tape. Reading of P_{AW}, measured by a water manometer, was simultaneously recorded on the videotape.

Experimental Procedures

To determine the pressure-area relation of the pharynx, the anesthetic machine was disconnected from the nasal mask. The latter was in turn connected to a pressure-control system capable of accurately manipulating P_{AW} from +20 to −20 cm H_2O in a stepwise fashion. Cessation of mechanical ventilation resulted in apnea caused by complete muscle paralysis. P_{AW} was immediately increased up to 20 cm H_2O, dilating the airway. While the subject remained apneic for 2 to 3 min, P_{AW} was gradually reduced from 20 cm H_2O to a closing pressure (P'_{close}) of the retropalatal airway in a stepwise fashion. The latter represented the pressure at which complete closure of the retropalatal airway occurred, as evident on the video screen. In this experimental setting, the retroglossal P_{AW} was not reduced below the retropalatal P_{AW}. Spo_2 was maintained above 95% during the apneic tests. This procedure of experimentally induced apnea allowed construction of the pressure-area relation of the visualized pharyngeal segment. The subject was manually ventilated for at least 1 min before and after the apneic test. Distance between the tip of the endoscope and the narrowing site was measured with a wire passed through the aspiration channel of the endoscope. Measurements were made for the retropalatal and retroglossal airways with patients lying supine and sitting at a 62° angle. Care was taken to maintain the neutral neck position throughout the procedure, particularly when the patient was in the sitting position, although we did not measure the head angle. After measurements of the static pharyngeal mechanics, lung volume changes from the supine to the sitting position were measured with a spirometer connected to a tightly fitted full facemask at atmospheric pressure. Patent airway was maintained during the lung volume measurement by triple airway maneuver (mandible advancement, neck extension, and mouth opening) with the use of two hands. Airway opening and absence of mask leak were confirmed by progressive increase of spirometer tracing in response to the postural change.

Data Analysis

The technique and accuracy of conversion of the monitor pharyngeal image to an absolute value of cross-sectional area have been reported previously.[15,18] In short, magnification of the imaging system was estimated at 1.0-mm interval distances between the endoscopic tip and the object (1-cm^2 grid) in range of 5–30 mm, producing a relation between distance and pixels corresponding to 1 cm^2. At a defined value of P_{AW}, the image of the pharyngeal lumen was traced and counted pixels included in the area (SigmaScan version 2.0; Systat Software, Inc., San Jose, CA). The pixel number was converted to the pharyngeal cross-sectional area according to the distance-magnification relation. Using tubes of known diameter, we tested the accuracy of our cross-sectional area measurements.[15] For a constant distance, the measured areas were systematically deviated from actual areas. The largest known area tested (0.95 cm^2) was underestimated by 11% because of image deformation at outer image area, and the smallest known area tested (0.03 cm^2) was overestimated by 13% because of reduction in image resolution. The measured luminal cross-sectional area (A) was plotted as a function of P_{AW}. We defined P'_{close} as the pressure corresponding to the zero area. At high values of P_{AW}, relatively constant cross-sectional areas were revealed; therefore, maximum area (A_{max}) was determined as the mean value of the highest three P_{AW} (18, 19, and 20 cm H_2O). As reported previously,[12–16] the pressure-area relation of each pharyngeal segment was fitted by the following exponential function: $A = A_{max} - B \times \exp(K \times P_{AW})$, where B and K are constants. A nonlinear least-squares technique was used for the curve fitting, and the quality of the fitting was provided by coefficient r^2 (SigmaPlot version 2.0; Systat Software, Inc.). A regressional estimate of P'_{close}, which corresponds to an intercept of the curve on the P_{AW} axis, was calculated from the following equation for each pharyngeal segment: $P'_{close} = \ln(B/A_{max}) \times K^{-1}$. The shape of the pressure-area relation was described by the value of K. When the pressure-area relation is curvilinear, compliance of the pharynx, defined as a slope of the curve, varies with changes in P_{AW}. Therefore, a single value of compliance calculated for a given P_{AW} does not represent collapsibility of the pharynx for entire ranges of P_{AW}. By contrast, the K value represents a rate of changes in the slope of the curve. When the K value is high, small reduction of P_{AW} results in significant increase in compliance, leading to remarkable reduction in cross-sectional area. Accordingly, collapsibility of the pharynx increases with increasing K value. We suggest that both P'_{close} and K values represent collapsibility of the pharynx, whereby the former determines the position of the exponential curve and the latter characterizes the shape of the curve.

Statistical Analysis

Our study indicates that a maximum SD of our primary variable, the P'_{close} of patients with OSA, is 2.8 cm H_2O.[12] Neill *et al.*[11] found a difference of 4.3 cm H_2O of upper airway closing pressure between supine and sitting (30° upper body elevation). Because the effect of 62° upper body elevation was assessed in this study, we expected that the P'_{close} difference between the positions would be greater than 5 cm H_2O. Appropriate sample size was determined to be seven or more for detecting the difference assuming $\alpha = 0.05$ (two tailed) and 80% power (SigmaStat 3.1; Systat Software, Inc.). All values are expressed by median (10th–90th percentiles). Wilcoxon signed rank test was used for comparison of static mechanics variables between the supine and sitting positions (SigmaStat 3.1). Mann–Whitney rank sum test was used for comparison of the static mechanics variables between the pharyngeal segments. Spearman rank-order test was performed for correlation analyses between P'_{close} differences between the positions and anthropometric and sleep

Table 1. Anthropometric Characteristics and Results of Sleep Studies

Characteristics	Data
Age, yr	52.0 (43.6–57.8)
Weight, kg	76.0 (61.6–87.0)
Height, m	1.65 (1.59–1.79)
BMI, kg/m^2	27.9 (23.8–31.9)
ODI	47.5 (12.7–56.0)
CT_{90}, %	18.7 (3.8–45.2)
Nadir Spo_2, %	86.2 (76.0–89.5)
Lowest Spo_2, %	67.0 (33.8–75.0)
AHI, hr^{-1}	42.2 (9.6–78.5)
ΔLV, ml	330 (140–564)

Values are presented as median (10th–90th percentile). Polysomnogram for AHI measurements was performed in only 7 patients. AHI = apnea hypopnea index, defined as number of apnea and hypopnea per hour of sleep; BMI = body mass index; CT_{90} = percentage of time spent with Spo_2 less than 90%; ΔLV = lung volume change in response to the position change from the supine to the sitting position; Lowest Spo_2 = a lowest Spo_2 value among the desaturation events; ODI = oxygen desaturation index, defined as number of desaturations exceeding greater than 4% per hour of monitoring; Spo_2 = oxygen saturation measured by pulse oximetry.

study data (SigmaStat 3.1). *P* less than 0.05 (two-tailed) was considered significant.

Results

Endoscopic measurements of static pressure–area relations of the retropalatal and retroglossal airways were successfully performed in both the supine and sitting positions in all patients. As listed in table 1, anthropometric characteristics and sleep study data varied among the patients with OSA. Median values of these variables indicate that they were middle-aged, overweight patients with moderate to severe OSA.

Figure 2 shows representative endoscopic pharyngeal images during step P_{AW} changes in one patient, clearly demonstrating that the sitting position significantly increased the cross-sectional area for a given P_{AW} at both retropalatal and retroglossal airways compared with the supine position. Table 2 summarizes changes in the static mechanic variables of the retropalatal and retroglossal airways of the patients in the supine and sitting positions. As indicated by relatively high r^2 values, the exponential function fitted reasonably well the measured pressure-area relations. Change from the supine to the sitting position significantly increased median A_{max} from 1.25 to 1.91 cm^2 at the retropalatal airway and from 1.75 to 2.42 cm^2 at the retroglossal airway. The K values representing stiffness of the pharyngeal airway were not statistically different in the positions. The position change significantly decreased median P'_{close} from 2.20 to −3.47 cm H_2O at the retropalatal airway and from 2.67 to −5.31 cm H_2O at the retroglossal airway. The P'_{close} values in the sitting position were below atmospheric pressure in all patients, whereas those in the supine position were above the atmospheric pressure (fig. 3). Median differences of the P'_{close} between the

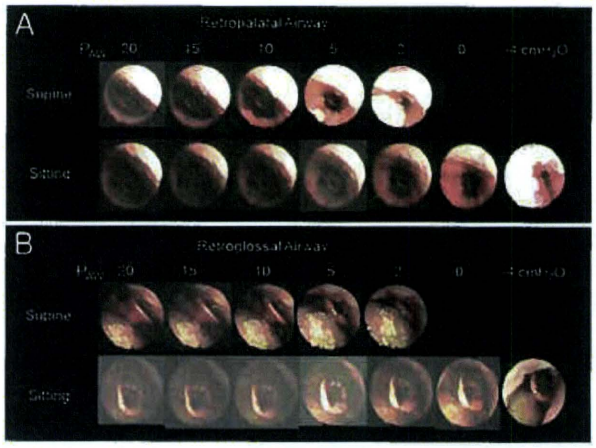

Fig. 2. Series of endoscopic images of retropalatal (*A*) and retroglossal (*B*) airways during supine and sitting postures at various airway pressures (P_{AW}) in a patient with obstructive sleep apnea. Note that the cross-sectional area significantly increased for a given airway pressure at both retropalatal retroglossal airways.

positions are 5.89 (3.73–11.6) cm H_2O and 6.74 (4.16–9.87) cm H_2O at retropalatal and retroglossal airways, respectively, and were not different in the pharyngeal segments. Median lung volume increase in response to the position change from the supine to the sitting position was 330 (140–564) ml.

