Obstructive Sleep Apnea of Obese Adults

Pathophysiology and Perioperative Airway Management

Shiroh Isono, M.D.*

Collapsible pharyngeal airway size is determined by interaction between structural properties of the pharyngeal airway and neural regulation of the pharyngeal dilating muscles. Obesity seems to have two distinct mechanical influences on the pharyngeal airway collapsibility. First, obesity increases soft tissue surrounding the pharyngeal airway within limited maxillomandible enclosure occupying and narrowing its space (pharyngeal anatomical imbalance). Second, obesity, particularly central obesity, increases visceral fat volume decreasing lung volume. Pharyngeal wall collapsibility is increased by the lung volume reduction, possibly through decreased longitudinal tracheal traction (lung volume hypothesis). Neural compensation for functioning structural abnormalities operating during wakefulness is lost during sleep, leading to pharyngeal obstruction. Instability of the negative feedback of the respiratory system may accelerate cycling of pharyngeal closure and opening. Improvement of the pharyngeal anatomical imbalance and maintenance of lung volume are the keys for safe perioperative airway managements of obese patients with obstructive sleep apnea.

OBSTRUCTIVE sleep apnea (OSA) is a common disorder of breathing during sleep in humans. Polysomnographic recordings of sleep stages, respiration, and oxygenation reveal characteristics of OSA (fig. 1). Complete cessation of airflow for more than 10 s (apnea) or airflow reduction more than 50% (hypopnea) despite continuing breathing efforts results in hypoxemia and hypercapnia. This obstructive apnea or hypopnea is caused by complete or partial closure of the pharyngeal airway.1 The apnea or hypopnea is usually terminated in association with cortical arousal, opening the pharyngeal airway. Breathing is reestablished with loud snoring, normalizing oxygenation, and often overshooting ventilation. OSA patients repeat the obstructive apnea or hypopnea, resulting in blood gas oscillation and sleep fragmentation. Clinical diagnosis of OSA is made when frequency of apnea and/or hypopnea per hour of sleep (apnea-hypopnea index [AHI]) is greater than five in adults. Severity of OSA is determined by the AHI: mild OSA = AHI 6–20 h⁻¹, moderate OSA = AHI 21–40 h⁻¹, and severe OSA = AHI > 40 h⁻¹.

Recent growing evidence indicates that OSA is an independent risk factor for development of hypertension,2 cardiovascular morbidity and mortality,3,4 and sudden death.5 Daytime sleepiness, a common clinical symptom in OSA patients, can result in increased risk of motor vehicle accident.6 Although presence of daytime sleepiness could have a significant impact on outcome of anesthesia and surgery, our major interest, here, is perioperative pharyngeal obstruction in OSA patients. Accordingly, anesthesiologists should consider OSA as a risk factor for perioperative pharyngeal obstruction regardless of daytime sleepiness symptom. Prevalence of OSA without daytime sleepiness in general adult population in the United States was reported to be 24% of middle-aged males and 9% of middle-aged females more than a decade ago.7 Obesity is a common feature of OSA patients. The National Health and Nutrition Examination Survey for 2003–2004, a nationally representative sample of the US population, indicates that the prevalences of overweight (body mass index [BMI] = 25 kg/m²), obesity (BMI > 30 kg/m²), and morbid obesity (BMI > 40 kg/m²) are 71, 31, and 3%, respectively, in adult males and 62, 33, and 7% in adult females.8 The prevalence of obesity has been significantly increasing for several decades in all developed countries, while the picture is less apparent outside the United States.9,10 More importantly, the prevalence of clinically severe obesity is increasing much faster than that of moderate obesity, and the number of morbidly obese patients quadrupled between 1986 and 2000, whereas the prevalence of obesity approximately doubled during the period11 (fig. 2).

The increasing prevalence of obesity has lead to an increase in the prevalence of OSA in the general population.12,13 Individual weight gain or loss significantly influences the severity of OSA.14 Although there seems to be close causal linkages between obesity and OSA, neither conclusive evidence nor an explanation for the causality has been provided to date. Obese patients with OSA are at a greater risk for both difficult mask ventila-
tion during anesthesia induction and postoperative up-
per airway obstruction.15,16 This review article discusses pathophysiology and perioperative airway management of obese adult patients with OSA based on currently available evidences.

Collapsibility of the Pharyngeal Airway in OSA Patients

The pharynx is a collapsible tube that has a variety of physiologic functions, such as speaking, eating, swallowing, and breathing. Coordination of more than 20 pairs of pharyngeal muscles surrounding the collapsible conduit modulates its size and stiffness under the supervision of neural control mechanisms. An obvious but important feature of pharyngeal obstruction is state dependency, in which the pharynx narrows or closes when the neural control mechanisms are depressed during sleep or general anesthesia. Collapsibility of the pharyngeal airway is not homogeneous and varies among subjects. Numerous studies measuring pharyngeal airway cross-sectional area with computed tomography and magnetic resonance imaging during wakefulness demonstrated a narrower pharyngeal airway in OSA patients.17,18 Interaction between neural and anatomical mechanisms during wakefulness, however, complicates interpretation of the airway imaging data.

By eliminating the neural control mechanisms during general anesthesia and total paralysis, Isono et al.19 revealed that OSA patients have structurally narrower and more collapsible pharyngeal airways than age- and BMI-matched non-OSA patients. The closing pressures of the passive pharynx in OSA patients were above atmospheric pressure (0.6 ± 1.5 cm H\textsubscript{2}O for mild OSA, 2.2 ± 3.0 cm H\textsubscript{2}O for moderate to severe OSA), whereas those in non-OSA subjects were below atmospheric pressure (−4.4 ± 4.2 cm H\textsubscript{2}O). Within the pharyngeal airway, positive closing pressures were demonstrated in almost 100% of OSA patients at the retropalatal airway but in only 50% at the retroglossal airway. In a subsequent study, Watanabe et al.20 revealed that obesity was a prominent feature in OSA patients with positive closing pressures exclusively at the retropalatal airway, whereas craniofacial abnormalities such as small maxilla and mandible were evident in OSA patients with positive closing pressures at both the retropalatal and retroglossal airways.

