

Cardiorespiratory Effects of Automatic Tube Compensation during Airway Pressure Release Ventilation in Patients with Acute Lung Injury

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Background: Spontaneous breaths during airway pressure release ventilation (APRV) have to overcome the resistance of the artificial airway. Automatic tube compensation provides ventilatory assistance by increasing airway pressure during inspiration and lowering airway pressure during expiration, thereby compensating for resistance of the artificial airway. The authors studied if APRV with automatic tube compensation reduces the inspiratory effort without compromising cardiovascular function, end-expiratory lung volume, and gas exchange in patients with acute lung injury.

Methods: Fourteen patients with acute lung injury were breathing spontaneously during APRV with or without automatic tube compensation in random order. Airway pressure, esophageal and abdominal pressure, and gas flow were continuously measured, and tracheal pressure was estimated. Trans-diaphragmatic pressure time product was calculated. End-expiratory lung volume was determined by nitrogen washout. The validity of the tracheal pressure calculation was investigated in seven healthy ventilated pigs.

Results: Automatic tube compensation during APRV increased airway pressure amplitude from 7.7 ± 1.9 to 11.3 ± 3.1 cm H₂O (mean \pm SD; $P < 0.05$) while decreasing trans-diaphragmatic pressure time product from 45 ± 27 to 27 ± 15 cm H₂O \cdot s⁻¹ \cdot min⁻¹ ($P < 0.05$), whereas tracheal pressure amplitude remained essentially unchanged (10.3 ± 3.5 vs. 10.1 ± 3.5 cm H₂O). Minute ventilation increased from 10.4 ± 1.6 to 11.4 ± 1.5 l/min ($P < 0.001$), decreasing arterial carbon dioxide tension from 52 ± 9 to 47 ± 6 mmHg ($P < 0.05$) without affecting arterial blood oxygenation or cardiovascular function. End-expiratory lung volume increased from $2,806 \pm 991$ to $3,009 \pm 994$ ml ($P < 0.05$). Analysis of tracheal pressure-time curves indicated nonideal regulation of the dynamic pressure support during automatic tube compensation as provided by a standard ventilator.

Conclusion: In the studied patients with acute lung injury, automatic tube compensation markedly unloaded the inspiratory muscles and increased alveolar ventilation without compromising cardiorespiratory function and end-expiratory lung volume.

AIRWAY pressure release ventilation (APRV) ventilates by periodic switching between two levels of continuous

positive airway pressure (CPAP) while allowing unsupported spontaneous breathing in any phase of the ventilator cycle.^{1,2} APRV provides adequate ventilatory support in patients with mild pulmonary insufficiency³ and severe acute lung injury (ALI).⁴ In patients with severe ALI, unsupported spontaneous breathing with APRV has been observed to improve ventilation-perfusion matching and arterial blood oxygenation when compared with controlled mechanical ventilation or breath-to-breath inspiratory assistance with pressure support ventilation.⁴

During unsupported spontaneous breathing with APRV, the flow-dependent resistance of the artificial airway (R_{et}) imposes an undesirable inspiratory muscle load that may contribute to increased oxygen consumption and patient discomfort. Automatic tube compensation (ATC) provides ventilatory assistance of each spontaneous breath by increasing airway pressure (P_{aw}) during inspiration and lowering P_{aw} during expiration, thereby maintaining calculated tracheal pressure (P_{tr}) constant.^{5,6} Thus, ATC should compensate for R_{et} and provide an "electronic" extubation.⁷ In patients with increased ventilatory demand or mild pulmonary insufficiency, ATC has been observed to decrease work of breathing and improve patient comfort more effectively than pressure support ventilation or CPAP.^{6,8,9} However, transient lowering of P_{aw} during ATC to facilitate exhalation should cause a faster decrease of P_{tr} to the preset CPAP level, which may promote alveolar collapse of fast lung compartments¹⁰ and may impair ventilation-perfusion matching in patients with ALI. Although ATC can be used to assist unsupported breaths during partial ventilatory support, its effect on inspiratory muscle load, end-expiratory lung volume (EELV), and gas exchange during APRV has not been assessed in patients with ALI.

The goal of the current study was to investigate, in patients at risk for alveolar collapse, whether spontaneous breathing assisted with ATC during APRV as provided by a standard ventilator will decrease inspiratory muscle load without reducing EELV and impairing gas exchange as a result of a faster decrease in tracheal pressure during expiration. Therefore, we examined cardiopulmonary function in patients with ALI breathing spontaneously during APRV, with and without ATC. To test the efficacy of P_{tr} calculation, measured and calculated P_{tr} were compared in pigs. In patients and pigs, efficacy of dynamic pressure support regulation provided by the used ventilator was analyzed.