Table 3 presents results of Spearman correlation analyses between P'_{close} position differences and lung volume change

Table 2. Static Mechanics of the Retropalatal and the Retroglossal Airways in Supine and Sitting Positions

	Supine	Sitting
Retropalatal airway		
A_{max}, cm^2	1.25 (0.65–1.97)	1.91 (1.52–3.40)**
B	1.74 (0.88–7.06)	1.17 (0.68–1.92)*
K	0.16 (0.11–0.22)	0.18 (0.09–0.26)
r^2	0.95 (0.92–0.97)	0.97 (0.92–0.99)
P'_{close}, cm H_2O	2.20 (0.84–6.12)	−3.47 (−8.51–−1.32)**
Retroglossal airway		
A_{max}, cm^2	1.75 (0.47–2.35)	2.42 (1.72–3.84)*
B	1.84 (1.20–3.70)	1.01 (0.65–2.19)**
K	0.21 (0.15–0.26)	0.15 (0.12–0.23)
r^2	0.97 (0.91–0.99)	0.97 (0.83–0.99)
P'_{close}, cm H_2O	2.67 (−2.22–5.02)	−5.31 (−9.70–−1.60)**

Values are presented as median (10th–90th percentile). Quality of the fit is provided by coefficient r^2.

$A = A_{max} - B \times \exp(-K \times P_{AW})$, where A and P_{AW} denote cross-sectional area of the pharyngeal airway and airway pressure; A_{max} = maximum cross-sectional area; B = constant obtained by fitting the pressure-area relationship of each pharyngeal airway to an exponential function; K = constant obtained by fitting the pressure-area relationship of each pharyngeal airway to an exponential function; P'_{close} = estimated closing pressure calculated by $\ln(B/A_{max})K^{-1}$ *, ** = $P < 0.05$, 0.01 *vs.* supine position, respectively.

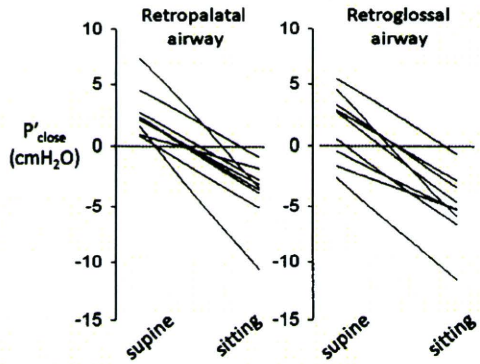

Fig. 3. Changes of closing pressures (P'_{close}) at the level of retropalatal and retroglossal airways in response to postural change from supine to sitting. Each line represents a different subject. Note that the P'_{close} at both pharyngeal segments decreased below the atmospheric pressure during sitting position in all patients with obstructive sleep apnea.

during the position change, anthropometric, and sleep study variables. We found no significant association or tendency of indirect association between the lung volume and the P'_{close} changes. Interestingly, influences of sitting position on retropalatal airway collapsibility were smaller in patients with more severe obstructive sleep apnea. No correlation was found at the retroglossal airway.

Discussion

We found that the postural change from supine to sitting enlarged both retropalatal and retroglossal airways and decreased P'_{close} at both pharyngeal segments by approximately 6 cm H_2O in completely paralyzed and anesthetized patients with OSA. The results clearly demonstrate that structural properties of the passive pharynx improve while patients are in the sitting posture.

Table 3. Results of Spearman Correlation Analyses between P'_{close} Difference in the Supine and Sitting Positions, and Lung Volume Change during the Position Change, Anthropometric, and Sleep Study Variables

	P'_{close} Difference	
	Retropalatal	Retroglossal
Lung volume change	−0.650	−0.317
Age	0.151	0.077
BMI	0.267	0.000
ODI	−0.900*	−0.650
AHI	−0.786*	−0.607

Values are correlation coefficients.

* $P < 0.05$.

AHI = apnea hypopnea index, defined as number of apnea and hypopnea per hour of sleep; BMI = body mass index; ODI = oxygen desaturation index, defined as number of desaturations exceeding greater than 4% per hour of monitoring.

Mechanisms of Pharyngeal Airway Patency Improvement during Sitting Position

Our results agree with the previous studies examining influences of sitting posture on pharyngeal collapsibility.[11,19] Using nasal occlusion technique, Neill *et al.*[11] found improvement of upper airway closing pressure from 0.3 ± 2.4 cm H_2O (supine) to −4.0 ± 3.2 cm H_2O (30° head elevation) in sleeping patients with OSA. By measuring pressure-flow relationship in non-OSA subjects under midazolam sedation, Ikeda *et al.*[19] found significant reduction of the critical closing pressure from −8.2 ± 5.2 cm H_2O (supine) to −13.3 ± 4.9 cm H_2O (30° head elevation). These studies did not assess pharyngeal segments responding to the postural changes, and the neuromuscular factors were not controlled in their experimental conditions. Although our study does not completely address the mechanisms by which sitting posture improves pharyngeal airway patency, we have confirmed the results of the previous studies and evidenced significant contribution of structural factors to the mechanisms by eliminating the neuromuscular factors. We consider two possible structural mechanisms that operate near pharyngeal airway (local structural mechanism) and from a distance (structural mechanism from a distance) for development of pharyngeal obstruction.[1]

Patients with OSA have significantly larger soft tissue volume surrounding the pharyngeal airway for a given maxillomandibular enclosure size, resulting in upper airway anatomical imbalance.[20,21] The soft tissues are not uniformly distributed within the maxillomandibular enclosure. The larger mass of the soft tissues, such as the tongue, anteriorly overrides on the pharyngeal airway wall while the patient is in the supine posture. In addition, the excessive anterior soft tissues are able to be displaced through the submandible region.[22,23] Accordingly, postural changes of direction of gravity acting on the soft tissues may significantly influence the anatomical balance.[24] In fact, we previously demonstrated that lateral posture significantly improved pharyngeal airway patency.[14] As illustrated in figure 4, a relatively larger vector of gravity perpendicular to the airway in the supine posture is divided into perpendicular and vertical components in the sitting posture. The perpendicular component of the gravity decreases during sitting posture and effective mass acting on the airway possibly decreases, possibly improving upper airway anatomical balance. In addition, gravity vertical to the airway created during sitting posture may displace the anterior soft tissue out of the maxillomandibular enclosure through the submandible region, improving anatomical imbalance. This longitudinal gravity may also increase longitudinal tension of the pharyngeal airway wall, stiffening the airway. In fact, Tsuiki *et al.* found significant elongation of the pharyngeal airway during the postural change from supine to sitting.[9] Furthermore, the postural change significantly alters venous blood distribution, decreasing total soft tissue volume inside the maxillomandibular enclosure. Redolfi *et al.*[25] recently demonstrated importance of fluid

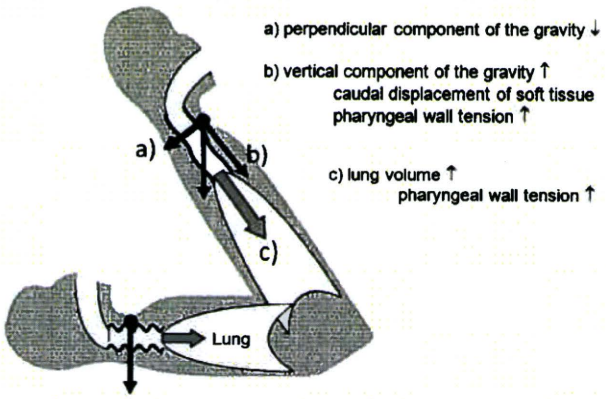

Fig. 4. A schema explaining possible mechanisms for improvement of pharyngeal airway patency during sitting posture. The detailed explanation is under Discussion (Mechanisms of Pharyngeal Airway Patency Improvement during Sitting Position).

distribution on the pharyngeal airway maintenance. Pae *et al.*[7] reported significant reduction of the tongue volume during the sitting posture supporting this possibility. These are speculative with little evidence and need to be tested in the future studies.

Recent studies suggest significant involvement of lung volume changes in development of OSA. Heinzer *et al.*[26] demonstrated that a 0.77-l lung volume increase during sleep in obese patients with OSA decreased the apnea hypopnea index by approximately half. Our group found significant reduction of retropalatal P'_{close} in response to 0.7-l lung volume increase in anesthetized and paralyzed patients with OSA.[13] Direct association between P'_{close} improvement and body mass index suggested greater lung volume dependence in obese patients with OSA. Therefore, in this study, we measured lung volume change from supine to sitting posture to examine potential contribution of the lung volume to the observed P'_{close} change as an alternative structural mechanism operating at a distance from the pharyngeal airway. However, we failed to find significant association between the P'_{close} improvement and lung volume changes in response to the postural change. This may not necessarily mean that the lung volume mechanism is unimportant in the postural improvement of the pharyngeal airway patency. Only one OSA patient with body mass index greater than 30 kg/m^2 was included in this study, and his lung volume increased by only 100 ml during sitting posture. The absolute lung volume changes in this study were unexpectedly small compared with those in previous studies, possibly because of a different degree of head elevation and positioning of the lower legs.[27] In particular, the total number of subjects tested in this study (n = 9) is small; therefore, the absence of a relation between the P'_{close} improvement and lung volume changes should be cautiously interpreted. Future studies need to examine contribution of the lung volume to postural changes of pharyngeal collapsibility in morbidly obese patients with OSA.

Clinical Implications

Induction of general anesthesia places patients at risk for both respiratory and circulatory derangements. The supine posture with the head in the sniffing position is a current standard for anesthesia induction. Compared with the supine posture, head-up posture significantly prolonged the apnea tolerance period in obese patients.[28] Valenza *et al.*[27] clearly demonstrated that the beach chair position and application of positive end expiratory pressure improved lung mechanics and oxygenation in obese patients. This study further demonstrated significant increase of the pharyngeal airway size and improvement of pharyngeal collapsibility in patients with OSA. It is noteworthy that the sitting posture successfully reduced the pharyngeal closing pressure below the atmospheric pressure in all patients with OSA, indicating that the sitting posture is the most effective mechanical intervention among the other postural interventions.[29] Taken together, respiratory function during anesthesia induction is best maintained by placing the patient in sitting posture with the head in the sniffing position while applying positive end expiratory pressure and the triple airway maneuver with two hands.[30] Despite these respiratory advantages, the sitting posture potentially decreases cerebral blood flow as a result of induced hypotension.[31,32] Accordingly, the beneficial effects of the sitting posture during anesthesia induction must be weighed against hemodynamic derangements particularly in patients with OSA with cardiovascular comorbidities, and the patient should be returned to the supine posture immediately after successful placement of a endotracheal tube.