Obesity and OSA

Fat distribution is not homogenous among obese persons. BMI represents overall increase in body weight for a person’s height and has a significant but weak correlation with OSA severity. Neck circumference represents regional obesity near pharyngeal airway and has stronger correlation to OSA severity than to BMI.21 The volume of adipose tissue deposited adjacent to the pharyngeal airway is related to the presence of OSA and OSA severity.22–24 More importantly, obese OSA patients accumulated more visceral adipose tissue than BMI-matched non-OSA persons.25 Recently, Schafer et al.26 reported that OSA severity is more significantly correlated with fat accumulation of the intraabdominal region than of the neck region. These are in agreement with the finding that waist circumference is a better predictor for OSA than neck circumference or BMI.27 Both neck fat deposits surrounding the pharyngeal airway and intraabdominal fat deposits away from the pharyngeal airway are likely
to be involved in the pathogenesis of OSA, although probably through different mechanisms, as discussed below.

Role of Leptin in Controlling Body Weight and Breathing

Leptin is an adipose-derived hormone that is responsible for signaling the appetite center receptors at the hypothalamus that the body has had enough to eat, and it regulates energy intake, body weight, and fat distribution. Evidence of a higher serum leptin level in obese persons suggests the potential of leptin resistance in the development of obesity. Interestingly, OSA patients are reported to have higher leptin levels than BMI-matched non-OSA persons. Chin et al. demonstrated the reduction of serum leptin levels in response to short-term nasal continuous positive airway pressure (CPAP) treatment, which suggests potential OSA contribution to development of leptin resistance in obese OSA patients. OSA, per se, seems to play a role in the resistance of these patients to weight loss.

Leptin-deficient obese mice (ob/ob mice) have higher resting arterial carbon dioxide level and depressed ventilatory response to hypercapnia than lean wild-type mice during wakefulness and sleep. Interestingly, leptin infusion in leptin-deficient mice reduced the resting arterial carbon dioxide and improved hypercapnic ventilatory response independent of weight changes, whereas it did not influence ventilation in wild-type mice, suggesting an important role of leptin in respiratory control in obesity. Recent extensive researches reveal interesting interaction between lipid metabolism and control of breathing. Excessive visceral adipose tissue linking to both metabolic syndrome and OSA secretes a number of hormones and proinflammatory cytokines, and these possibly influence breathing in obese OSA patients. A breakthrough for OSA pathogenesis is expected from this new area in the future.

A Local Structural Mechanism (Upper Airway Obesity): Excessive Upper Airway Soft Tissue

Whereas OSA patients have increased total fat volume surrounding the pharyngeal airway, fat accumulation on a more specific region, such as the parapharyngeal fat pad or tongue, was not consistently associated with the presence of OSA, which could be due to either necessity of diffuse rather than localized accumulation of adipose tissue or necessity of total soft tissue volume including both adipose and nonadipose tissue surrounding the pharyngeal airway for OSA development. Schwab et al. beautifully demonstrated by use of three-dimensional volumetric analysis that the volume of the tongue and lateral walls independently increases risk of sleep apnea.

A Local Structural Mechanism: Upper Airway Anatomical Balance

Structurally, the pharyngeal airway is a space inside rigid craniofacial bony enclosure formed by the cervical vertebrae, maxilla, and mandible. Within the bony enclosure, the airway shares its space with soft tissue such as the tongue and soft palate. According to this mechanical simplification of the anatomical structures surrounding the pharyngeal airway, the balance between the craniofacial bony enclosure size and the amount of soft tissue is considered to determine the airway space (fig. 3). Either an increase in amount of the soft tissue within the bony enclosure or a decrease in the bony enclosure size would result in limitation of space available for the airway and, consequently, a narrowing of the airway.

Tsuiki et al. recently tested this concept by comparing the upper airway anatomical balance between OSA and craniofacial dimension–matched non-OSA subjects. Using lateral cephalograms, they measured the tongue cross-sectional area as an index for the soft tissue volume surrounding the pharyngeal airway and the lower craniofacial cross-sectional area as an index for the craniofacial bony enclosure size. As clearly presented in figure 4, the tongue was greater in non-OSA persons with greater lower craniofacial size, suggesting optimal tongue size for a given craniofacial dimension. OSA patients, however, demonstrated a significantly greater tongue for a given craniofacial dimension than non-OSA persons, indicating the importance of anatomical imbalance for development of OSA rather than absolute soft tissue volume of the upper airway alone.
A Structural Mechanism from a Distance: Lung Volume Hypothesis

Obesity is associated with significant reduction of lung volume such as functional residual capacity (FRC) and expiratory residual volume due to diminished chest wall compliance, and total lung capacity and vital capacity are only impaired by extreme obesity.\(^{34}\) Whereas FRC reduction accounts for development of severe hypoxemia during obstructive events in obese OSA patients, lung volume decrease, \textit{per se}, is indicated to contribute to pharyngeal airway obstruction. Hoffstein \textit{et al.}\(^{35}\) hypothesized significant lung volume dependence of pharyngeal airway patency as an important factor in the pathophysiology of OSA based on the finding that obese OSA patients demonstrated significantly greater reduction of the smaller pharyngeal cross-sectional area in response to slow exhalation from total lung capacity to residual volume during small (0.5 l) and large (1.0 l) tidal breathing, respectively, in supine adults.\(^{42}\) The caudal tracheal traction during lung inflation is considered to increase longitudinal tension of the pharyngeal airway wall, thereby unfolding the pharyngeal mucosa and stiffening the airway.\(^{43,44}\) Interestingly, the magnitude of tracheal traction seems to be the sum of forces associated with a mediastinal shift during lung inflation and intrathoracic pressure swing with and without lung inflation, which is suggestive of a tracheal tug during pharyngeal obstruction, leading to the reestablishment of pharyngeal airway patency.\(^{43}\)

