

Original

Comparison Between Proportional-Assist Ventilation and Pressure Support Ventilation as Assessed by Measurement of Thoracic and Abdominal Expansibility

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We compared the level of assistance for spontaneous inspiration between proportional-assist ventilation load-adjustable gain factors (PAV+) and pressure support ventilation (PSV) in patients who received assisted mechanical ventilation in the intensive care unit. We measured thoracic and abdominal expansibility waveforms during each mode of ventilation to understand the difference in the assistance level. The study group comprised 8 patients who underwent assisted ventilation for at least 24 hours. After patients underwent PSV for 12 to 24 hours, the expansibility of the chest and abdomen was assessed, and blood gas analyses were performed. Patients were then switched to the PAV+ for 12 to 24 hours, and the same measurements were performed. The difference in the time from the start of inspiration to peak inspiratory distension was expressed as the phase angles (one respiratory cycle = 360 degrees). Compared with during PSV (100%), PAV increased the expansibility of the chest and abdomen significantly ($112.0 \pm 2.7\%$ and $118.0 \pm 3.7\%$, respectively, $p < 0.0001$). During PAV+, the expansibility of the abdomen was significantly greater than that of the chest ($p < 0.005$). The time taken to peak inspiration was shorter during PAV+ than during PSV (7.6 ± 3.6 degrees shorter for the chest, $p = 0.004$ and 12.2 ± 2.7 degrees shorter for the abdomen, $p = 0.002$). These indicate enhanced motion of the diaphragm by PAV+, which could be a promising ventilatory mode to promote patients to recovery from respiratory failure.

Key Words: proportional assist ventilation, breathing pattern, thoracic and abdominal expansibility, patient-ventilator synchrony

Introduction

Among various modes available for assisted mechanical ventilation, pressure support ventilation (PSV) is widely used¹. In this mode, the ventilator, once triggered by the patient effort, provides a pre-set level of constant pressure until a cycling-off criterion is reached. Proportional-assist ventilation (PAV) mechanically assists the inspiratory flow and volume by amplifying the patients' own spontaneous efforts to breathe². The PAV is characterized by larger variance in respiratory rate and tidal volume than PSV. PAV has been reported to improve patient-ventilator synchrony, as compared with

PSV³⁻¹³. However, few studies have examined how breathing patterns are improved during PAV¹².

PAV with load-adjustable gain factors (PAV+) is a new mode designed to support spontaneous breathing that is based on the original concept for PAV² and further refined¹³. Respiratory resistance¹⁴ and elastance¹⁵ are measured once every 4 to 10 breaths to determine a ventilatory support level that optimally amplifies the patient effort, and the pressure delivered is adjusted according to the measured changes in flow and volume.

With PAV+, the work of breathing (joules/l) can be calculated on the basis of the pressure generated

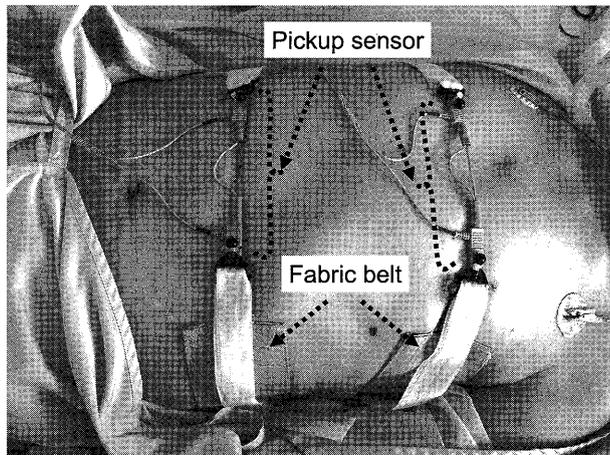


Fig. 1 Measured sites (sites applies sensors)

The measured sites (sites applies sensors) were the axillary line (mid-breast line) for the chest and about 10 cm above the umbilicus for the abdomen (the midpoint between the inferior margin of the sternum and the umbilicus, where diaphragmatic movement is most easily detected).

by the inspiratory muscles (P_{mus} , inspiratory effort) and ventilator-delivered pressure¹³. For assistance in determining the optimal support level, the total work of breathing and the patient's work of breathing can be monitored on the "work of breathing" bar. The work of breathing during spontaneous breathing in healthy subjects has been reported to be 0.3 to 0.7 joules/ l^{16} . The support level should be set so that the patient's work of breathing is within this range, thereby maximizing respiratory comfort.