In conclusion, postural change from supine to sitting significantly enlarged pharyngeal cross-sectional area and decreased closing pressures at both retropalatal and retroglossal airways in anesthetized and paralyzed patients with obstructive sleep apnea. Sitting may be an advantageous posture compared with supine posture during induction of anesthesia in these patients for airway maintenance. The possible value of the sitting position during general anesthesia induction should be investigated further in obese patients with OSA.

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JA SYMPOSIUM

Dyspnea and its interaction with pain

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Definition of dyspnea

A wide range of respiratory sensations such as shown in Table 1 can be sensed by humans. Among these respiratory sensations, the last three sensations, i.e., chest tightness, work/effort sensation, and respiratory discomfort (air hunger), are the main sensations that constitute the sensation of "dyspnea." Although dyspnea is often defined as an uncomfortable sensation of breathing, this definition is too simple to understand the precise mechanisms of dyspnea. According to the definition proposed by the American Thoracic Society [1], dyspnea is a term used to characterize a subjective experience of breathing discomfort that consists of qualitatively distinct sensations which vary in intensity. This broad definition may contribute to the better understanding of mechanisms of dyspnea and improvement of therapeutic approaches to dyspnea. Although it is the primary symptom of many diseases of the respiratory systems, dyspnea can also arise in other forms of diseases such as those affecting cardiovascular or neuromuscular systems. Dyspnea is commonly observed in several clinical settings such as cancer, chronic obstructive pulmonary disease, and cardiac failure, and it is not rare for anesthesiologists to take care of these patients in the operating room, intensive care unit, or palliative care unit.

Sensory infrastructure of the respiratory system

Assuming that dyspnea is generated through the sensory infrastructure of the respiratory system (Fig. 1), stimulation of sensory receptors in the respiratory system is the natural starting point of the generation and modulation of dyspnea. Several sensory receptors in the respiratory system such as shown in Table 2 are considered to be responsible for generation and modulation of dyspneic sensation. These receptors play significant role in the control of breathing. The control of breathing consists of three controls, namely, chemical control, neural control, and behavioral control, and the stimulation of sensory receptors in the respiratory system contributes to all three controls. In other words, control of the breathing system is associated with the generation and modulation of dyspnea through activation of sensory receptors in the respiratory system.

Measurements of dyspnea

Dyspnea may be evaluated by assessing the functional impairment caused by dyspnea associated with daily

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Table 1 Different types of respiratory sensation

Respiratory sensations
Respiratory motion
Lung position
Irritation
Urge to cough
Pain
Chest tightness
Work/effort sensation
Respiratory discomfort (air hunger)

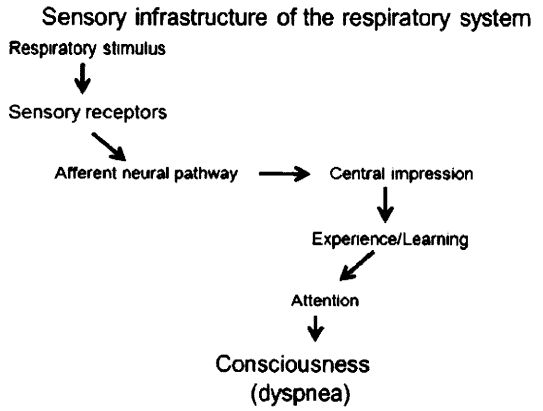

Fig. 1 Sensory infrastructure of the respiratory system

Table 2 Receptors responsible for generation and modulation of dyspnea

1. Vagal receptors (irritant, pulmonary stretch, C-fiber)
2. Chemoreceptors (peripheral, central)
3. Muscle and tendon receptors
4. Upper airway receptors
5. Central corollary discharge receptors

activities of life, because the dyspneic patient is frequently unable to perform the daily activities of life as a result of discomfort associated with breathing. A simple scale that can be used to measure functional dyspnea was originally developed by Fletcher [2], who first published a five-point scale. Similar categorical scales such as the Medical Research Council (MRC) scale [3] and the oxygen cost diagram (CD) [4] have been used clinically for many years, but these scales have the notable drawback of lacking clear limits between grades. Nevertheless, evaluation of dyspnea using this type of scale is useful. For example, Boushy et al. [5] found that grades of preoperative dyspnea correlated with postoperative survival. Similarly, Mittman [6] reported that an increased risk of death after thoracic surgery from 8% in patients without dyspnea to 56% in patients who were dyspneic.

The visual analogue scale (VAS) and the modified Borg scale [7] are the most commonly used scales in clinical dyspnea research. Patients or subjects rate their dyspnea intensity on a scale from 0 to 10 where 0 represents 'no discomfort at all' and 10 represents 'the worst discomfort imaginable.' The VAS consists of a 100-mm horizontal or vertical line anchored at one end by a label such as 'no discomfort' and the other end by a level such as 'intolerable discomfort.' The Borg scale is a 10-point category-ratio scale with verbal expressions of severity anchored to specific numbers. The reliability and validity of the VAS and the Borg scale as a measure of dyspnea have been reported [8]. However, the use of single-dimensional tools such as VAS may incur the strong risk of oversimplifying assessment of the dyspnea problem. Considering that dyspnea, similar to pain, is a multidimensional subjective experience, the use of multidimensional tools for assessment of dyspnea seems to be more appropriate than the use of unidimensional tools. However, the multidimensional nature of dyspnea is seldom recognized in measurement methods, and existing measurement instruments have not been adequate to address this problem. Recently, Banzett et al. [9] introduced the first multidimensional dyspnea profile (MDP), an instrument under development in their laboratory, for evaluation of experimentally induced dyspnea. Their results demonstrated that the MDP was sufficiently sensitive and specific to show clear differences in sensory qualities with different stimuli, suggesting that the clinical use of MDP for measuring the multiple dimensions of dyspnea may be promising.

Motor commandafferent mismatch

According to the recent theory of dyspnea, dyspnea is the result of a mismatch or a dissociation between motor command and incoming afferent information from sensory receptors. Campbell and Howell [10] proposed the concept of length–tension inappropriateness of the respiratory muscles as the cause of dyspnea. The term length refers to the change in lung volume whereas tension refers to the respiratory muscle tension required to produce that change. The importance of respiratory muscle contraction in genesis of dyspnea was supported by the breath-holding experiments of Campbell et al. [11] who reported that totally paralyzed normal subjects had no sensation comparable to breath-holding even when the apnea lasted for 4 min. However, several studies [12, 13] have shown that the contractile activity of respiratory muscles is not essential to generation of dyspnea. For example, Banzett et al. [13] examined changes in air hunger sensation following the addition of CO_2 to inhalation during total neuromuscular blockade in the presence of adequate

ventilation, concluding that respiratory muscle contraction is not important in the genesis of air hunger evoked by hypercapnia. The original hypothesis of Campbell and Howell was expanded by Schwartzstein et al. [14], who incorporated the concept that dyspnea is the result of a dissociation between the ventilatory drive and the degree of ventilation produced. In other words, by using the afferent feedback from peripheral sensory receptors, the brain can assess the effectiveness of the motor commands issued to the ventilatory muscles. This dissociation between neural activity and consequent mechanical or ventilatory outputs has also been termed neuromechanical dissociation [15]. Experimental and clinical data are consistent with the concept of neuromechanical dissociation [15–17]. Thus, when the matching between motor command and incoming afferent information from sensory receptors is appropriate, no dyspnea occurs or the intensity of dyspnea should be minimum (Fig. 2). In contrast, when the matching between motor command and incoming afferent information is inappropriate, the resultant neuromechanical dissociation can cause dyspnea or intensify the sensation of dyspnea.

Similarity of pain and dyspnea

Although dyspnea and pain are distinctly different sensations, dyspnea shares many clinical, physiological, and psychological features with pain [1]. Considering the analogies between pain and dyspnea, it is quite conceivable that there may be some neurophysiological link between pain and dyspnea. There is much evidence to show that dyspnea activates several distinct areas in the brain cortex such as the anterior right insula, the cerebellar vermis, the amyglada, the anterior cingulated cortex, and the posterior cingulated cortex [18–21]. These brain areas are similarly activated by pain and other unpleasant sensations. For example, a variety of painful stimulations produce strong insular activation [22–24], and a similar area can be activated during nausea [25] and during thirst [26]. The thalamus appear to be the pivotal part of the pathway relaying pain and dyspnea, and thalamocortical projections to the specific cortical regions seem to be common to both pain and dyspnea. However, this does not necessarily mean that dyspnea and pain activate identical neural structures or that they share identical neural pathways.