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Material and Methods

Patient Investigations

Investigations in patients were performed in the Department of Anesthesiology and Intensive Care Medicine at the University of Bonn, Germany. After approval by the Bonn University Ethics Committee, informed consent for inclusion in the study was obtained from the next of kin of 14 mechanically ventilated patients with ALI.^{11,12} Patients with a history of chronic lung or heart disease and those with unstable cardiopulmonary function were excluded. Severity of illness was assessed with the Simplified Acute Physiologic Score¹³ and the Lung Injury Score¹² at inclusion in the study.

Routine clinical treatment of the patients included the use of a radial artery catheter and a thermistor-tipped quadruple-lumen pulmonary artery catheter (CCO 746HF8; Baxter Edwards Critical-Care, Irvine, CA).

Cardiovascular Measurements

Heart rate was obtained from the electrocardiogram. Systemic mean arterial pressure, central venous pressure, pulmonary artery pressure, and pulmonary artery wedge pressure were transduced (Combitrans; Braun AG, Melsungen, Germany) and recorded (CS/3, Datex-Engström, Helsinki, Finland). Cardiac output was continuously estimated with the thermal dilution technique (Vigilance, Baxter Edwards Critical-Care). In addition, intermittent determinations of cardiac output were performed using 10 ml of iced 0.9% saline solution as indicator, averaging five determinations performed at random moments during the ventilatory cycle. Standard formulas were used to calculate cardiac index (CI), systemic vascular resistance index, and oxygen delivery index.

Ventilatory and Lung Mechanics Measurements

Gas flow was measured at the proximal end of the endotracheal tube with a heated pneumotachograph (No. 2; Fleisch, Lausanne, Switzerland) connected to a differential pressure transducer (Huba Control, Würenlos, Switzerland). P_{aw} was measured at the proximal end of the endotracheal tube with another differential gas-pressure transducer (SMT, Munich, Germany). Esophageal pressure (P_{es}) was measured with a balloon catheter (International Medical, Zutphen, The Netherlands) connected to a differential pressure transducer (SMT). The validity of the esophageal balloon measurements in the supine subject was tested with the occlusion method of Brunner and Wolff.¹⁴ Intraabdominal pressure (P_{ab}) was measured with a pressure transducer (Combitrans) in the urinary bladder during transient clamping of the Foley catheter after installation of 50 ml saline solution.¹⁵ All signals were sampled with an analog-digital converter board (PCM-DAS16S/12, Mansfield, MA) installed in a personal computer. Digitized signals were

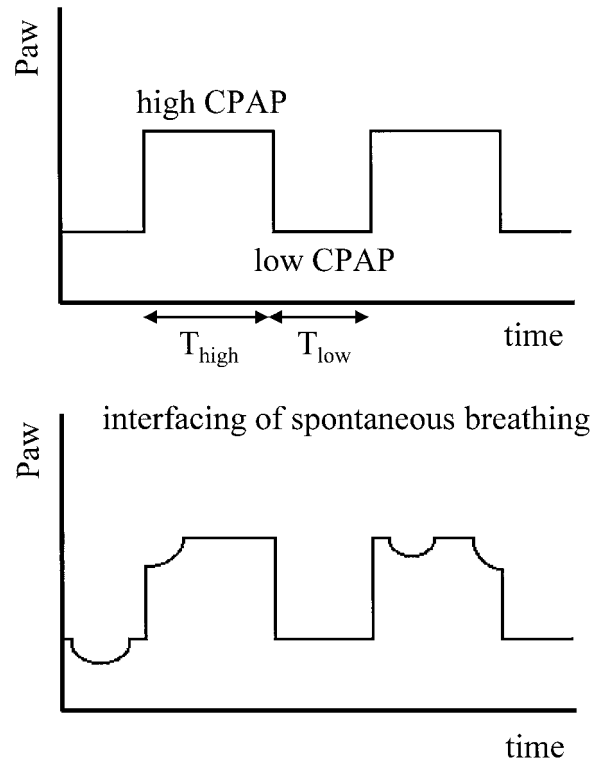


Fig. 1. Schematic diagram of airway pressure (P_{aw})–time course during airway pressure release ventilation (APRV). (*Top*) Mechanical ventilation is provided by time-cycled changes between a high and low level of continuous positive airway pressure (CPAP). T_{high} = time on high CPAP; T_{low} = time on low CPAP. (*Bottom*) With APRV, unrestricted spontaneous breathing is possible during each phase of the ventilatory cycle. The ventilator setting used in this study did not allow the patient to trigger P_{aw} changes to keep T_{high} and T_{low} constant. Interfacing of spontaneous breathing included spontaneous breaths on the lower CPAP level, breaths during which the P_{aw} change to the upper CPAP level, and breaths during which the P_{aw} change to the lower CPAP level occurred.

plotted in real time on the computer screen and stored on magnetic media for offline analysis.

