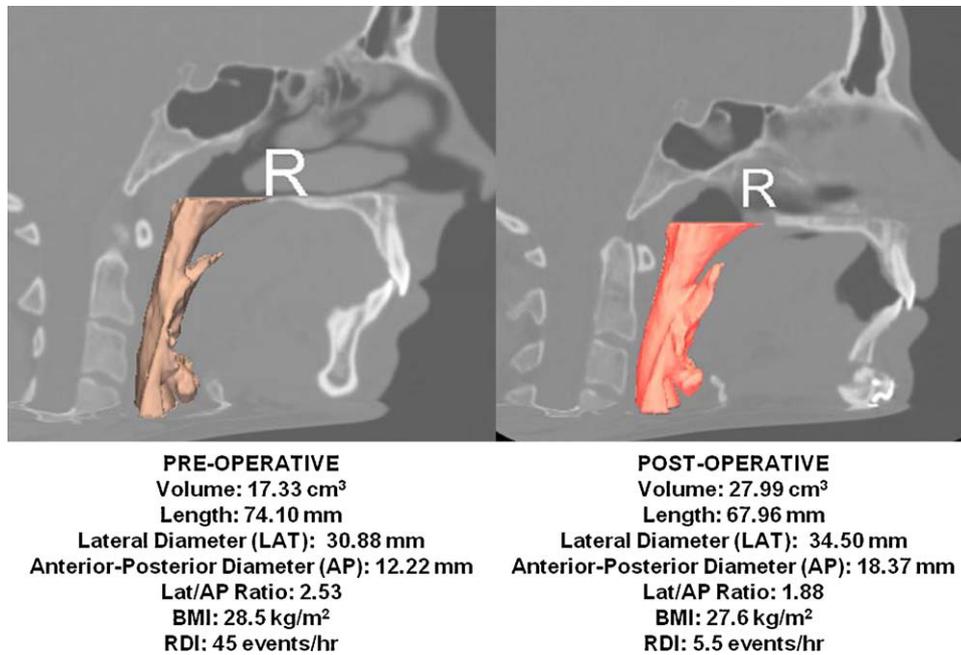


Fig. 11. Pre- and postoperative airway anatomy in a patient with no clinical symptoms post-operatively and substantial improvement on postoperative polysomnography. This 36-year-old man underwent MMA with genial tubercle advancement (GTA) for the treatment of severe OSA (pre-operative RDI: 45 events/hr). The maxilla was advanced 9 mm and the mandible advanced 11 mm. His preoperative and postoperative airway models demonstrate a substantial increase in airway volume, later and anterior-posterior diameters and a decrease in airway length after MMA/GTA. A 6-month post-operative polysomnograph revealed a marked improvement in sleep disruption (RDI: 5.5 events/h). The patient remains clinically asymptomatic at 1-year postoperatively.

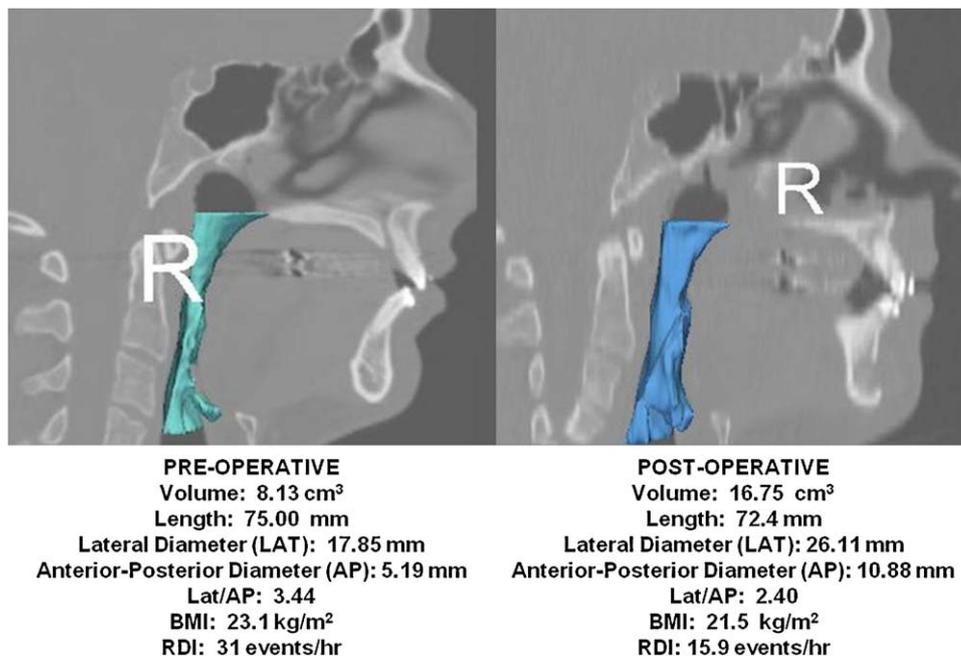


Fig. 12. Pre- and postoperative airway anatomy in a patient with no clinical symptoms postoperatively and significant residual central disease on postoperative polysomnography. This 30-year-old man underwent MMA with genial tubercle advancement (GTA) for the treatment of severe OSA (preoperative RDI: 31 events/h), characterized by purely obstructive apneas/hypopneas with very few central events. The maxilla was advanced 10 mm and the mandible advanced 15 mm. His preoperative and postoperative airway models demonstrate a substantial increase in airway volume, lateral and anterior-posterior diameter and decreased airway length after MMA/GTA. A 6-month postoperative polysomnograph revealed significant central apneas and chemoreceptor-sensitive disease (RDI: 15.9 events/h). Though he remains clinically asymptomatic, his significant residual disease related to chemoreceptor-related phenomena. He may benefit from CO₂-modulating therapy and sleep-stabilizing pharmacotherapy.

With regard to decreased genioglossus activity during NREM sleep in patients with OSA, the anatomic predisposition to collapse (i.e. narrow airway) overcomes the genioglossus contribution, resulting in airway collapse. Advancement of the genioglossus, commonly done in conjunction with MMA, can serve as a proxy to correct the deficient reflex responsiveness of the muscle.

The concept of a threshold pressure for collapse (P_{crit}) is important in the context of treatment planning for the patient undergoing MMA. Surgeons and patients continue to struggle with the trade-off between maximal advancement and facial esthetics. Future studies should be conducted to evaluate the effect of any given magnitude of MMA on the P_{crit} . Once a dose–response relationship is established, clinicians will be able to approximate the magnitude of advancement required to effectively treat each specific patient and, conversely, the likelihood of success with a given amount of advancement.

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Competing interests

The authors have no competing interests.

Ethical approval

Ethical approval was not required for this review article.

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