In the present study, we noninvasively and in real time measured and analyzed motion waveforms of the chest and abdomen during assisted ventilation with PSV and PAV+ in patients, who underwent assisted ventilation in the intensive care unit, to clarify how patient-ventilator synchrony improves the breathing pattern and thus the assist level. Comparison of the two separate motion waveforms can provide direct and clear information on the difference of the patient-ventilator synchrony in ventilation support. We discuss the origin of differences in the recorded waveforms.

Methods

The study group comprised 8 patients who underwent assisted ventilation for at least 24 hours in the intensive care unit. The study was approved by

the Research and Ethics Committee of Tokyo Women's Medical University. All patients or their families provided written informed consent. A Puritan Bennett® 840 Ventilator System (Covidien Co., Ltd., CO, USA) equipped with a PAV+ software option was used for mechanical ventilation. The initial ventilation was pressure-assist control mode in patients who could make the transition to spontaneous breathing.

The level of positive end-expiratory pressure (PEEP) was determined on the basis of the point of maximum static compliance derived from a low flow inflation-deflation curve, in which the lung is largely expanded (i.e., the alveoli are assumed to be expanded) in response to the smallest change in pressure^{16)~19)}. When switching to spontaneous breathing, a recruitment maneuver^{16)~18)} was performed (three consecutive inflation with 55 cm H₂O applied for 1.5 to 2.5 seconds) to confirm that the lung was appropriately expanded as evaluated by a pressure-volume (PV) curve. The PAV support level was set at 50% or 60% of the estimated work of breathing. The PSV pressure level was set so that the expiratory tidal volume or peak airway pressure were equivalent to the values obtained at the PAV support level.

To measure the expansibility of the chest and abdomen and the time to peak inspiratory distension, we used an electroencephalograph equipped with respiratory analysis function (EEG-9100, Nihon Kohden Co., Ltd., Tokyo, Japan) and a respiratory pickup sensor, an accessory that can detect ventilatory patterns (TR-751T, Nihon Kohden Co., Ltd.). To monitor the movement of the chest and abdomen, a fabric belt able to transmit stretch-related motion was connected to the sensor and was then tightly attached to the body surface. The sensor is made of electroconductive rubber. Changes in the movement of the chest and abdomen during ventilation were detected as resistance changes of the rubber sensor and depicted as waveforms. Within the measured range of the sensor expansion, the resistance change is proportional to the circumference change. As shown in Fig. 1, the measured sites (sites applies sensors) were the axillary line (mid-

Table 1 Demographic characteristics of patients

Patient (no.)	Sex (M/F)	Age (years)	Diagnosis	Main treatments
1	M	44	Subarachnoid hemorrhage	Open head clipping
2	M	72	Esophagus cancer, Pleural adhesion due to pyothorax	Esophagus resection
3	M	74	Cerebral bleeding	Removal of cerebral hematoma
4	M	78	Guillain-Barre syndrome	γ -globulin therapy
5	M	55	Esophagus cancer, pulmonary emphysema	Esophagus resection
6	F	46	Ovarian tumor, Liver cirrhosis, Interstitial pneumonia	Adnexectomy
7	M	66	Esophagus cancer	Esophagus resection
8	M	61	Cerebral infarction	Intracranial decompression

Table 2 Expiratory tidal volume and arterial blood gas analysis

Patient (no.)	T _{Ve} (ml)		pH		PaCO ₂ (mmHg)		PaO ₂ (mmHg)	
	PSV	PAV+	PSV	PAV+	PSV	PAV+	PSV	PAV+
1	480	430	7.53	7.52	33	27	132	167
2	410	450	7.48	7.49	36	29	146	118
3	410	480	7.48	7.43	35	41	97	105
4	400	380	7.48	7.45	34	42	145	101
5	820	820	7.4	7.48	43	42	126	133
6	480	490	7.48	7.41	42	44	157	91
7	780	790	7.42		39		95	
8	450	480	7.42		38		96	

T_{Ve}: expiratory tidal volume

PAV+: proportional-assist ventilation load-adjustable gain factors

PSV: pressure support ventilation

PaCO₂: arterial partial pressure of carbon dioxide arterial

PaO₂: partial pressure of oxygen

breast line) for the chest and about 10 cm above the umbilicus for the abdomen (the mid-point between the inferior margin of the sternum and the umbilicus, where diaphragmatic movement is most easily detected). Changes in the external circumference of the body trunk were expressed as expansibility. The time from the start of inspiration to the peak of inspiratory distension was measured. The start of inspiration is defined as a minimum point of each expansibility waveform.