Interaction between pain and dyspnea

Pain and dyspnea are frequently coexistent in many clinical situations, and there is some evidence to suggest a causal association between pain and dyspnea. Because dyspnea shares many clinical, physiological, and psychological features with pain, it is quite conceivable that the two symptoms can interact with one another. However, the interaction between dyspnea and pain has not been fully explored, and information about the interaction between the two symptoms is apparently insufficient. In a previous study [27], it has been shown that pain produced a small but consistent increase in dyspneic sensation whereas dyspnea caused either no effect on pain or even a slight attenuation in pain. The explanation for the finding that pain augments the dyspneic sensation is that pain stimulus increases ventilatory drive and thereby may cause an increase in the sense

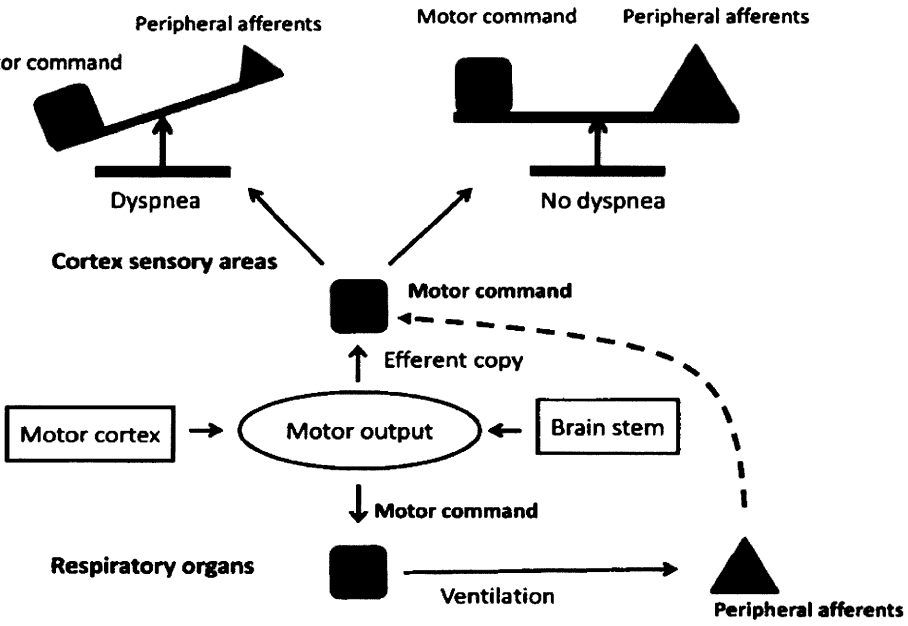

Fig. 2 The concept of motor command–afferent mismatch

of dyspnea. This explanation coincides with the concept of the motor command theory that dyspnea is closely related to the intensity of inspiratory effort yielded by the central motor output. A recent neurophysiological study by Morélot-Panzini and co-workers [28] showed that experimentally induced dyspnea can inhibit the spinal nociceptive flexion reflex. It is likely that that dyspnea, similar to pain, might induce counterirritation, causing a C-fiber stimulation, and thereby might trigger endogenous analgesic mechanisms at the subcortical level through the activation of diffuse noxious inhibitory descending controls (DNICs) [29].

Sex difference in interaction between pain and dyspnea

It has been reported that the DNIC is less sensitive in females than in males [30]. Sex difference in pain sensitivity has been a major topic of pain research and, compared with males, females report less tolerance of nociceptive stimuli [31]. In contrast, although women with COPD appear to experience dyspnea more frequently than men after adjusting for smoking burden and lung function [32], there is no clear evidence to show that sex difference exists in dyspnea. Considering the sex difference in pain sensitivity, it is possible that there may be a sex difference in the interaction between dyspnea and pain. In our recent study, we demonstrated that a sex difference exists in the responses of thermal pain threshold to dyspnea in healthy young subjects [33]. Thus, dyspnea causes an increase in thermal pain threshold in male subjects whereas thermal pain threshold does not change appreciably in female subjects, indicating that there is a difference in pain response between male and female. This sex difference in the inhibitory influence of dyspnea on pain sensation may in part be explained by the difference in the sensitivity of DNICs between males and females [30]. Detailed analysis of the relationship between maximal negative airway pressure and changes in thermal pain threshold revealed that an increase in negative airway pressure causes a progressive increase in thermal pain threshold only in males. Because negative airway pressure probably reflects the increased activity of respiratory muscles as a consequence of heightened ventilatory demand, response to the heightened activity of respiratory muscles may be a crucial factor that causes the sex difference in thermal pain threshold.

Effects of different types of dyspnea on pain perception

Although dyspnea consists of qualitatively distinct sensations, whether different types of dyspnea differently interact with pain has not been fully examined. The sensation of work/effort increases when muscle load is increased. Thus, work/effort stimulus may activate C-fibers in the respiratory system, which in turn activates DNICs. Chest tightness may stimulate C-fiber as well as vagal irritant receptors through bronchoconstriction. In contrast, air hunger may not stimulate C-fibers in the respiratory system. Therefore, it is possible that air hunger would have little or no effect in producing analgesia, compared with the effects of work/effort and chest tightness. We examined whether different forms of dyspnea exert a different effect on pain. Our results experiment showed that both air hunger and work/effort cause a similar degree of pain inhibition (Fig. 3). The inhibition of pain during air hunger may not be explained exclusively by the mechanisms of DNICs because air hunger stimulus may not activate C-fibers in the respiratory system, and without C-fiber stimulation DNICs may not be activated. Rather, it is likely that additional networks located in the limbic/paralimbic system and subcortical structures contribute to pain inhibition during air hunger. In fact, there is much evidence that several brain areas such as the anterior cingulate cortex, insular cortex, and amygdala, which are activated by air hunger, have descending projections to the midbrain and brainstem, specifically to the periaqueductal gray

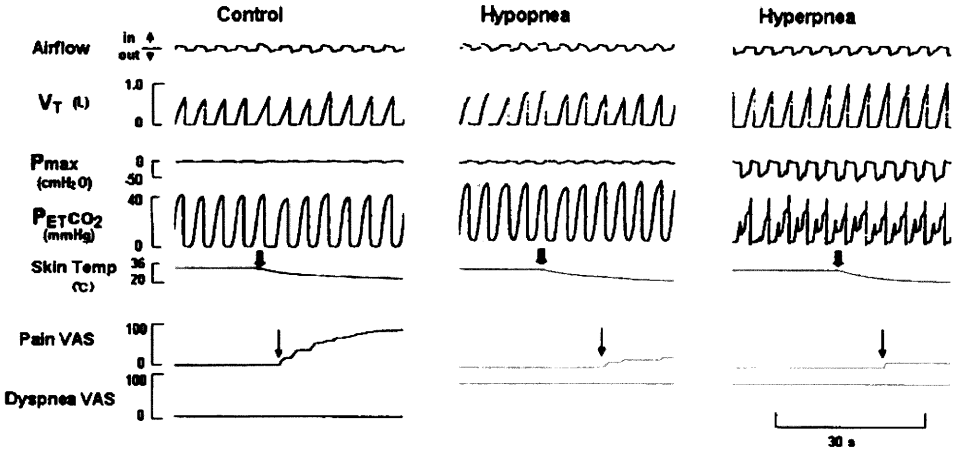

Fig. 3 Effects of air hunger and work/effort on pain threshold. Pain was induced by a cold pressure test, and pain threshold time was measured. Hypopnea and hyperpnea caused air hunger and work/effort sensation, respectively. Note that both air hunger and work/effort caused prolongation of pain threshold time and a slower rise in pain visual analogue score (VAS) than that of the control response, indicating an inhibition of pain

matter (PAG) and the rostral ventromedial medulla (RVM) [34, 35]. It is quite likely that activation of corticolimbic areas by air hunger is capable of producing descending inhibition of spinal nociceptive activity through connection to the PAG and RVM, causing an analgesic effect.

In conclusion, dyspnea seems to activate not only DNICs but also corticolimbic inhibitory controls, thus causing analgesia.

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麻酔管理に役立つ呼吸生理

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麻酔管理に役立つ呼吸生理

西野　卓*

キーワード：呼吸生理，呼吸調節，呼吸メカニックス，ガス交換，低酸素血症

■ はじめに

ヒトは酸素を用いた好気性代謝によって生命を維持しているが，そのためには大気中の酸素を生体内に摂取し，生体内の二酸化炭素を大気中へ排出するガス交換が不可欠である。このようなガス交換は肺を中心とした呼吸器系を介して換気という形で行われているが，手術中には麻酔薬や手術の影響によって正常なガス交換機能が低下し，生体内部環境に負荷がかかる。このようなガス交換機能の低下を理解するためには，呼吸運動を制御する部分，すなわち呼吸調節機構とガス交換を担う部分すなわち呼吸器の基本的な生理を理解することが必要となる。本項では臨床症例を通して，これらの問題について，考えてみることにする。

1 呼吸調節系のしくみ

◉ 症例 1

69 歳，男性，身長 163 cm，体重 60 kg

局所麻酔下で眼科手術中に不穏状態となる。外回り医師がミダゾラム 2 mg を静注したところ，呼吸が停止し，チアノーゼ状態となった。

このような症例に遭遇した場合，自発呼吸がどのような機序で維持されることを理解していれば，なぜ呼吸が停止したかを比較的容易に理解することができる。自発呼吸の維持にもっとも重要な役割を果たしているのが，呼吸化学調節機構である。この機構は呼吸中枢がその出力を介して肺換気を生み出し，その結果生じた血液ガス変化を化学受容器が感知し，化学受容器からの情報によって呼吸中枢活動が制御されるという調節系である。この調節系の最大の特徴はネガティブフィードバックが働き，血液ガスが一定に保たれることである。この系が正常に働く場合，血液ガス中の P_{CO_2} と換気はほぼ直線的な関係があり，P_{CO_2} 上昇に比例して換気が増大する。この関係を示すものを CO_2 換気応答曲線と呼んでいる。また，血液ガス中の P_{O_2} と換気の関係は P_{CO_2} を一定とした状態では双曲線様の関係となり，これを低酸素換気応答曲線と呼ぶ。症例 1 の場合，ミダゾラム投与前に正常な呼吸状態であったと仮定すると，図 1-a の a 点に位置していたはずである。ミダゾラム投与により突然呼吸が停止したので a 点は b 点に移動し，その後時間経過とともに血液中の P_{CO_2} の上昇があるが，換気は抑制されたままで c 点に留まっている状態となっている。本来は CO_2 換気応答曲線上を P_{CO_2} 上昇に伴って d 点まで動くはずである。呼吸停止中も体内の酸素は消費され，肺胞でのガス分圧は CO_2 の分圧のみが上昇し，低酸素が発生する。低酸素応答曲線（図 1-b）から，低酸素が発生しても換気亢進は起こらず，換気はミダゾラム投与前の a 点から投与後の c 点に移動している。すなわち，症例 1 で起きたことは，薬物による呼吸化学調節系の強い抑制が自発呼吸を極度に抑制し，その結果，肺胞内の酸素濃度低下が発生したと理解できる。