Tidal volume (V_T) and minute ventilation (V_E) were derived from the integrated gas flow signal and converted to body temperature pressure saturated conditions. Respiratory rate, inspiratory time, and duty cycle (inspiratory time/cycle time) were determined from the gas flow signal. Mean, inspiratory, minimum, and maximum P_{aw} values were determined for each respiratory cycle. Diaphragmatic pressure time product (PTP_{di}) was determined from trans-diaphragmatic pressure ($P_{di} = P_{es} - P_{ab}$) as the area under the P_{di} -time curve, which was only considered if P_{di} was below a baseline value defined at end expiration to assure that the pressure change resulted from patient activity.¹⁶ Spontaneous breaths during APRV may occur on the high or low CPAP levels, as well as during airway pressure release or restoration (fig. 1). Therefore, this P_{di} baseline value was calculated separately for each of the four phases of the mechanical ventilatory cycle (*i.e.*, high CPAP level, low

CPAP level, P_{aw} release, and restoration of high CPAP level) to compensate for changes in P_{di} caused by changes in P_{aw} during APRV. Breaths resulting from restoration of the high CPAP alone, *i.e.*, without detectable deflection in P_{es} indicating lack of patient activity, were defined as mechanical breaths. Spontaneous breaths were defined as breaths on both CPAP levels during which no step change in P_{aw} occurred. In an additional analysis, ventilatory variables for these pure mechanical and spontaneous breaths were calculated separately. All ventilatory variables were averaged over a period of 5 min.

Tracheal pressure was continuously estimated as described previously,⁵ using the measured gas flow and P_{aw} tracings as:

$$P_{tr} = P_{aw} - K_1 \cdot \dot{V}^{K_2}$$

where K_1 and K_2 are tube coefficients describing the nonlinear pressure-flow curve of the tracheal tube. Mean, minimum, and maximum P_{tr} values were calculated.

Gas Analysis

Arterial blood gases and pH were determined immediately after sampling with standard blood gas electrodes (ABL 620; Radiometer, Copenhagen, Denmark). Oxygen saturation and hemoglobin in each sample were analyzed using spectrophotometry (OSM 3; Radiometer, Copenhagen, Denmark). Fractions of inspired and expired oxygen, carbon dioxide, and nitrogen were measured continuously with mass spectrometry (Random Access Mass Spectrometer M-100; Marquette Helige, Freiburg, Germany).

Determination of End-expiratory Lung Volume

Multibreath nitrogen washout maneuvers were started consistently from the low CPAP level by changing fraction of inspired oxygen from baseline level to 1.0. Calculation of EELV was described in detail previously.¹⁷ The viscosity-corrected gas flow signal was integrated offline with the measured nitrogen fraction from the beginning to the end of the washout during both inspiration and expiration. The EELV calculation procedure was started with the first oxygen washin breath. As the first breath usually still contains a certain amount of nitrogen, this inspired nitrogen volume was subtracted from the cumulative nitrogen volume calculated from the washout procedure. Mean values of two consecutive EELV determinations were used for the analysis. The coefficient of variation of repeated EELV measurements was 6.8% in this setting.

Protocol

After inclusion into the study, patients remained supine and received continuous infusions of sufentanil and midazolam as necessary, to achieve a Ramsay sedation

score of 3.¹⁸ Fluid replacement and infusion of all drugs remained unchanged throughout the study.

Pressure-limited ventilatory support was provided with a demand valve CPAP circuit of a standard ventilator (Evita 4; Dräger, Lübeck, Germany). The low and high CPAP levels were adjusted to a tidal volume of 8 ml/kg and maximum lung compliance, measured during transient apnea induced with repeated intravenous bolus doses of propofol up to a total dose of 2–4 mg/kg. Ventilator rate was set to maintain arterial carbon dioxide tension P_{aCO_2} between 45 and 55 mmHg and fraction of inspired oxygen to maintain arterial oxygen tension greater than 80 mmHg. Ventilator settings were not changed thereafter. During ATC, the ventilator increased P_{aw} during inspiration and lowered P_{aw} during expiration to maintain a constant preset P_{tr} . P_{tr} was estimated by the ventilator as:

$$P_{tr} = P_{aw} - K_1 \cdot \dot{V}^2$$

as described previously.¹⁹ An example of P_{aw} , P_{tr} , P_{es} , and gas flow tracings during ATC is shown in figure 2. All patients maintained spontaneous breathing during ventilatory support with the settings described above. Patients were assigned to receive APRV with and without ATC in random order. Measurements and data collection were performed during stable conditions confirmed by constancy ($\pm 5\%$) of V_E , oxygen saturation, expiratory carbon dioxide fraction, mean arterial pressure, and CI for at least 30 min. Before each intervention, the patients' lungs were inflated manually to an airway pressure of 40 cm H₂O for approximately 20 s to restore lung history.