In an elegant study by Heinzer \textit{et al.}\(^{45}\) regarding significant lung volume dependence of pharyngeal patency in obese sleeping OSA patients (mean BMI = 31.9 kg/m\(^2\)), it was revealed that the CPAP needed to prevent flow limitation increased from 11.9 to 17.1 cm H\(_2\)O in response to lung volume reduction of 0.6 l. Tagaito \textit{et al.}\(^{46}\) found a significant reduction of retropalatal airway closing pressure of 1.2 cm H\(_2\)O by an increase in lung volume of 0.7 l in anesthetized, paralyzed OSA patients (median BMI = 26 kg/m\(^2\)). Considering the 5- to 7-cm H\(_2\)O dif-

Figure 4. Box plots showing differences of the tongue cross-sectional area (T-CSA) between non-obstructive sleep apnea subjects (control) and patients with obstructive sleep apnea (OSA) for each of three subgroups defined based on the lower face cage (LF) cross-sectional area. \textit{Lower and upper boundaries indicate 25th and 75th percentages. A solid line within the box marks the median, and vertical lines indicate the 10th and 90th percentages. Solid circles are outliers. Definitions of the subgroups: small LF subgroup, LF-CSA < 65 cm\(^2\); intermediate (IM) LF subgroup, 65 cm\(^2\) < LF-CSA < 71 cm\(^2\); large LF subgroup, LF-CSA > 71 cm\(^2\). * \(P < 0.05\) versus control. \(\Phi \) \(P < 0.05\) versus small LF subgroup. From Tsuiki \textit{et al.}\(^{53}\); reprinted with permission.
ferences of the pharyngeal closing pressure between normal and OSA patients and the study of Heinzer et al. of obese OSA patients, the observed closing pressure changes seem to be small in the study population. Notably, improvement of the retropalatal closing pressure during lung inflation was directly associated with BMI. In response to 0.5-l changes of lung volume, retropalatal closing pressure was roughly estimated to change by 2 cm H2O in OSA patients with BMI of 32 kg/m2, whereas it was estimated to change by 0.5 cm H2O in those with BMI of 25 kg/m2, suggesting that the lung volume dependence of pharyngeal closing pressure may be more evident in obese OSA patients than in nonobese OSA patients. From Tagaito et al.; modified with permission.

Sequential Neuroanatomical Interaction

Figure 6 illustrates sequential neuroanatomical interaction during OSA. Reflexive increase of pharyngeal dilator muscles is an instantaneous response to pharyngeal narrowing or obstruction. Mechanoreceptors in the upper airway mucosa sense the increased negative pressure, which triggers the ascension of the neural signal to hypoglossal motor neurons through the superior laryngeal or glossopharyngeal nerves and nucleus of the solitary tract. An early report indicated abolishment of the negative pressure reflex during non–rapid eye movement (NREM) sleep in non-OSA subjects. However, depression of the neural control mechanisms at sleep onset is subject to sequential neural activation responses such as airway reflexes and chemical and arousal responses. Therefore, it is possible to hypothesize the development of OSA to deficiency of the neural compensatory mechanisms for the structural abnormalities. Regrettfully, no researcher has succeeded in testing or proving the hypothesis, primarily because of the complexity of the neuroanatomical interaction; however, recent extensive research in this field has significantly increased our understanding of the complexity, as is discussed below.

Neural Responses to Anatomical Abnormalities of the Pharynx

Obstructive sleep apnea is a state-dependent disease possibly caused by complicated neuroanatomical interaction. Mezzanotte et al. reported that OSA patients have significantly greater basal genioglossal muscle activity than age- and BMI-matched non-OSA subjects during wakefulness. They further demonstrated that the augmented genioglossal activity was reduced by application of CPAP in OSA patients, whereas CPAP application had no effect on the genioglossal activity in non-OSA subjects. This is considered for compensating the structurally narrower and more collapsible pharyngeal airway. Sleep, however, significantly depresses this neural compensatory mechanism, and OSA develops only during sleep. The genioglossal muscle activity physiologically decreases at sleep onset in both non-OSA subjects and OSA patients. Although the pharyngeal airway of non-OSA persons may narrow, airway space is maintained in response to depression of the neural control mechanisms. However, this neural depression is crucial for OSA patients who heavily rely on their airway patency to the neural mechanisms. Depression of the neural control mechanisms at sleep onset is subject to sequential neural activation responses such as airway reflexes and chemical and arousal responses. Therefore, it is possible to hypothesize the development of OSA to deficiency of the neural compensatory mechanisms for the structural abnormalities. Regrettfully, no researcher has succeeded in testing or proving the hypothesis, primarily because of the complexity of the neuroanatomical interaction; however, recent extensive research in this field has significantly increased our understanding of the complexity, as is discussed below.

Neural Responses to Anatomical Abnormalities of the Pharynx

Obstructive sleep apnea is a state-dependent disease possibly caused by complicated neuroanatomical interaction. Mezzanotte et al. reported that OSA patients have significantly greater basal genioglossal muscle activity than age- and BMI-matched non-OSA subjects during wakefulness. They further demonstrated that the augmented genioglossal activity was reduced by application of CPAP in OSA patients, whereas CPAP application had no effect on the genioglossal activity in non-OSA subjects. This is considered for compensating the structurally narrower and more collapsible pharyngeal airway. Sleep, however, significantly depresses this neural compensatory mechanism, and OSA develops only during sleep. The genioglossal muscle activity physiologically decreases at sleep onset in both non-OSA subjects and OSA patients. Although the pharyngeal airway of non-OSA persons may narrow, airway space is maintained in response to depression of the neural control mechanisms. However, this neural depression is crucial for OSA patients who heavily rely on their airway patency to the neural mechanisms. Depression of the neural control mechanisms at sleep onset is subject to sequential neural activation responses such as airway reflexes and chemical and arousal responses. Therefore, it is possible to hypothesize the development of OSA to deficiency of the neural compensatory mechanisms for the structural abnormalities. Regrettfully, no researcher has succeeded in testing or proving the hypothesis, primarily because of the complexity of the neuroanatomical interaction; however, recent extensive research in this field has significantly increased our understanding of the complexity, as is discussed below.