◉ 症例 2

30 歳，女性

ペインクリニックの外来待合室で突然不安になり，息苦しさが出現すると同時に過呼吸状態となり，やがて四肢のしびれ感が出現した。近くにいた医師が紙袋を取り出し，袋の中でゆっくり呼吸をするようにアドバイスしたところ，症状は落ち着き，過呼吸は治まった。

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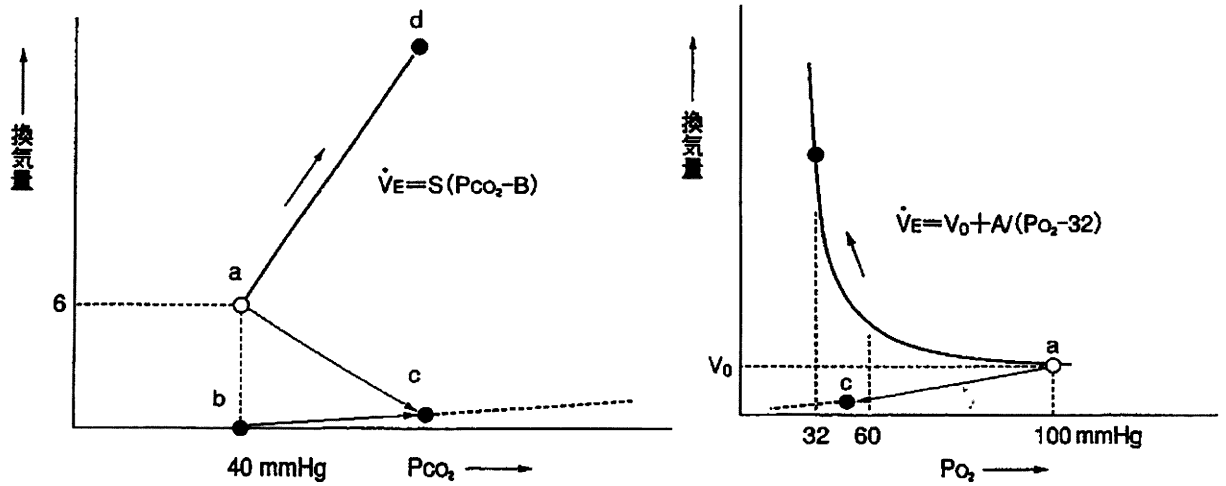


(a) CO_2換気応答曲線　　(b) 低酸素換気応答曲線

図 1　CO_2 換気応答曲線と低酸素換気応答曲線

CO_2 換気応答曲線（a）はほぼ直線で表すことができ，低酸素換気応答曲線（b）は双曲線で表すことができる。

この症例はいうまでもなく，過換気症候群と呼ばれている病状を表すものであり，不安や感情など大脳皮質で発生する神経活動が呼吸中枢活動を活性化する一つの例である。このような高位中枢が呼吸を制御する系は行動性調節系と呼ばれており，泣いたり笑ったりする場合の呼吸や意識の存在が呼吸維持に関与する場合に主な役割を果たすと考えられている。

◉ 症例 3

57 歳，男性

直腸内視鏡検査を鎮静下で行うため，ミダゾラム 2 mg を静注した。検査中に少し嘔吐し咳き込んだ。その後過換気状態となったが，チアノーゼが認められた。酸素吸入によっても低酸素状態は改善せず，努力性呼吸となり，Sp_{O_2}は 70%となった。ただちに気管挿管，補助呼吸を行ったが，換気には強い力を要した。

この症例では症例 1 のような薬物による呼吸抑制は発生していない。しかし，咳反射が出現しており，また誤嚥が発生したことも経過から明らかである。呼吸生理学の見地からは咳反射がどのような機序で発生するのかが重要であり，また，誤嚥がどうして発生してしまったのかを明らかにすることも重要である。咳は吸気後に爆発的な呼気活動を示す特殊な呼吸運動であり，通常は気道粘膜の刺激で発生する呼吸反射である[1]。咳反射は誤嚥防止の役割を果たす重要な反射の一つであるが，咳反射のみで誤嚥を防止することはできない。咳反射，呼気反射，喉頭閉鎖反射，無呼吸反射，嚥下反射など一連の反射を気道防御反射と呼び，これらの反射が協調して機能することで誤嚥が防止されている[2]。このような反射は迅速性が必要とされ，このような反射を制御している系を神経調節系と呼んでいる。

以上の 3 症例は呼吸調節系の働きを示したもので，これらの症例から，呼吸調節系には①化学調節系，②行動調節系，③神経調節系の 3 つの系から成り立っていることが理解できる。これらの調節系の中心に立つのは延髄に存在する呼吸中枢である（図 2）。さて，症例 3 で低酸素状態がなぜ発生したかについて考えてみたい。この症例は自発呼吸は過呼吸状態であり，低酸素血症の原因が呼吸化学調節系抑制にあるとは考えにくい。むしろ，低酸素血症の原因は呼吸器の異常すなわち肺機能の異常にあると考えるほうが自然である。このような呼吸調節系の異常に原因を求めることができない低酸素発生は，ガス交換を担う部分すなわち呼吸器に異常が存在する可能性がある。そこで，呼吸器の機能を理解する必要性が出てくる。

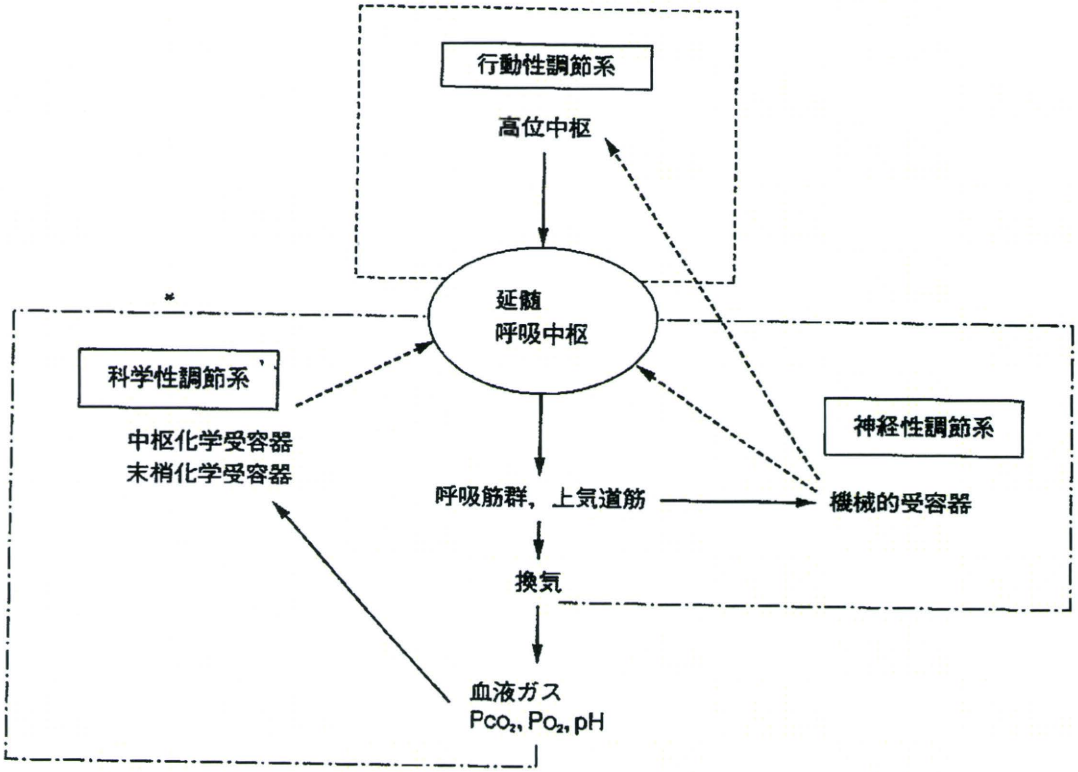


図 2　呼吸調節系の模式図

2 呼吸器機能の基礎知識

呼吸器機能を理解するにあたって，基本的に理解しておくべきポイントを表に示した。

表　肺機能生理の基礎知識

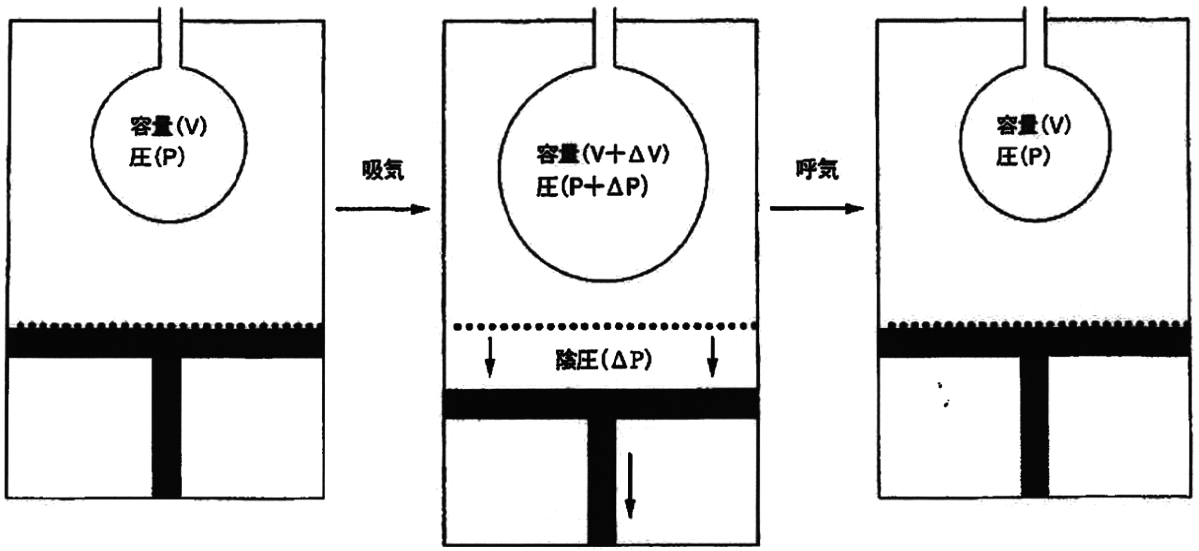
A．解剖-胸郭の構成
B．コンプライアンスと気道抵抗
C．不均等換気
　a．重力の影響
　b．換気/血流比
　c．シャントと死腔
D．呼吸筋の特徴