Animal Investigations

Investigations in animals were performed in the laboratories of the Department of Clinical Physiology at the University Hospital of Uppsala, Sweden. After obtaining approval from the local animal ethics committee, seven healthy pigs (Hampshire, Yorkshire, and Swedish mixed-country breed; mean weight, 28 ± 4 kg) were studied. Anesthesia was induced with 0.04 mg/kg intramuscular atropine, 6 mg/kg tiletamin-zolazepam, and 2.2 mg/kg xylazine, followed by infusion of 30 mg \cdot kg⁻¹ \cdot h⁻¹ ketamine, 0.1 mg \cdot kg⁻¹ \cdot h⁻¹ midazolam, and 1–2 μ g \cdot kg⁻¹ \cdot min⁻¹ remifentanyl. The animals were then tracheotomized and ventilated *via* a cuffed endotracheal tube with an ID of 7 mm (Hi-Contour[®] 107; Mallinckrodt Medical, Athlone, Ireland). Pigs were breathing spontaneously during APRV with and without ATC on a low CPAP level of 5 cm H₂O and a high CPAP level of 10 cm H₂O. Ventilatory rate was set at 20 breaths/min with a release time of 1.5 s. P_{tr} was measured 2–3 cm below the distal end of the endotracheal tube with a fenestrated polyethylene catheter (Erich Jaeger GmbH, Höchberg, Germany) without balloon connected to a differential pressure

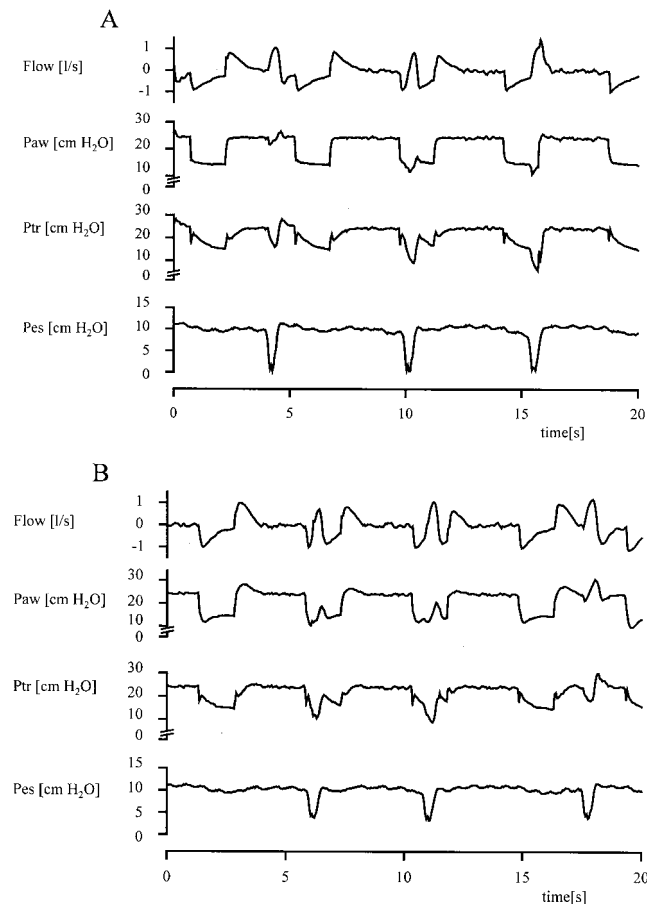


Fig. 2. Original tracings (patient no. 14) of gas flow, airway pressure (P_{aw}), calculated tracheal pressure (P_{tr}), and esophageal pressure (P_{es})—time courses during airway pressure release ventilation (APRV) with superimposed spontaneous breathing during different phases of the ventilatory cycle. (A) APRV alone. (B) APRV with additional automatic tube compensation (ATC). Note that during ATC, P_{aw} is intermittently increased during inspiration and decreased during expiration. However, spontaneous inspiratory efforts still caused an initial decrease in P_{tr} below the preset CPAP level that was followed by an increase of P_{tr} above the preset CPAP level, indicating a delay of the dynamic pressure support provided by ATC.

transducer (SMT, Munich, Germany). All other ventilatory and lung mechanics variables were measured or calculated as described above. Measured and estimated P_{tr} —time curves were compared by calculating the root mean square of differences.