Sequential Neuroanatomical Interaction

Figure 6 illustrates sequential neuroanatomical interaction during OSA. Reflexive increase of pharyngeal dilator muscles is an instantaneous response to pharyngeal narrowing or obstruction. Mechanoreceptors in the upper airway mucosa sense the increased negative pressure, which triggers the ascension of the neural signal to hypoglossal motor neurons through the superior laryngeal or glossopharyngeal nerves and nucleus of the solitary tract. An early report indicated abolishment of the negative pressure reflex during non–rapid eye movement (NREM) sleep in non-OSA subjects. However,
recent human and animal studies support depression but preservation of the negative pressure reflex during NREM sleep and light anesthesia, whereas the reflex was significantly depressed during rapid eye movement sleep and deep anesthesia.\textsuperscript{51,52} In normal adults, Malhotra et al. demonstrated that the magnitude of the genioglossal muscle activation is directly associated with inspiratory negative airway pressure during both wakefulness and NREM sleep, whereas the slope of the association was greater during wakefulness than NREM sleep.\textsuperscript{53} Interestingly, elimination of inspiratory pump muscle contraction using iron lung attenuated the negative pressure reflex, suggesting modulation of the reflex by the central pattern generator.\textsuperscript{54}

Persistence of pharyngeal obstruction despite the negative pressure reflex leads to hypocapnia and hypoxemia, increasing chemical stimuli to both inspiratory pump muscles and pharyngeal dilator muscles, although with differing responses. Whereas chemical stimuli progressively increase diaphragm activity, activation of the genioglossal muscle occurred only below threshold hypoxemia or above threshold hypocapnia in animal experiments.\textsuperscript{55,56} Greater increase of inspiratory collapsing forces compared with the pharyngeal dilating forces favors pharyngeal narrowing; therefore, chemical control of the pharyngeal muscles had been considered to only slightly contribute to reversal of pharyngeal airway patency. However, it was recently demonstrated that application of the combination of inspiratory resistive loading and hypocapnia increased basal genioglossal activity and elicited progressively augmenting genioglossal activation with increasing chemical stimuli in normal individuals during NREM sleep, suggesting the importance of chemical control of the pharyngeal muscles under mechanical loading such as pharyngeal obstruction.\textsuperscript{57}

Development of hypoxemia, hypocapnia, and increased negative thoracic pressure during persistent pharyngeal obstruction plays a role in inducing arousal from sleep, a final stage of the neural mechanisms, restoring patent pharyngeal airway. The arousal response has long been believed to be the most important survival response because its impairment indicates persistence of the pharyngeal obstruction and development of severe hypoxemia, and eventual brain damage and death.\textsuperscript{58} However, Younes et al. recently proposed a different perspective in which arousal is probably an incidental event that interferes with the underling neural compensatory mechanisms for restoration of pharyngeal patency without arousal.\textsuperscript{59} In fact, OSA patients did not require cortical arousal for increasing inspiratory flow in response to experimentally induced severe inspiratory flow limitation in 39% of the trials during NREM sleep, and frequency of the flow response without arousal increased with delta power of electroencephalogram (deeper sleep).\textsuperscript{59} Accordingly, it is speculated that delay in arousal response by hypnotics may be beneficial for some, although certainly not all, OSA patients, allowing completion of the neural compensatory mechanisms either by chemical stimuli or by other neural excitatory influences on the pharyngeal muscle tone.\textsuperscript{60} Furthermore, arousal from sleep in response to pharyngeal obstruction is associated with a burst of the pharyngeal muscle activation and hyperventilation. Although these brisk respiratory responses aid in instantaneous reestablishment of patent pharyngeal airway and reoxygenation, these often lead to unnecessary reduction of the central respiratory drive to both pump muscle and pharyngeal dilator muscles during sleep inclination, predisposing destabilizing breathing and subsequent pharyngeal obstruction.

**Cyclical Neuroanatomical Interaction: Higher Loop Gain of the Respiratory System**

Multiple negative feedback loops of the respiratory system aim to control and stabilize breathing by adjusting arterial blood gas tensions. The respiratory chemical control loops of OSA patients, however, do not maintain a constant blood gas level during sleep, leading to cyclical chemical stimuli in association with periodic OSA events. In addition, waxing and waning–type breathing instability continues even after tracheostomy in OSA patients, suggesting an inherent unstable nature of the respiratory feedback system in these patients.\textsuperscript{61} Stability of the respiratory system is determined by magnitude of the loop gain (fig. 7).\textsuperscript{62} The unstable system with a high loop gain overly responds to occurrence of abnormal breathing and starts cycling OSA events increasing AHI. In contrast, the system with a low loop gain is stable but possibly fails to correct the abnormal breathing, prolong-

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig7.png}
\caption{Influences of different magnitude of respiratory loop gain on breathing stability. Different ventilatory responses to reduced tidal volume are illustrated. \textit{Height of an arrow} represents tidal volume. \textit{Dotted line} represents optimal ventilation level. An individual with a high respiratory loop gain (A) will instantaneously respond to the abnormal breathing but overshoot the ventilatory response, resulting in rapid decline in the ventilation. Waxing and waning pattern of unstable breathing continues in this person. In contrast, an individual with low respiratory loop gain (C) will slowly respond to the abnormal breathing and fail to establish a desired ventilation level. Breathing stability can be accomplished in an individual with an optimal loop gain (B).}
\end{figure}

Anesthesiology, V 110, No 4, Apr 2009
ing apnea. In fact, Younes et al. demonstrated that severe OSA patients have higher loop gain during sleep than do mild OSA patients, suggesting importance of ventilatory instability for increasing AHI. Interestingly, Wellman et al. found a significant association between the loop gain and AHI in an OSA subgroup with closing pressure near atmospheric pressure, whereas the closing pressure was significantly associated with AHI in the whole group of OSA patients.