1）解剖-胸郭の構成

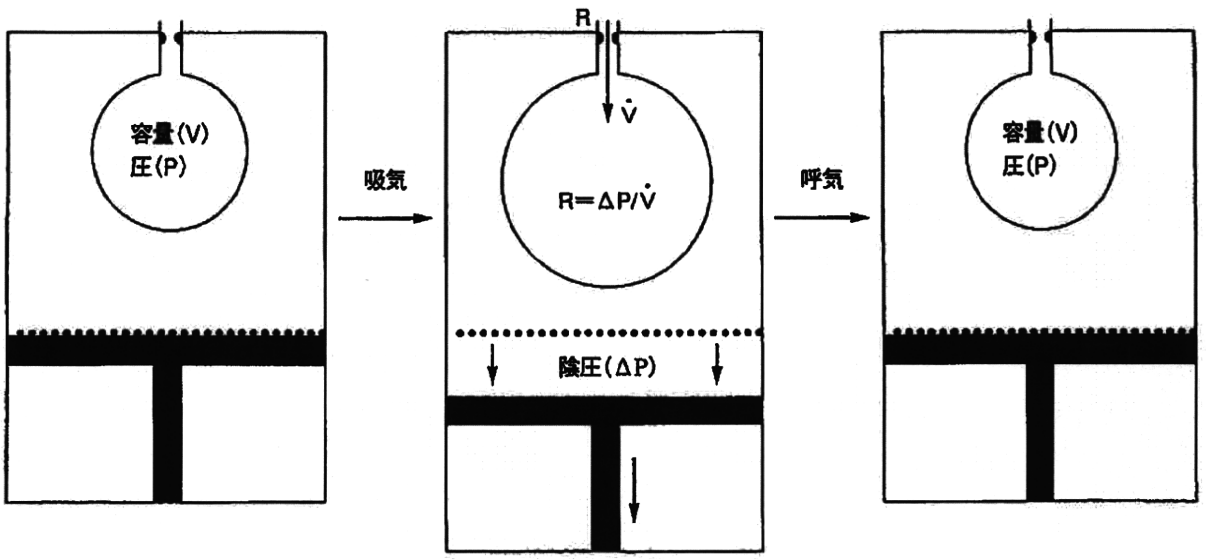
胸郭を一つの容器と考えると，その容器の中に肺が存在することになる（図 3）。胸壁も肺も弾性に富み，バネとしての性質をもっている。呼吸器系の安静呼気位は肺気量分画の機能的残気量位になるが，そのレベルで胸壁は外側に広がろうとする力を示し，肺は縮もうとする力が働き，ちょうど釣り合った状態である。したがって，胸壁に穴が開けば，肺は瞬間的に縮み，胸郭は外方に膨張する。また，胸膜部は陰圧となっている。

2）コンプライアンスと気道抵抗

肺は弾性に富み，外力を加えることで膨張し，外力を取り去れば元の形に戻る性質がある（図 3）。肺容量の変化を考える場合，肺は気道と肺胞から成り立つことを常に念頭に置かなければならない。ここで，加える外力を ΔP としてその外力で膨張する肺容量を ΔV とすると，ΔV と ΔP の比すなわち ΔV/ΔP は肺コンプライアンスと呼ばれ，肺の軟かさを示す一つの指標となっている（図 3-a）。肺コンプライアンスは量と圧の関係であり，時間的要素は含まれていない。一方，外力によって肺を膨張させる場合，肺は流入するガス容量によって膨張の程度が決まる。流入するガス容量すなわち流量は単位時間あたりの量変化であり，ガスが流れる際の流量（$\dot{V}$），圧力（ΔP），抵抗（R）には $R=\Delta P/\dot{V}$ の関係がある。したがって，圧が一定で抵抗が増加すれば流量は減少し，抵抗はガスの流れにくさを表す指標となる。ときどき，



(a) コンプライアンスの測定



(b) 気道抵抗の測定

図 3　コンプライアンスと気道抵抗

臨床では“肺が硬くなる”という表現がなされることがあるが，これは肺コンプライアンスが低下した場合と気道抵抗が上昇した場合の両方の可能性を意味し，これだけではその原因が肺胞にあるのか気道にあるかは識別できない。

3) 不均等換気

肺胞とその入口の気道は肺の基本的ユニットと考えられるが，肺内に存在する肺胞は決して均一ではない。たとえば，気道は少し狭いがコンプライアンスの高い肺胞もあれば，気道は広いがコンプライアンスの低い肺胞もある。また，気道が広く，コンプライアンスの高い肺胞や逆に気道が狭く，コンプライアンスの低い肺胞もある。そのため，肺内には大きさの異なる肺胞が存在し，それぞれの肺胞の換気量も異なることになる。異なる大きさの肺胞が連結している場合，肺胞を球体と考えるとラプラスの定理（P=2T/R）が応用できる（図 4）。ここで，P は肺胞内圧，T は表面張力，R は半径である。仮に異なる大きさの肺胞の表面張力が同じとすると，小さい肺胞の内圧は大きな

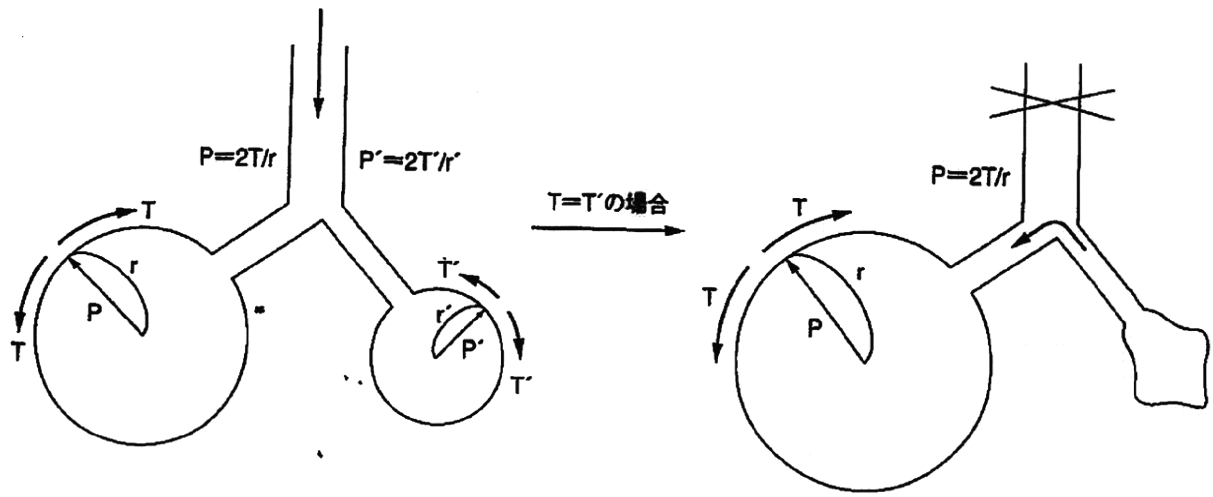


図 4　肺胞へのラプラスの法則の応用

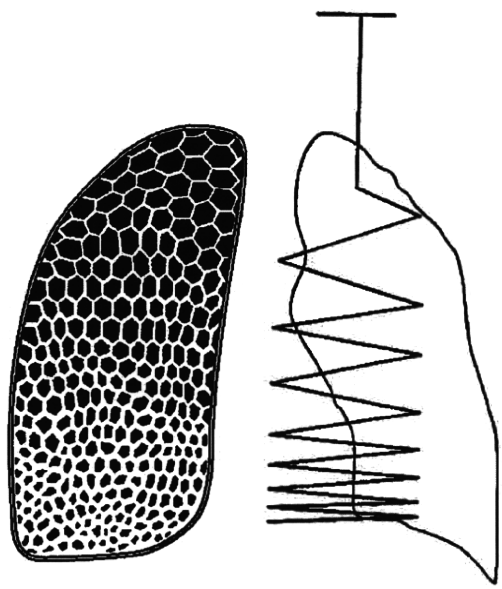


図 5　肺への重力の影響

肺胞より大きくなり，圧の高いほうから低いほうにガスが流れ，小さい肺胞はますます小さくなり，最終的には虚脱してしまうことになる。しかし，生体にはこのような不都合を避けるための機序が備わっている。すなわち，表面張力を下げる物質サーファクタントが肺胞内面に存在し，この物質が小さい肺胞の表面張力をより低く保つように働き，肺胞虚脱を防止しているのである。感染などによる肺障害が存在する場合，サーファクタント分泌の障害が発生し，肺胞が虚脱しやすい状態になり，不均等換気が発生することは容易に想像できる。

(a) 重力の影響

病的な状態がなくとも不均等換気は存在し，そのもっとも大きな原因は重力の影響である。重力は立位ならば肺尖部から肺底部に，仰臥位ならば肺上部から下部にかけて働き，肺をバネ秤に例えれば，垂直方向の上部ではバネは開いた状態，下部ではバネが比較的閉じた状態である（図 5）。これを肺胞に置き換えれば，肺上部では肺胞が開いた状態で，下部では比較的閉じた状態となる。換気量の変化は肺上部では少なく，肺下部では比較的大きいことになる。病的状態による不均等換気を臨床的に検出する方法の一つとして，クロージングボリューム（closing volume）を測定する方法がある。これは，最大吸気位から徐々に呼気を行った場合に最初に肺胞が虚脱する点での肺容量と残気量との差を指している。また，クロージングボリュームに残気量を加えたものはクロージングキャパシティ（closing capacity）と呼ばれている。クロージングキャパシティと機能的残気量（functional residual capacity：FRC）の関係は臨床的に重要であり，FRC レベルがクロージングキャパシティよりも大きければ通常の呼吸で虚脱している肺胞はないことを意味し，逆に FRC レベルがクロージングキャパシティよりも小さい場合には，通常の呼吸でも虚脱している肺胞が存在することを意味している[3]。