Statistical Analysis

To detect differences in PTP_{di} , EELV, and CI between the ventilatory settings with the given two-sided crossover design at a significance level of 5% ($\alpha = 0.05$) with a probability of 81% ($\beta = 0.19$) based on an estimated difference of 0.82 of the parameter's mean within patient SD, the number of patients to be studied is at least 14.

Results are expressed as mean \pm SD. Data were evaluated for normal distribution with the Shapiro-Wilk W

test. For comparison of APRV with and without ATC, the t test for dependent samples was used. Differences were considered to be statistically significant at $P < 0.05$.

Results

Animal Study

The root mean square of differences between measured and calculated P_{tr} was 0.34 ± 0.06 cm H₂O during APRV and 0.41 ± 0.09 cm H₂O during APRV with ATC, indicating a small error for P_{tr} calculation. During ATC, spontaneous inspiratory efforts consistently caused an initial decrease in the measured P_{tr} below the preset CPAP level that was followed by a marked increase of P_{tr} above the preset CPAP level (data not shown). Thus, during ATC, the dynamic pressure support was provided with an average time delay of 166 ± 19 ms by the ventilator.

Patient Investigations

The patients demographic and clinical data are shown in table 1. Changes in variables reflecting ventilation and respiratory mechanics are given in table 2. ATC during APRV increased P_{aw} amplitude (ΔP_{aw} , $P < 0.05$) by both lowering minimum P_{aw} ($P < 0.001$) and increasing maximum P_{aw} ($P < 0.001$). The higher ΔP_{aw} increased V_E by approximately 10% ($P < 0.001$), decreased P_{aco_2} ($P < 0.05$), and reduced inspiratory muscle load as reflected by a decrease in PTP_{di} ($P < 0.05$; fig. 3). Although minimum P_{aw} was lowest during APRV with ATC, end-expiratory P_{aw} was not different between the tested ventilatory modalities. ATC increased mean P_{aw} only by a small amount (19.8 ± 2.9 vs. 20.1 ± 2.7 cm H₂O; $P < 0.05$), whereas the increase in inspiratory P_{aw} was higher (21.0 ± 2.7 vs. 22.4 ± 3.1 cm H₂O; $P < 0.001$). Inspiratory peak flow ($\dot{V}_{max,i}$) was always higher than expiratory peak flow ($\dot{V}_{max,e}$). Whereas $\dot{V}_{max,e}$ increased with ATC ($P < 0.001$), $\dot{V}_{max,i}$ did not further increase (table 2). Registrations of estimated P_{tr} indicated an average delay of 159 ± 21 ms of the dynamic pressure support during ATC.

Analysis of pure mechanical breaths revealed an increase in V_T from 348 ± 157 to 487 ± 157 ml ($P < 0.05$), resulting in an increase in V_E from 1.7 ± 1.4 to 3.3 ± 2.4 l ($P < 0.05$) during ATC. V_T of pure spontaneous breaths did not change significantly (333 ± 273 ml vs. 361 ± 241 ml) with ATC.

End-expiratory lung volume increased during ATC from $2,806 \pm 991$ to $3,009 \pm 994$ ml ($P < 0.05$; fig. 4), without affecting arterial oxygen tension/fraction of inspired oxygen (table 3). All other cardiorespiratory variables remained unchanged throughout the study (table 3).

Table 1. Patient Characteristics

Sex	Age (yr)	SAPS	LIS	Ventilator Days	Tube (mm)	FIO ₂	T _{high} (s)	T _{low} (s)	CPAP _{high} (cm H ₂ O)	CPAP _{low} (cm H ₂ O)	Precipitating Cause of ALI
M	52	11	2.3	12	ET 8.0	0.40	2.5	1.2	22	16	Peritonitis, sepsis
F	58	7	2.3	14	ET 7.0	0.30	3.0	3.0	24	18	Peritonitis, sepsis
M	75	15	2.7	7	TC 8.0	0.50	3.0	1.0	27	17	Aortic aneurysm
M	58	13	2.3	4	ET 8.0	0.45	3.0	3.0	22	15	Pneumonia
M	57	12	2.3	11	ET 7.5	0.35	3.0	3.0	23	15	Multiple trauma
M	61	9	2.0	11	ET 8.0	0.30	3.0	1.0	22	15	Peritonitis, sepsis
M	48	7	2.3	9	ET 8.5	0.40	2.3	1.0	29	17	Pancreatitis
M	58	16	2.3	7	ET 7.5	0.30	3.0	3.0	25	15	Abdominal sepsis
F	31	12	2.0	5	ET 7.5	0.40	3.0	3.0	22	15	Acid aspiration
M	76	19	2.0	7	ET 8.0	0.30	3.0	3.0	18	11	Pneumonia
M	34	17	2.3	8	ET 8.5	0.60	2.2	0.8	26	18	Atypical pneumonia
M	64	17	2.3	7	ET 7.5	0.35	2.0	0.8	28	18	Pneumonia
M	65	15	1.7	9	ET 7.5	0.35	3.0	2.0	21	13	Pneumonia
M	65	21	2.3	17	ET 8.0	0.40	3.0	1.5	25	15	Abdominal sepsis

SAPS = Simplified Acute Physiologic Score; LIS = Lung Injury Score; FIO₂ = fraction of inspired oxygen; T_{high}, T_{low} = preset duration of high and low continuous positive airway pressure (CPAP) levels; ALI = acute lung injury; ET = endotracheal tube; TC = tracheal cannula.