Among the various components of the respiratory loop gain, controller gain predominantly determined by chemoresponsiveness, such as hypoxic and hypercapnic ventilatory responses, influences breathing instability contributing to pathogenesis of OSA. Chemoresponsiveness, however, varies among OSA patients, and majority of them have normal or blunted chemoresponsiveness during wakefulness. Notably, Verbraecken et al. found that hypercapnic ventilatory response was increased in eucapnic OSA patients, whereas the response was blunted in chronic hypercapnic OSA patients. Makinodan et al. found significant direct association between hypercapnic ventilatory response and serum leptin level in non-OSA persons and eucapnic OSA patients, although age- and BMI-matched chronic hypercapnic OSA patients had higher serum leptin level and lower hypercapnic ventilatory response. Furthermore, Wang et al. recently reported a significant association between hypercapnic ventilatory response and AHI in asymptomatic nonobese OSA patients. These results suggest a contribution of increased hypercapnic ventilatory response to nocturnal breathing instability and OSA pathogenesis in OSA patients with higher serum leptin level and hypercapnic ventilatory response. Oxygen therapy for OSA, i.e., desensitization of peripheral chemosensitivity, is reported to decrease loop gain and AHI by a half in OSA patients with higher loop gain before oxygen administration, suggesting some role of hypoxic ventilatory response in OSA pathogenesis.

Changes of chemosensitivity upon arousal from sleep to wakefulness may further facilitate the breathing instability.

Plant gain is another important component of the respiratory loop gain and is determined by efficacy of gas exchange for a given ventilatory change. For example, changes of arterial carbon dioxide tension per unit of ventilation are greater at lower lung volume because of less buffering capacity of total lung carbon dioxide stores. Low FRC, low dead space, low metabolic rate, low cardiac output, and high arterial carbon dioxide increase efficacy of the gas exchange, and all combined theoretically increase plant gain, producing an unstable respiratory system. It is of note that these are common particularly in obese patients with severe OSA. Although no study has assessed contribution of these conditions to nocturnal breathing instability in OSA patients, increased plant gain of the respiratory feedback system may be also involved in the OSA pathogenesis.

Higher respiratory loop gain may play a role in initiating and cycling the neuroanatomical interaction (respiratory negative feedback loop) in OSA patients (fig. 6). In addition to increase of frequency of the cycling (AHI), it should be noted that the higher loop gain of the respiratory negative feedback system possibly exaggerates each step of the neuroanatomical interaction, amplifying ventilatory oscillation (fig. 6). Central respiratory drive should also project to hypoglossal motor neurons, and therefore, one would expect similar augmenting and decrementing changes of pharyngeal dilator muscles to inspiratory pump muscles. Accordingly, amplification of the neuroanatomical interaction possibly minimizes activity of the pharyngeal dilator muscles at the nadir of the cycling, increasing pharyngeal collapsibility. Certainly, contribution of breathing instability to OSA is an interesting and promising hypothesis; however, further extensive research is required in this area.

**Perioperative Airway Management**

Although we still do not fully understand the mechanisms of pharyngeal obstruction during sleep, anatomical imbalance surrounding the pharyngeal airway, lung volume reduction, and breathing instability seem to significantly contribute to development and deterioration of OSA in obese persons, as summarized in figure 8. Development of a safe and appropriate anesthetic management strategy of obese OSA patients should be based on the understanding of the OSA pathogenesis. No standard airway management strategy, however, has been established and validated to date despite the recent release of practical guidelines for perioperative OSA managements. Below are my personal opinions based on the OSA pathophysiology and my limited clinical experience.
Preoperative OSA Assessment and Airway Management

The first and most important recognition necessary for anesthesiologists is high prevalence of undiagnosed OSA in the surgical patient population (more than 24%). All obese persons undergoing surgery should be suspected of having OSA preoperatively. In addition to an OSA questionnaire, including typical clinical symptoms such as habitual snoring, tiredness or daytime sleepiness, observed apnea, and high blood pressure (STOP), a variety of clinical assessments of anatomical balance surrounding the pharyngeal airway are helpful. The modified Mallampati score assesses relative tongue size within the limited oral cavity, and classes 3 and 4 suggest the anatomical imbalance and presence of OSA. Excessive soft tissue for the limited maxillomandibular enclosure expands to the submandible space, and therefore, excessive submandible soft tissue on the profile of OSA patients would indicate anatomical imbalance. Tsui et al. reported that cricomental space, defined as the perpendicular distance from a line between the cricoid cartilage and the inner mentum to the skin of the neck, of more than 1.5 cm excluded OSA patients with a negative predictive value of 100%. Notably, the profile of OSA patients resembles that of patients with difficult tracheal intubation characterized by increased submandibular angle. The caudal soft tissue displacement shifts the mobile hyoid bone caudally, increasing distance between the mandible and hyoid bone, which is easily identified by lateral head and neck radiograph such as the cephalogram for assessment of craniofacial dimensions, and presence of OSA should be strongly suspected when the distance is greater than 20 mm. It should be noted that tracheal intubation is difficult in patients with both shorter and longer thyromental distance and that a low hyoid bone was associated with difficult tracheal intubation, suggesting common anatomical abnormalities between OSA and difficult tracheal intubation but probably through different structural mechanisms.

After diagnosis of OSA and OSA severity with polysomnography, portable sleep monitoring, or nocturnal pulse oximetry, preoperative prescription of nasal CPAP may be beneficial, particularly in severe OSA patients, as suggested by the American Society of Anesthesiologists guideline. Although few data support routine preoperative use of nasal CPAP, preoperative acclimation of the device is a key for successful postoperative use. In addition, 1 week of nasal CPAP treatment can improve pharyngeal collapsibility and increase pharyngeal cross-sectional area. Nasal CPAP treatment possibly improves leptin resistance and facilitates weight reduction before surgery. Anesthesiologists should also recognize that untreated OSA patients, particularly asymptomatic OSA patients, do not easily accept CPAP treatment. Appropriate timing of the surgery should be discussed among the anesthesiologist, surgeon, and patient, considering the expected advantage of the preoperative OSA treatments and disadvantage of delaying the surgery. In long-term successful CPAP users, there is little reason for the surgery to be delayed or cancelled unless there is necessity for treatment of comorbidities. Although choosing regional anesthesia seems preferable for avoiding perioperative respiratory complications in obese OSA patients for superficial procedures or surgery for extremities as recommended by the American Society of Anesthesiologists guideline, potential failure or difficulty of regional anesthesia, such as spinal or epidural anesthesia, should be always included in planning of perioperative airway management.