The protocol for the ventilation mode was as follows. After patients underwent PSV for 12 to 24 hours, the respiratory rate, tidal volume, arterial blood gas values, and the expansibility of the chest and abdomen were examined. Patients were then switched to PAV+. After 12 to 24 hours, similar analyses were performed. Before each ventilatory mode, a recruitment maneuver was performed (55 cm H₂O for 1.5 to 2.5 seconds x 3 consecutive times)¹⁷⁻¹⁹.

The mean expansibility of the chest and abdomen

was calculated from 5 consecutive, stable breaths. The expansibility during PSV was regarded as 100%. The expansibility during PAV+ was expressed as the relative change as compared with the value during PSV. The time from the start of inspiration to peak inspiratory distension was expressed as the phase angle, given that one respiratory cycle was as 360 degrees, thereby allowing data on patients with different respiratory cycles to be quantitatively compared.

For statistical analysis, Spearman's rank correlation was used to analyze respiratory rate, tidal volume, and arterial blood gas values during PSV and PAV+. The Wilcoxon signed-rank test was used to analyze the expansibility of the chest and abdomen and the time from the start of inspiration to peak of inspiratory distension. The non-paired t-test and Mann-Whitney U test were used to compare changes in the expansibility of the chest and changes in the expansibility of the abdomen during PAV+. All data are expressed as means \pm standard

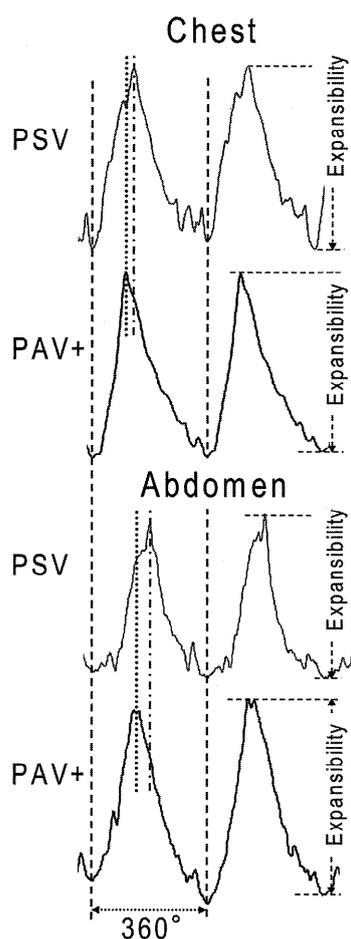


Fig. 2 Waveforms of the changes in the movement of the chest and abdomen during PAV+ and PSV

error. P values of less than 0.05 were considered to indicate statistical significance.

Results

Table 1 shows demographic characteristics of patients, including sex, age, diagnosis, and main treatments. PAV+ was applied at a ventilation support level of 50% to 60% and a PEEP of 10.1 ± 1.0 cm H₂O. PSV was applied at a ventilation support level of 3 to 7 cm H₂O and a PEEP of 10.1 ± 1.0 cm H₂O. Inspired oxygen concentration was between 30 and 40% in the both methods. The mean respiratory rate was 15.5 ± 2.5 breaths per minute during PAV+ and 15.5 ± 2.2 breaths per minute during PSV. The mean expiratory tidal volume was 540.0 ± 59.2 mL during PAV+ and 528.7 ± 60.3 mL during PSV. The results of arterial blood gas analysis during PAV+ were as follows: pH, 7.46 ± 0.02 ; arterial partial pressure of carbon dioxide (PaCO₂), 37.5 ± 3.0 mmHg; and arterial partial pressure of oxygen

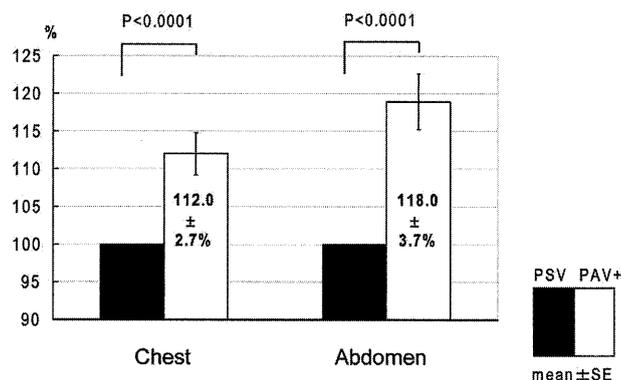


Fig. 3 Changes in the thoracic expansibility and the abdominal expansibility during PAV+ and PSV. Means \pm standard error (SE) are given.