Discussion

This study was designed to evaluate the effect of ATC on the cardiorespiratory function in patients with ALI ventilated using APRV. Compensation of the tracheal tube resistance with ATC increased the P_{aw} amplitude by lowering minimum P_{aw} and increasing

maximum P_{aw}, thereby augmenting alveolar ventilation and attenuating the patients' inspiratory muscle load, as reflected by a decrease in PaCO₂ and PTP_{di}. Despite the transient decrease of P_{aw} to facilitate exhalation, ATC effected no deterioration in EELV or arterial blood oxygenation.

Partial ventilatory support is used increasingly, not only to separate patients from mechanical ventilation, but to provide stable ventilatory assistance of a desired degree during ventilatory failure.^{4,20-23} During APRV, spontaneous breathing is possible in any phase of the mechanical ventilator cycle,^{2,24} but spontaneous breaths are mechanically supported only when they coincide with the restoration of the high CPAP level. Therefore, the patient has to overcome the entire load imposed by the resistance of the artificial airway. ATC provides a dynamic assistance of each breath by increasing P_{aw} during inspiration and lowering P_{aw} during expiration to maintain calculated P_{tr} constant at a preset level.⁶ Thus, ATC minimizes the flow-dependent pressure decrease across the tracheal tube and compensates for R_{ct}. Because the ventilator we used does not generate subambient pressures, expiratory assistance with ATC was provided by transient lowering of P_{aw} below the set CPAP level. Expiratory assistance may become incomplete during ATC with low CPAP levels. In our patients, both the high and the low CPAP levels were markedly positive and thus guaranteed adequate margin for ATC during inspiration and expiration alike.² Theoretically, during ATC with ideal regulation of dynamic pressure support, the increase in ΔP_{aw} should have resulted in a lower ΔP_{tr} since P_{tr} should not decrease with spontaneous inspiration and should not increase with spontaneous expiration. The observed lack of a decrease in ΔP_{tr} with ATC in our study may be explained by a nonideal regulation of dynamic pressure support by the ventilator.

Table 2. Ventilatory Variables

	APRV	APRV + ATC
RR (min ⁻¹)	18.3 ± 5.5	17.7 ± 3.9
V _E (l/min)	9.4 ± 1.8	10.1 ± 1.6*
V _T (ml)	556 ± 174	592 ± 143
V̇ _{max,i} (l/s)	0.94 ± 0.22	0.94 ± 0.31
V̇ _{max,e} (l/s)	0.72 ± 0.15	0.84 ± 0.20*
T _I (s)	1.5 ± 0.4	1.5 ± 0.5
T _E (s)	2.0 ± 0.8	1.9 ± 0.5
P _{aw,ee} (cm H ₂ O)	16.8 ± 2.7	16.9 ± 2.6
P _{aw,mean} (cm H ₂ O)	19.8 ± 2.9	20.1 ± 2.7†
P _{aw,insp} (cm H ₂ O)	21.0 ± 2.7	22.4 ± 3.1*
P _{aw,max} (cm H ₂ O)	22.4 ± 3.0	24.6 ± 3.7*
P _{aw,min} (cm H ₂ O)	14.9 ± 2.4	13.3 ± 2.3*
P _{tr,ee} (cm H ₂ O)	16.8 ± 2.7	16.8 ± 2.6
P _{tr,mean} (cm H ₂ O)	19.7 ± 2.8	20.1 ± 2.7*
P _{tr,insp} (cm H ₂ O)	18.9 ± 2.8	20.0 ± 3.0†
P _{tr,max} (cm H ₂ O)	23.2 ± 3.1	24.0 ± 3.6†
P _{tr,min} (cm H ₂ O)	12.9 ± 3.3	13.9 ± 3.1†
ΔP _{tr} (cm H ₂ O)	10.3 ± 3.5	10.1 ± 3.5
ΔP _{es} (cm H ₂ O)	10.2 ± 3.2	7.8 ± 2.3†
Paco ₂ (mmHg)	52 ± 9	47 ± 6†

All values are mean ± SD.

* P < 0.001. † P < 0.05.