Airway Management during Anesthesia Induction

Obstructive sleep apnea is a risk factor for both difficult mask ventilation and tracheal intubation. Langeron et al. reported that age older than 55 yr, BMI greater than 26 kg/m², snoring, beard, and lack of teeth are independent risk factors for difficult mask ventilation. The first three factors may relate to OSA. Considering high closing pressure of the pharyngeal airway in OSA patients, there would be no doubt in the strong linkage between OSA and difficult mask ventilation.

High prevalence of OSA was reported among patients with difficult tracheal intubation. Tracheal intubation with direct laryngoscopy was demonstrated to be more difficult in OSA patients than in non-OSA persons (21.9 and 16.7% vs. 2.6 and 3.3%), but BMI was not matched between the groups in these studies. Within the OSA group, severe OSA patients had a higher prevalence of difficult tracheal intubation than mild and moderate OSA patients. Both obesity and craniofacial abnormalities possibly contribute to difficult tracheal intubation in OSA patients. Difficult tracheal intubation in obese persons is controversial. Voyagis et al. found that direct laryngoscopy was more difficult in obese persons than in nonobese persons (20.2 vs. 7.6%). Difficult tracheal intubation in obese persons was confirmed by Juvin et al. but prevalence of OSA patients was higher in the obese group than in the lean group. In contrast, Ezri et al. found no difference of laryngeal view during direct laryngoscopy between obese and nonobese groups, whereas a history of OSA was associated with difficult laryngoscopy. Unfortunately, no study has compared difficulty in direct laryngoscopy between obese and nonobese subjects while controlling presence and severity of OSA and craniofacial characteristics. Interestingly, a high Mallampati score and large neck circumference were associated with difficult tracheal intubation within obese persons, suggesting potential involvement of anatomical imbalance in difficult tracheal intubation.
Kheterpal et al.\textsuperscript{16} identified five risk factors—limited or severely limited mandibular protrusion, thick/obese neck anatomy, sleep apnea, snoring, and BMI $> 30$ kg/m$^2$—as independent predictors of difficult or impossible and difficult tracheal intubation during anesthesia induction. This suggests that obese OSA patients with limited mandible protrusion are in the highest risk group for potentially fatal airway complications. It should be noted that except for limited mandibular protrusion, the risk factors for airway disaster overlap those identified for difficult mask ventilation and tracheal intubation. Advancement of the mandible is a key structural arrangement for safe airway maintenance maneuver during mask ventilation as well as tracheal intubation with direct laryngoscopy.\textsuperscript{91,92} Mobility of the mandible could be a key structural property for safe anesthesia induction and is worthy of future investigations.

During anesthesia induction, potential difficult or impossible mask ventilation should always be considered in obese patients with OSA and without preoperative OSA assessment.\textsuperscript{15,16} The obese OSA patients are to be placed in the sniffing or ramped position with elevation of torso and head combined with the semiupright position.\textsuperscript{93} These head and body positions decrease pharyngeal closing pressure by improving the pharyngeal anatomical balance and increasing lung volume in addition to improvement of laryngeal view during direct laryngoscopy. Inhalation of pure oxygen for more than 3 min with a tightly fitted anesthesia mask can increase apnea tolerance time despite potential development of pulmonary atelectasis,\textsuperscript{94} and application of CPAP or bilevel positive-pressure ventilation (intermittent positive-pressure ventilation with positive end-expiratory pressure) improves oxygenation and prevents airway obstruction during anesthesia induction.\textsuperscript{95–97} Triple airway maneuvers, including mandible advancement, neck extension, and mouth opening, should be performed by use of two hands, as Safar et al. originally proposed.\textsuperscript{98–100} Responses to mechanical interventions in obese persons differ from those in nonobese persons. Isono et al.\textsuperscript{101} demonstrated that mandible advancement significantly decreased the retropalatal closing pressures in nonobese persons but not in obese persons. In contrast, the retroglossal airway never failed to respond to mandible advancement in both nonobese and obese persons, indicating an advantage of intermittent positive-pressure ventilation through an oral airway during anesthesia induction by opening the mouth, particularly in obese OSA patients.\textsuperscript{100,101} Certainly, mouth opening alone decreases the mandible enclosure size and increases closing pressures.\textsuperscript{102} and the advantage of nasal ventilation was recently reported in nonobese subjects without airway maneuvers.\textsuperscript{103} However, mouth opening allows establishment of the oral airway route and adequate mask ventilation by avoiding breathing through the most collapsible and difficult retropalatal airway, which is part of the nasal airway route.\textsuperscript{93,100}

Although timing of administration of muscle relaxants is controversial,\textsuperscript{104} use of muscle relaxants during anesthesia induction may be beneficial for pharyngeal airway maintenance, although various factors need to be considered. Inspiratory negative airway pressure acts as a collapsing force. Muscle relaxants can eliminate unfavorable strong negative airway pressure induced by increased chemical drive during difficult mask ventilation. Intravenous anesthetics rapidly and significantly decrease inspiratory negative airway pressure by depressing the chemical drive and may be an appropriate induction drug. Among them, ketamine has a less depressant effect on pharyngeal dilating muscle activity while it increases pharyngeal secretion and possibly offsets the beneficial effect.\textsuperscript{105} Slow induction with spontaneous breathing is not recommended in these patients. Failure of airway maintenance with strong negative intrathoracic pressure can induce pulmonary edema.\textsuperscript{106} Maintenance of positive airway pressure is a key for successful airway maintenance regardless of using or not using muscle relaxants. Clearly, use of succinylcholine also does not ensure recovery of either muscle function or pharyngeal patency before development of severe hypoxemia in these patients with decreased FRC.\textsuperscript{107} When an airway disaster occurs during anesthesia induction with nondepolarizing muscle relaxant, administration of high-dose sugammadex can rapidly reverse its action, particularly rocuronium-induced paralysis, but sugammadex is currently only available in European countries. But again, this may not ensure reversal of patent pharyngeal airway without recovery of consciousness.\textsuperscript{108} Reversal of both muscle paralysis and consciousness level is necessary for restoring airway patency in the situation. Insertion of supralaryngeal airways without delay is strongly recommended for airway disasters.