(PaO₂), 119.1 ± 11.3 mmHg. During PSV, the respective values were as follows: pH, 7.46 ± 0.02 ; PaCO₂, 37.5 ± 1.3 mmHg; and PaO₂, 124.1 ± 8.9 mmHg. The respiratory rate, tidal volume, and arterial blood gas values did not differ between the groups. Table 2 shows the expiratory tidal volume and the results of arterial blood gas analysis in individual patients. Arterial blood gas analysis was not performed during PAV+ in Patients 7 or 8.

Figure 2 shows the waveforms of the changes in the movement of the chest and abdomen during PAV+ and PSV. When the expansibility of the chest during PSV was regarded as 100%, the expansibility of the chest during PAV+ ($112.0\% \pm 2.7\%$) significantly increased ($p < 0.0001$; Fig. 3). When the expansibility of the abdomen during PSV was regarded as 100%, the expansibility of the abdomen during PAV+ ($118.0\% \pm 3.7\%$) also significantly increased ($p < 0.0001$; Fig. 3). During PAV+, the expansibility of the abdomen was significantly greater than the expansibility of the chest ($p < 0.005$). This finding indicates that the motion of the diaphragm is more enhanced than that of the chest during PAV+.

For the chest, the mean relative time to reach peak inspiration was 147.6 ± 4.6 degrees during PAV+ and 155.2 ± 5.1 degrees during PSV. The mean value during PAV+ was 7.6 ± 3.6 degrees less than that during PSV. The mean time for the chest to reach peak inspiration was significantly shorter during PAV+ ($p = 0.04$). For the abdomen, the mean time taken to reach peak inspiration was 106.0 ± 4.6

degrees during PAV+ and 118.2 ± 2.0 degrees during PSV. The mean value during PAV+ was 12.2 ± 2.7 degrees less than that during PSV. The mean time for the abdomen to reach peak inspiration was significantly shorter during PAV+ ($p = 0.002$).

Discussion

We found that spontaneous breathing supported by PAV+ significantly increased the expansibility of the chest and abdomen and shortened the time to reach peak inspiration, as compared with PSV. The increased expansibility of the chest and abdomen during PAV+ is attributed to the fact that PAV+ adjusts the ventilatory volume and inspiratory flow in proportion to instantaneous respiratory work, whereas PSV provides a pre-set level of constant pressure. Thille et al. reported²⁰ that one-fourth of patients exhibit a high incidence of patient-ventilator asynchrony during PSV. In contrast, PAV+ changes the support pressure according to the patient's depth of breathing. Therefore, PAV+ is considered to provide better coupling with patients' inspiratory efforts regulated by the respiratory center^{3)~13)}. Better patient-ventilator synchrony provided by PAV+ is considered to increase the expansibility of the chest and abdomen as compared with PSV. It also enhances the motion of the diaphragm more than that of the chest during PAV+. During spontaneous breathing, the dorsal part of the diaphragm moves as well as the precordium²¹⁾. In our study, the motion of the abdomen increased during PAV+, supporting the hypothesis that breathing during PAV+ is physiologically more similar to spontaneous breathing than is breathing during PSV.

The present study showed that PAV+ shortened the time from the start of inspiration to peak inspiratory expansion of the chest and abdomen, as compared with PSV. The assisted ventilation during PAV+ promptly responded to patients' inspiratory efforts, particularly during the early phase of diaphragm contraction. This induces an increase in the supporting pressure and thus results in the rapid completion of the inspiratory phase. Wysocki et al.²²⁾ reported that breathing patterns at rest and during exercise were similar during PSV and PAV+ in

healthy volunteers with external thoracic restriction, mimicking a patient with increased elastic work of breathing. However, inspiratory muscle effort during exercise was lower with PAV+ because this mode provided a significant automatic increase in assistance. Improved patient-ventilator synchrony may decrease the need for sedatives to treat poor synchrony with the ventilator³⁾¹³⁾ and thereby lower the incidence of sedation-related complications.