APRV = airway pressure release ventilation; ATC = automatic tube compensation; RR = respiratory rate; V_E = minute ventilation; V_T = tidal volume; V̇_{max,i} = maximum inspiratory flow; V̇_{max,e} = maximum expiratory flow; T_I = inspiratory time; T_E = expiratory time; P_{aw,ee} = end-expiratory airway pressure; P_{aw,mean} = mean airway pressure; P_{aw,insp} = mean inspiratory airway pressure; P_{aw,max} = mean of maximum airway pressures; P_{aw,min} = mean of minimum airway pressures; P_{tr,ee} = end-expiratory tracheal pressure; P_{tr,mean} = mean tracheal pressure; P_{tr,insp} = mean inspiratory tracheal pressure; P_{tr,max} = mean of maximum tracheal pressures; P_{tr,min} = mean of minimum tracheal pressures; ΔP_{tr} = tracheal pressure amplitude; ΔP_{es} = esophageal pressure amplitude; Paco₂ = arterial carbon dioxide tension.

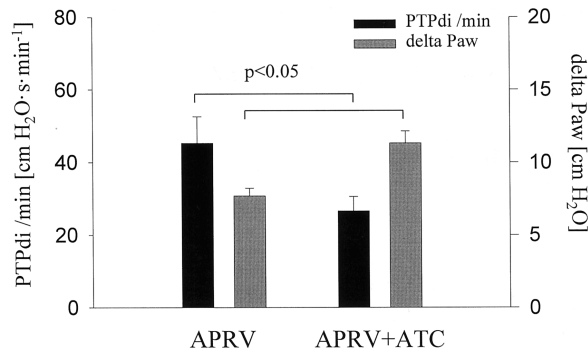


Fig. 3. Changes in transdiaphragmatic pressure–time product (PTP_{di}) as an index of patients’ inspiratory muscle load and the airway pressure amplitude (ΔP_{aw}) applied by the ventilator during airway pressure release ventilation (APRV) and APRV with automatic tube compensation (ATC).

Gottfried *et al.*²⁵ described an algorithm that allows real-time determination of the pressure decrease across the endotracheal tube from gas flow and airway pressure measured at the proximal end of the tracheal tube. The reliability of this algorithm has been confirmed in a mechanical lung model.⁵ In the ventilator used in this and previous studies,¹⁹ a simplified algorithm to estimate P_{tr} during ATC by setting the tube coefficient $K_2 = 2$ was used. Because the expiratory coefficient found by Guttman *et al.*⁵ was consistently less than 2, use of the simplified algorithm should result in incomplete compensation of R_{ct} during expiratory ATC for expiratory flows less than 1 l/s. Furthermore, registrations of P_{aw} and estimated and measured P_{tr} indicate that during ATC, dynamic pressure support is provided with a time delay by the used ventilator, thereby resulting in a lack of decrease in ΔP_{tr} (fig. 2). In addition, the algorithm to calculate P_{tr} during ATC is based on ideal laboratory conditions. In patients, effective pressure decrease across the tracheal tube may be underestimated by the ATC algorithm because of changes in the tube geometry from kinking or mucous secretions. Therefore, in the clinical setting, ATC as provided by the used intensive care ventilator does not completely compensate for the resistance imposed by the artificial airway.

Previous investigations have evaluated ATC as a ventilatory support modality in volunteers or ventilated patients during variable ventilatory demand.^{6,8,19,26,27} In tracheotomized and intubated patients, work of breathing necessary to overcome tracheal tube resistance decreased with ATC compared with pressure support ventilation and CPAP.^{6,8,26} Similarly, volunteers ranked ATC to be more comfortable than pressure support ventilation.^{19,27} Despite the observed advantages of ATC, the transient decrease in P_{aw} that facilitates exhalation may be detrimental to patients at risk for alveolar collapse. Observations in a four-compartment bench lung model indicate that in fast-emptying compartments with low compliance, alveolar pressure may decrease below P_{tr} during early expiration or with short expiratory times.²⁸

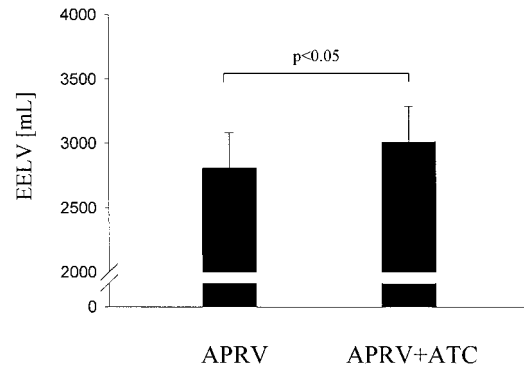


Fig. 4. Differences in end-expiratory lung volume (EELV) during spontaneous breathing with airway pressure release ventilation (APRV) and APRV with automatic tube compensation (ATC).