Gastroesophageal reflux is common in both obese persons and OSA patients with lower esophageal sphincter hypotonia.\textsuperscript{109} Although pulmonary aspiration during anesthesia induction is relatively rare, it is an important cause of anesthesia-related mortality.\textsuperscript{110} Rapid sequence induction with succinylcholine is often chosen in obese persons. Although this induction technique may be appropriate for obese persons with symptomatic gastroesophageal reflux and full stomach, its benefits should be weighed against risks of rapid development of severe desaturation and difficulty in both tracheal intubation and mask ventilation in obese OSA patients with no other risk of pulmonary aspiration.\textsuperscript{111} Awake intubation should be considered when any element of the triple airway maneuver, including mandible advancement, neck extension, and mouth opening, is disturbed in obese patients with severe OSA. In fact, limited mandible advancement is an independent risk factor for impossible mask ventilation.\textsuperscript{10} Limited neck
mobility due to cervical spine pathology and halo traction can significantly impair the performance of the airway maintenance maneuvers during mask ventilation as well as tracheal intubation. Preservation of the neural compensatory mechanisms is a key for airway maintenance during awake fiberoptic intubation. Although adequate regional airway anesthesia is mandatory, it should be recognized that the upper airway anesthesia alone could block the mechanical receptors on the mucosa for the negative pressure reflex, narrowing the cross-sectional area of the pharynx. Conscious sedation is preferable if needed and is to be achieved by titrating the sedative with caution. Deep sedation should be avoided, and the Ramsey sedation score should be maintained above 4. A sitting position or semiupright position increases airway space behind the epiglottis and improves endoscopic view during the tracheal intubation.

Emergence from Anesthesia and Tracheal Extubation

Regardless of intraoperative body position, a semiupright position or lateral position is recommended for every obese OSA patient at the end of surgery for better oxygenation and pharyngeal airway maintenance. Residual inhalation anesthetics and paralysis are capable of depressing peripheral chemosensitivity, which leads to decreased hypoxic ventilatory response and increased arousal threshold. Selective impairment of pharyngeal muscle contraction was demonstrated during partial paralysis and augmented by subanesthetic inhalation anesthetic. Complete reversal of neuromuscular block should be confirmed by neuromuscular monitor. Reversal with sugammadex seems to be preferable for restoration of pharyngeal dilator muscles to neostigmine, but sugammadex is currently unavailable in the United States. Full awakening after establishment of spontaneous breathing is strongly recommended upon tracheal extubation. External stimuli, such as suctioning, nasal airway insertion, and even patient care surrounding the head and neck, can cause vigorous coughing and hemodynamic instability and, therefore, should be performed before or after emergence from anesthesia. Use of β blockers and antihypertensive drugs may be beneficial for preventing hemodynamic instability during emergence from anesthesia and extubation in OSA patients with cardiovascular diseases. Emergence agitation in these patients is extremely dangerous, possibly resulting in accidental extubation and injuries in addition to losing signals from cardiorespiratory monitors.

Incidence of claims for death or brain damage during anesthesia induction significantly decreased after release of the practice guideline for management of the difficult airway from the American Society of Anesthesiologists. The incidence at tracheal extubation, however, did not decrease during the decade, and regretfully, the extubation strategy recommended by the task force has not been revised in the 2003 guideline. Severe pharyngeal edema developed during upper airway surgery in severe OSA patients can result in choking immediately after endotracheal extubation. A high incidence of severe respiratory compromises (6.1%: 19 in 311) including one death and six reintubations after anterior cervical spine surgery was also attributable to pharyngeal edema. Even modest pharyngeal swelling caused by laryngoscopy and excessive fluid infusion during surgery may possibly have significant influences on pharyngeal airway maintenance immediately after surgery. Development of a technique for prediction of upper airway patency immediately after extubation would significantly increase safety of extubation procedure in patients with difficult airways, such as obese OSA patients. Anesthesiologists should recognize occurrence of pharyngeal obstruction even without loud snoring and be able to diagnose airway patency immediately after extubation by assessing synchrony of thoracoabdominal movements.

Postoperative Analgesia

Considering the high prevalence of cardiovascular comorbidities in OSA patients, adequate pain relief is of great importance. Postoperative analgesia, however, cannot be achieved without risks of respiratory depression and development of severe hypoxemia, particularly in obese OSA patients. Opioids, the most common analgesics after surgery, decrease both hypoxic and hypercapnic ventilatory responses when administered either intravenously or intrathecally, suggesting possible impairment of the sequential neural control mechanisms during OSA and failure or delay of pharyngeal opening (fig. 6). In fact, Catley et al. reported a high prevalence of OSA with severe hypoxemia within 16 h after surgery in patients receiving morphine for analgesia (456 episodes in 10 of 16 patients), whereas use of regional analgesia resulted in less frequency of such events (0 episode in 16 patients). Routes (intravenous, intramuscular, intrathecal, or epidural) and techniques (patient controlled or nurse controlled) of the opioid administration for postoperative analgesia do not seem to influence the risk of respiratory complications. The American Society of Anesthesiologists guideline recommends exclusion of opioids from neuraxial postoperative analgesia in OSA patients if possible. However, adequate analgesia for a major surgery is often difficult to achieve without use of opioids, and there is no consensus regarding individual determination of an optimal opioid dose. Importantly, Brown et al. recently demonstrated increased opioid sensitivity in severe OSA children. Future investigation on opioid sensitivity in adult OSA patients.
is necessary for the development of a safe postoperative analgesia strategy for OSA patients.

Because of potential postoperative respiratory depression or OSA deterioration by residual general anesthetics, paralysis, and opioids, respiration and oxygen saturation should be continuously monitored in all OSA patients receiving opioid analgesia at least for 24 h after surgery. The level of postoperative patient care and monitoring would significantly depend on compliance of nasal CPAP and use of opioids for postoperative analgesia in addition to severity of OSA and obesity and invasiveness of surgery (Table 1).