(b) 換気/血流比

換気不均等が重力によって生じると同様に，肺

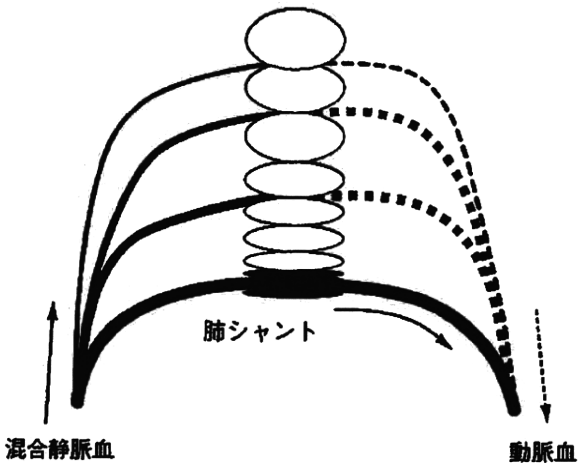


図 6　肺シャントの模式図

内血流も重力の影響を受けて肺内血流不均等が生じる。すなわち，肺上部の血流量は少なく，肺下部の血流量は比較的多いことになる。しかも，重力の影響は換気量への影響よりも強い。また，肺循環は低圧系で肺血管壁は薄く，受動的な血管拡張や重力，肺血管周囲圧の影響を受けやすい。肺血管抵抗は肺容量が FRC のときに最小となる。肺容量が FRC よりも大きくなると，伸展した肺胞壁が肺胞毛細血管を圧迫し血流抵抗は増大する。一方，肺容量が FRC より減少すれば，肺胞以外の比較的太い血管が肺収縮によって圧迫され，やはり血管抵抗が増す。肺循環の特徴は肺胞内毛細血管レベルにおいて，血管の開存が肺動脈圧，肺静脈圧，肺胞内圧のバランスによって規定されることである。肺胞とその肺胞に接する肺血管を一つの単位と考え，肺胞の換気量（$\dot{V}$）と換気量（$\dot{Q}$）の比が 1 ならば，これはガス交換には理想的である。一方，$\dot{V}/\dot{Q}$ 比が 1 よりも大きければ，肺胞を流れる以上の換気が存在し，ガス交換に関与しない換気が存在することを意味している[4]。逆に，$\dot{V}/\dot{Q}$ 比が 1 より小さければ，ガス交換に関与しない血流が存在することを意味している。このような，$\dot{V}/\dot{Q}$ 比の考え方は肺の部分あるいは肺全体にも当てはまる。たとえば，立位での肺尖部位では換気に比較して肺血液量は少なく，$\dot{V}/\dot{Q}$ 比は 1 以下であり，相対的にガス交換に関与しない換気が多いことを意味している。一方，$\dot{V}/\dot{Q}$ 比が 1 以上の肺底部では，相対的にガス交換に関与しない肺血液量が多いことを意味している。

(c) シャントと死腔

$\dot{V}/\dot{Q}$ 比が 0 となる場合は換気されない肺胞に血流が流れ，混合静脈血はそのまま肺胞を去ることになり，これを肺シャントと呼んでいる（図 6）。肺シャントは正常状態でも存在するが，病的状態での肺シャントは無気肺で肺胞が虚脱した場合や肺胞と血管床との間に拡散障害などが存在する場合に発生する。後者の場合，換気がガス交換に関与できない場合であり，これを死腔換気という。肺全体のシャントの程度はシャント率で表現することができる。この場合，肺血流量を Q_T，シャント血流量を Q_S，肺毛細管血の酸素含有量を Cc'_{O_2}，動脈血酸素含有量を Ca_{O_2}，静脈血酸素含有量を CV_{O_2} とするとシャント率は $\frac{Q_S}{Q_T}=\frac{Cc'_{O_2}-Ca_{O_2}}{Cc'_{O_2}-CV_{O_2}}$ と表現できる。臨床的にはシャント簡易計算図を用いれば，比較的簡単にシャント率を求めることができる。また，100% 酸素を吸入させた場合，$\frac{Q_S}{Q_T}=\frac{0.003\ (P_{A_{O_2}}-Pa_{O_2})}{0.003\ (P_{A_{O_2}}-Pa_{O_2})+(Ca_{O_2}-CV_{O_2})}$ の簡易式から容易にシャント率を計算できる。

4) 呼吸筋の特徴

横隔膜および肋間筋は主呼吸筋であり，換気に際してポンプとしての機能を果たしている。呼吸筋には骨格筋と同様に長さ-張力関係が認められ，静止長に応じて張力が変化する。肺容量が増えると静止長は減少するので，呼吸筋の収縮力は低下する。また，ドーム型をした横隔膜の場合，肺容量の増加に伴い横隔膜は平らな状態となり，収縮力低下が助長することになる（図 7）。

◉ 症例 4

48 歳，女性，身長 158 cm，体重 145 kg，体型指数（BMI）46

子宮筋腫のため全身麻酔下で手術予定。純酸素吸入 Sp_{O_2} 98% の状態下でプロポフォールで麻酔導入すると同時に Sp_{O_2} は 95% に低下した。筋弛緩投与後に気管挿管し，過換気としたが Sp_{O_2} の改善は認められなかった（血液ガス値：pH 7.48，Pc_{O_2} 30 mmHg，Pa_{O_2} 70 mmHg，FI_{O_2} 1.0）であった。しかしここで，呼気終末陽圧（positive end-

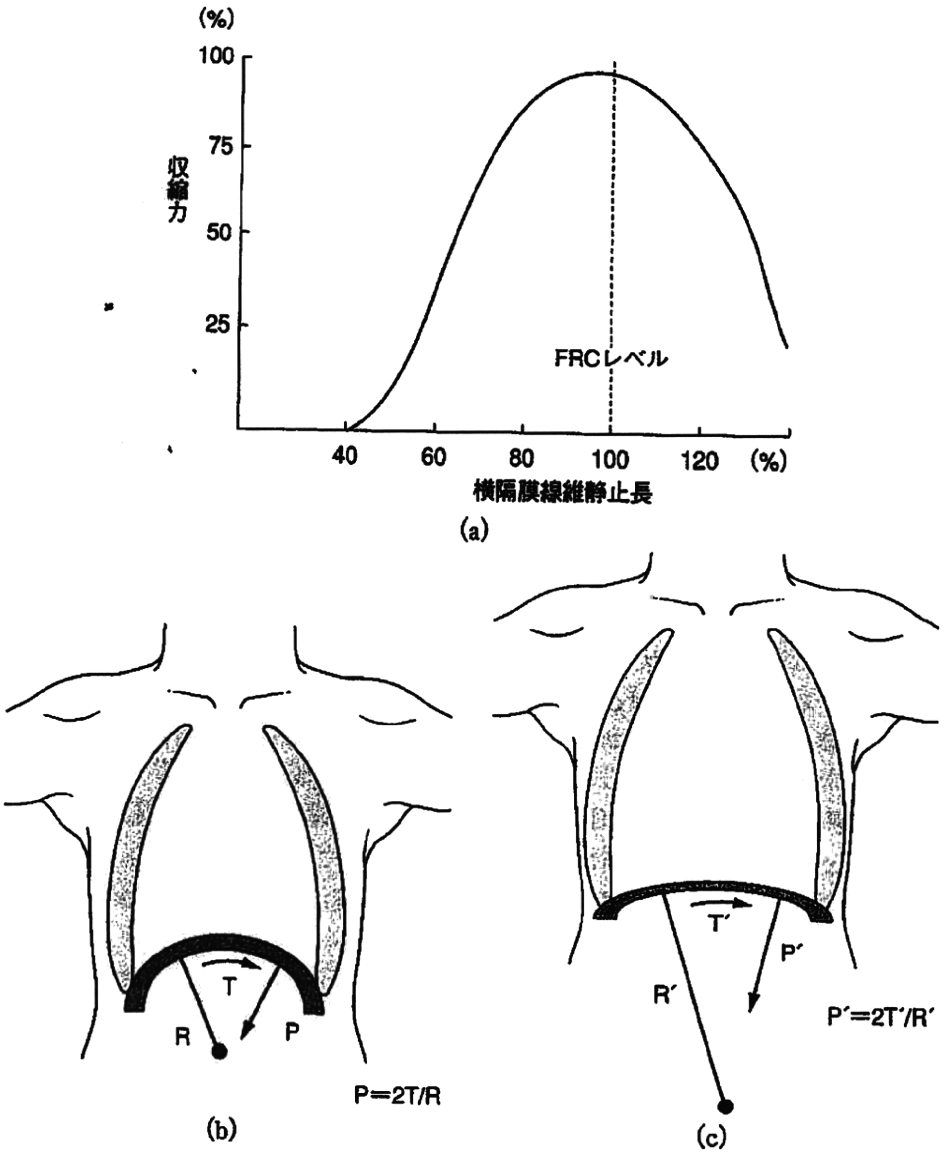


図 7　横隔膜の長さ-張力関係

expiratory pressure：PEEP）を施行すると Sp_{O_2}は劇的に改善した。

この症例は，肥満症例に発生する低酸素血症のもっとも典型的なものである。このような症例で考慮すべき問題は①体位，②麻酔の影響，③FRC とクロージングキャパシティの関係である[5]。まず，FRC は体位の影響を受け，立位や坐位に比べて仰臥位では著しく低下する。次に，仰臥位で麻酔を導入すると，胸壁の緊張が低下すると同時に，腹部側から胸腔側への横隔膜の押し上げがあり，FRC の著しい低下が発生する[6]。FRC の低下に伴い，FRC がクロージングキャパシティを下回ると，安静状態での肺容量では無気肺となる部分が出現し，肺シャントが増加し，低酸素が出現する。PEEP の施行は FRC の増加をもたらし，FRC がクロージングキャパシティを超えるようになれば，無気肺は消失し，酸素化は改善する（図 8）。クロージングキャパシティは年齢の影響を受け，仰臥位では 50 歳前後で FRC がクロージングキャパシティを超えるようになる[7]。