PAV+ permits non-invasive¹¹⁾, real-time assessment of total and patient work of breathing. Results can be obtained by only setting the support level, PEEP level, oxygen concentrations, and trigger and expiratory sensitivities. Clinicians can thereby evaluate the appropriateness of ventilatory support level and assess the treatment course, which can change rapidly. PAV+ may thus be a promising ventilatory mode to assist spontaneous breathing as required by the individual patient.

Some studies reported that PAV+ improved respiratory comfort in awake patients with respiratory failure who underwent non-invasive mechanical ventilation, as compared with PSV⁷⁾¹⁰⁾. However, respiratory comfort cannot be assessed in sedated patients. Mols et al.⁹⁾ reported that PAV+ improved respiratory comfort as compared with PSV in healthy volunteers in whom decreased respiratory system compliance was induced by banding of the chest and abdomen. This difference in respiratory comfort level was attributed to better adaptation of ventilatory support to the volunteer's needs during PAV+.

Our study had several limitations. First, the sample size was small, and patient selection was not controlled because patients with common causes of respiratory failure, such as pneumonia, were not included in the study. Second, all patients underwent PSV and then were switched to PAV+. No patient underwent these procedures in the reversed order. Therefore, we cannot rule out the possibility that the measured values may have been influenced by time-related factors. Third, although PSV and PAV+ were compared in the same patient, our subjects had different underlying diseases and condi-

tions, which may have influenced the synchronization between the motion of the abdominal walls and the motion of the diaphragm. Surgical wounds in the chest and abdomen may also have affected our results.

Conclusions

We analyzed waveforms of the expansibility of the chest and abdomen and found that spontaneous breathing supported by PAV+ significantly increased the expansibility of the chest and abdomen, enhanced the motion of the diaphragm more than that of the chest, and shortened the time from the start of inspiration to peak inspiratory expansion, as compared with PSV. These results support the notion that the pattern of breathing during PAV+ is physiologically more similar to spontaneous breathing than the pattern of breathing during PSV.

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胸郭および腹壁伸展度測定による部分的補助換気 (proportional assist ventilation) と 圧支持換気 (pressure support ventilation) の比較

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集中治療室において自発呼吸補助を行った患者を対象に換気補助レベル設定が調整可能な部分補助換気 (proportional-assist ventilation with load-adjustable gain factors : PAV+) と圧支持換気 (pressure support ventilation : PSV) について, 胸郭および腹壁伸展度を測定することにより自発呼吸に対する補助効果を比較した. 24 時間以上自発呼吸補助換気を行った患者 8 名を対象とした. PSV の換気圧は, 一時的に PAV+へ移行させ, サポート率が 50% になる換気量, または最高気道内圧とほぼ等しい値になるように設定した. 胸郭および腹壁伸展度測定は脳波計の呼吸解析機能と呼吸ピックアップを利用し, 胸部は乳線上を, 腹部は胸骨下縁と臍の midpoint を検出部位として体幹の外周変化を伸展変化として表現した. 患者には PSV を 12~24 時間施行後に血液ガス分析, 胸部 X 線撮影を行い, PAV+へ移行させ, 12~24 時間後の同様の測定を行った. 伸展度合いの差異は振幅の相対的变化で表し, 吸気開始から吸気伸展ピークまでの時間差は, 呼吸周期を 360 度に規格化した角度で表現し比較した. 胸部および腹部の伸展度は PSV を 100% とすると, PAV+では胸部は $112.0 \pm 2.7\%$ で, 腹部は $118.0 \pm 3.7\%$ で有意に PAV+で胸部と腹部の伸展が大きかった ($p < 0.0001$). そして PAV+で腹部伸展度は, 胸部伸展度に比し有意に大きかった ($p < 0.005$). 胸部および腹部の吸気ピークに到達する時間は PAV+では PSV に対して, 胸部では平均 7.6 ± 3.6 度 ($p = 0.004$), 腹部では平均 12.2 ± 2.7 度 ($p = 0.002$) と, PAV+の方では短かった. これらは, PAV+が横隔膜運動を促進させていることを意味し, PAV+を使用することで呼吸不全からの回復が促進されると期待できる.