Postoperative Airway Management

All obese OSA patients should be optimally positioned postoperatively. A sitting position or lateral position is advantageous over a supine position. Use of a pillow to produce the sniffing position is beneficial for airway maintenance. These positional interventions are not sufficient to prevent pharyngeal obstruction in moderate to severe OSA patients. Nasal CPAP with oxygen should immediately be applied in the postanesthetic care unit or ward if the patients accept the treatment. A CPAP machine designed to automatically determine the optimal CPAP level is preferable after surgery. A bilevel positive-pressure machine is necessary for OSA patients with obesity hypoventilation syndrome. Although the literature suggests the usefulness of postoperative CPAP, OSA patients, particularly new CPAP users, do not always wear the mask postoperatively. It is not known whether a single postoperative event of pharyngeal obstruction can result in severe fatal hypoxemia. Although oxygen administration is not a fundamental treatment for OSA, it is beneficial for mild OSA patients or OSA patients with CPAP failure as an alternative to CPAP treatment. Continuous oxygen therapy is recommended while opioids are used for postoperative analgesia.

In conclusion, improvement of the pharyngeal anatomical imbalance and maintenance of lung volume are the keys for safe perioperative airway management of obese patients with OSA.

Table 1. Personal Recommendation of Postoperative Patient Care and Monitoring for an Obese Patient with Severe Obstructive Sleep Apnea

<table>
<thead>
<tr>
<th></th>
<th>Ward with No Monitoring</th>
<th>Ward with Pulse Oximetry</th>
<th>PACU or ICU with Pulse Oximetry</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPAP (+)</td>
<td>Acceptable</td>
<td>Desirable</td>
<td>Unnecessary</td>
</tr>
<tr>
<td>Opioid (–)</td>
<td>Not recommended</td>
<td>Acceptable</td>
<td>Desirable</td>
</tr>
<tr>
<td>Opioid (+)</td>
<td>Not recommended</td>
<td>Not recommended</td>
<td>Desirable</td>
</tr>
<tr>
<td>CPAP (–)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Opioid (–), nasal airway (+)</td>
<td>Acceptable</td>
<td>Desirable</td>
<td>Unnecessary</td>
</tr>
<tr>
<td>Opioid (–), nasal airway (–)</td>
<td>Not recommended</td>
<td>Not recommended</td>
<td>Desirable</td>
</tr>
<tr>
<td>Opioid (+)</td>
<td>Not recommended</td>
<td>Not recommended</td>
<td>Desirable</td>
</tr>
</tbody>
</table>

For example, postanesthesia care unit (PACU) or intensive care unit (ICU) management with cardiorespiratory monitoring is desirable and management in the ward is not recommended if the patient is unable to use continuous positive airway pressure (CPAP) and use of opioid is planned for postoperative analgesia.

The author thanks Sara Shimizu, M.D. (Head of the Department of Plastic Surgery, JFE Kawatetsu Chiba Hospital, Chiba, Japan), who greatly helped to improve the manuscript.

References

20. Watanabe T, Isono S, Tanaka A, Tazawa H, Nishino T: Contribution of
body habitus and craniofacial characteristics to segmental closing pressures of the passive pharynx in patients with sleep-disordered breathing. Am J Respir Crit Care Med 2009; 179:114–20
75. Nuckton TJ, Giddlen DV, Browner WS, Cramman DM: Physical examination...
should anaesthetists have to demonstrate that face mask ventilation is possible.

**Analysis:**

1. **Face Mask Ventilation:**
   - Face mask ventilation is a critical skill that anaesthetists must demonstrate. The text suggests that demonstrating the ability to perform face mask ventilation is essential for anaesthetists. This is supported by various studies, including one by ANESTHESIOLOGY (1999; 91:612–6) that discusses the comparison of maximal breathing and tidal volume breathing techniques.

2. **Obesity and Intubation:**
   - Obesity is recognized as a significant challenge in intubation, as highlighted in the text. Studies such as those by Desmonts JM (1998) and El-Khatib MF (1998) have shown that obesity increases the difficulty of intubation. The Mallampati classification is mentioned as a tool for predicting difficult laryngoscopy among obese patients. 

3. **Preoxygenation:**
   - Preoxygenation is crucial for patients, especially those who are morbidly obese. Studies like those by Liang Y, Kimball WR, Kacmarek RM, Zapol WM, Jiang Y (2008) support the importance of preoxygenation in these patients.

4. **Ventilatory Responses:**

5. **Carotid Body:**
   - The carotid body is a critical sensor that responds to changes in oxygen levels. The text references studies by Wyon N, Joensen H, Yamamoto Y, Lindahl SG, Eriksson LI (2004) that explore the role of the carotid body in respiratory responses.

6. **Respiratory Complications:**

**Conclusion:**

The text underscores the importance of demonstrating the ability to perform face mask ventilation and the need for careful consideration of obesity in intubation procedures. Preoxygenation is highlighted as a critical technique, and understanding ventilatory responses to hypoxia and hypercapnia is essential for effective care in morbidly obese patients. Carotid body responses to these conditions are also discussed, emphasizing the role of these sensors in respiratory regulation.


Fries Apparatus for Artificial Respiration

Swedish citizen K. A. E. Fries of Stockholm filed in 1911 for a U.S. Patent on his “Apparatus for Producing Artificial Respiration.” He hoped to resuscitate individuals “nearly drowned or suffocated by smoke, gas, or steam, or who for some other reason are in need of artificial respiration.” Patterned loosely after the supine method of Silvester, the Fries approach shifted the victim’s arm positions to exert “pressure on a proper part of the person’s chest.” Using the Fries Apparatus (as depicted above, from the Wood Library-Museum Archives) “one person, even an inexperienced one,” could “without exertion perform the same amount of work for a long time as two or more practiced persons . . . .” Granted in 1913, US Patent 1,057,633 mentioned that the Fries Apparatus might “also be used for gymnastic purposes.” (Copyright © the American Society of Anesthesiologists, Inc. This image appears in the Anesthesiology Reflections online collection available at www.anesthesiology.org.)

George S. Bause, M.D., M.P.H., Honorary Curator, ASA’s Wood Library-Museum of Anesthesiology, Park Ridge, Illinois, and Clinical Associate Professor, Case Western Reserve University, Cleveland, Ohio. UJYC@aol.com.