◉ 症例 5

4 歳，男児

鼠径ヘルニア手術のため，セボフルラン緩徐導入法で麻酔を導入した。導入後 3 分でシーソー呼

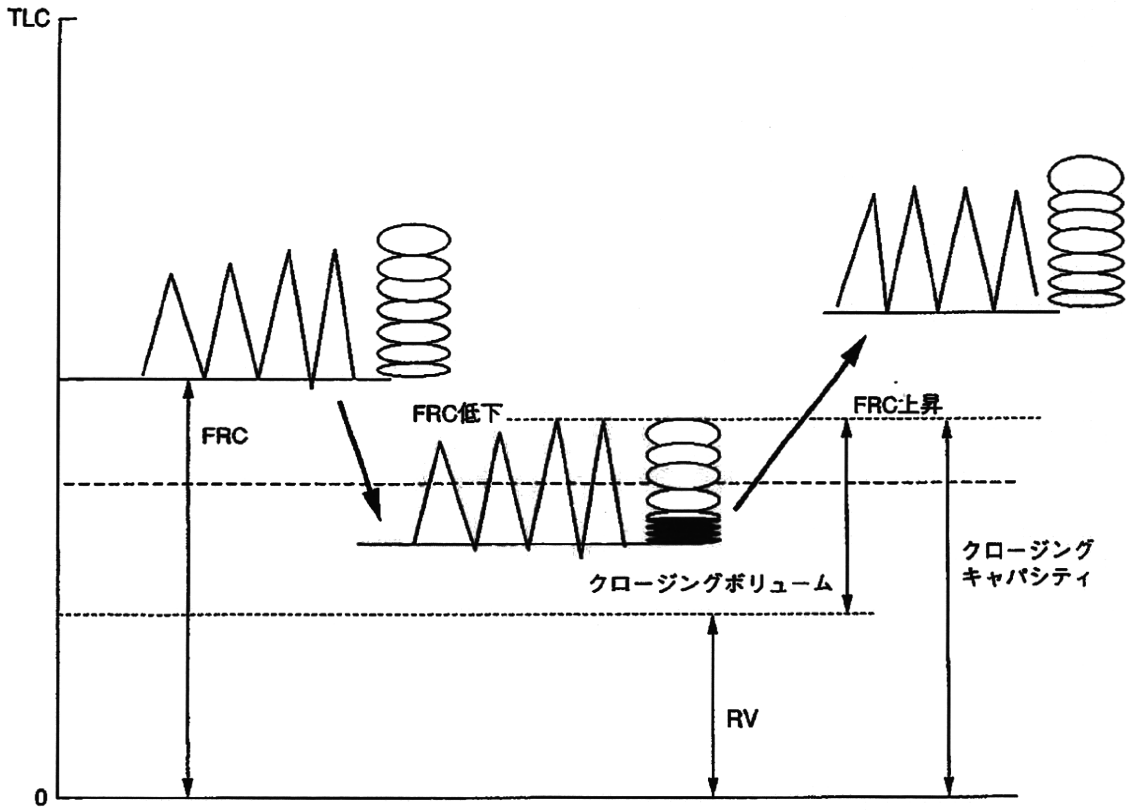


図 8　FRC とクロージングキャパシティの関係

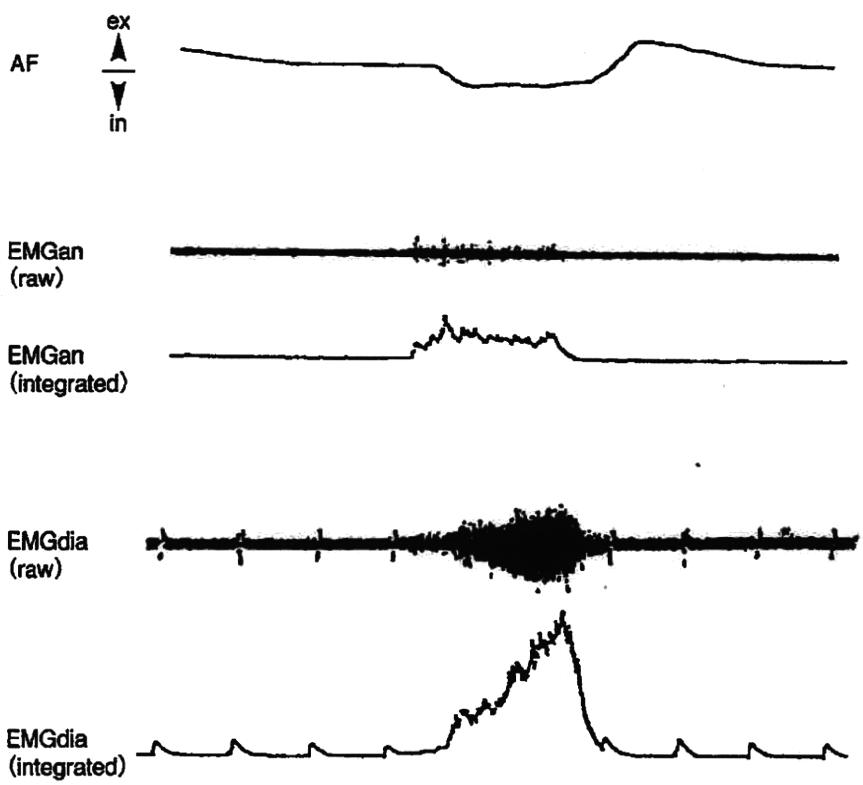


図 9　上気道筋と呼吸筋の収縮のタイミング

吸状態となり，チアノーゼが出現した。ただちに気管挿管したが，奇異性呼吸は改善しなかった。

ヒトの呼吸系には，スムーズな換気をもたらすためのいくつかの仕組みが備わっている。その中で呼吸筋の協調性は特に重要な問題である。体外から新鮮ガスを取り入れる場合，ガスは上気道，下気道を経て肺胞に到達するが，その原動力は呼吸筋による陰圧発生のポンプ機能である。大きな陰圧の発生は上気道系を虚脱状態にするため，上気道系にはこれに対抗する必要がある。たとえば，上気道保持に上気道筋群が律動的に収縮するが，そのタイミングは横隔膜収縮よりも先行する（図9）。また，その収縮は主呼吸筋の収縮に伴って発生する上気道内の陰圧に十分拮抗するくらい強力である。別のいい方をすれば，覚醒状態では呼吸筋収縮によって発生する圧力と上気道筋群収縮によって発生する圧力との力のバランスで上気道保持が維持されている。当然ながら，これらの力のバランスは麻酔の影響を受ける。一般的に，麻酔は横隔膜より上気道筋群を選択的に抑制し，麻酔時には上気道の閉鎖が生じやすい状態になっている。また，小児では麻酔時には肋間筋活動が横隔膜活動に比較して，より強い抑制を受けることが報告されており，小児症例で認められる上気道確保後の奇異呼吸の原因は麻酔による選択的肋間筋抑制によると考えられる。

◉ 症例 6

45 歳，男性，身長 170 cm，体重 62 kg

胃癌の手術後，硬膜外除痛法が不十分で疼痛を訴えている。十分な深呼吸ができず，血液ガス値は低酸素を認めた。

手術が呼吸機能に大きな影響を与えることに疑う余地はない。手術による呼吸機能への影響として，① 術後疼痛，② 術操作による呼吸筋への損傷，③ 反射性呼吸筋活動抑制が考えられる[8]。一般的に胸部手術や腹部手術では呼吸機能障害が発生しやすく，FRC の低下や肺活量の低下が認められている。また，上腹部と下腹部の比較では，上腹部手術の影響のほうがはるかに強いことが示されている[9]。さらに，手術の影響は年齢によっても左右され，高齢者ほど手術の影響を強く受ける。

◉ 症例 7

63 歳，男性，身長 168 cm，体重 63 kg

直腸穿孔による汎発性腹膜炎で緊急手術が行われた。術後，筋弛緩からの回復が悪いため人工呼吸管理（V_T 500 ml，RF 10・min^{-1}）となった。術直後の血液ガス分析でやや呼吸性アシドーシス（pH 7.30，Pa_{CO_2} 50 mmHg，Pa_{O_2} 100 mmHg，$F_{I_{O_2}}$ 0.4）を認めたため，1 回換気量を増加した（V_T 800 ml）。6 時間後に急激に酸素化が悪化（Pa_{O_2} 60 mmHg，$F_{I_{O_2}}$ 0.4）し，胸部単純 X 線写真で両側に浸潤影が見られ急性呼吸促迫症候群（acute respiratory distress syndrome：ARDS）と診断された。

術後呼吸不全の原因はさまざまではあるが，医原性肺損傷は明らかにこれを増悪化させる。医原性肺損傷の主な原因は肺胞の過膨張と虚脱-拡張の繰り返し（shear stress）である。上述の症例では血液ガス値を正常化しようとして，1 回換気量を増加させたが，このような処置により肺胞の一部は過膨張状態となり，肺障害が拡大し，結果的には ARDS 発生を促した症例と思われる。このような肺障害発生を防止するために，人工呼吸管理において圧-肺容量曲線と気道再開通の関係については十分理解しておく必要がある。

■ ま と め

酸素を利用した好気的代謝は，肺を中心とした“呼吸”によって大気から酸素を取り入れ，代謝の結果生じた二酸化炭素を大気中に排出することで維持されている。この維持には呼吸調節（ソフト）と呼吸器（ハード）が正常に働くことが必要である。周術期には生体にさまざまに侵襲が加わり，正常な呼吸が影響を受けることが多い。周術期に発生する呼吸不全は換気障害と酸素化障害に分類されることが多いが，大まかに前者は呼吸調節の異常，後者は呼吸器の異常ととらえることもできる。呼吸器系の病態および患者管理には呼吸の基本的な“仕組み”を理解することが必要である。

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