Therefore, the faster decline of P_{tr} with ATC during transient decrease in P_{aw} to facilitate expiration may result in lower mean alveolar pressures in fast-emptying lung compartments and may promote alveolar collapse. These observations are supported by findings in pigs with oleic acid lung injury demonstrating rapid increase in atelectasis within 0.6 s during ventilatory support with positive end-expiratory pressure levels less than 20 cm H₂O.¹⁰

Lowering P_{aw} to facilitate expiration with ATC during APRV in our patients with ALI did not compromise EELV or arterial oxygenation. Surprisingly, EELV even increased in the presence of ATC. This observation may be explained by an unchanged end-expiratory pressure during APRV with and without ATC. Because R_{ct} depends on gas flow, lowering P_{aw} during expiration with ATC is more pronounced during early expiration when gas flow is high. In contrast, ATC has no or only minimal effect on P_{aw} at end expiration, because flow rate at end expiration is minimal even during APRV with variable expiratory times as a result of interfacing of spontaneous breathing. Because $\dot{V}_{max,i}$ was always higher than $\dot{V}_{max,e}$ and R_{ct} is flow-dependent, R_{ct} should be higher during inspiration than during expiration. Thus, compensation

Table 3. Cardiorespiratory Variables

	APRV	APRV + ATC
PaO ₂ /Fio ₂ (mmHg)	273 ± 68	293 ± 74
Do ₂ I (ml · min ⁻¹ · m ⁻²)	551 ± 47	562 ± 30
CI (l · min ⁻¹ · m ⁻²)	3.5 ± 0.5	3.6 ± 0.4
SVRI (dyne · s · cm ⁻⁵ · m ²)	1,588 ± 534	1,553 ± 498
HR (min ⁻¹)	82 ± 11	86 ± 20
MAP (mmHg)	82 ± 12	82 ± 12
CVP (mmHg)	15 ± 6	15 ± 7
PAP (mmHg)	30 ± 7	28 ± 6
PCWP (mmHg)	14 ± 4	15 ± 4

All values are mean ± SD.

APRV = airway pressure release ventilation; ATC = automatic tube compensation; PaO₂ = arterial oxygen tension; Fio₂ = fraction of inspired oxygen; Do₂I = oxygen delivery index; CI = cardiac index; SVRI = systemic vascular resistance index; HR = heart rate; MAP = mean arterial pressure; CVP = central venous pressure; PAP = mean pulmonary artery pressure; PCWP = pulmonary capillary wedge pressure.

of R_{ct} with ATC resulted in higher mean P_{aw} and may itself cause an increase in EELV. This may be attenuated by differences in inspiratory and expiratory performance of ATC.

Furthermore, ATC resulted in higher inspiratory P_{aw} and maximum P_{aw} during APRV. Pelosi *et al.*²⁹ demonstrated in patients with ALI that transient increasing inspiratory plateau pressure from 30 to 45 cm H₂O improves EELV and arterial oxygenation. Thus, the observed increase in EELV during APRV with ATC might be partially caused by higher inspiratory P_{aw} and maximum P_{aw} .

However, the observed increase in EELV with ATC was not associated with an improvement in arterial oxygenation. Whether this reflects further expansion of already open lung units and no recruitment of collapsed lung tissue remains to be analyzed.

In our patients, ATC during APRV resulted in an increase in ΔP_{aw} caused by both lowering minimum P_{aw} and increasing maximum P_{aw} . Because with ATC the ventilator regulates calculated P_{tr} instead of P_{aw} , transient increase and decrease of P_{aw} occurs not only during spontaneous breaths but also during the periodic changes of the CPAP levels that constitute APRV. Consequently, ATC during APRV resulted in a higher ΔP_{aw} and V_T of the mechanical breaths, causing an increase in V_E .

The higher V_E and the lower P_{aCO_2} suggest an increase in alveolar ventilation with ATC on condition that ventilatory dead space ventilation and carbon dioxide production remained unchanged. Although previous studies¹⁹ suggested that inspiratory pressure support can decrease carbon dioxide production, this cannot sufficiently explain the decrease in P_{aCO_2} observed in our patients.

In agreement with studies using ATC as primary ventilatory support modality,⁸ V_T of the spontaneous breaths did not increase in our patients with ATC. Obviously, our patients reduced their inspiratory effort rather than increased V_T of spontaneous breaths assisted with ATC. This supports the concept that patients have certain ventilatory targets that they try to maintain even if the ventilatory assistance changes within a certain range.³⁰

During APRV, ATC consistently decreased PTP_{di} as an index for inspiratory muscle load by 40%. Similar reduction in work of breathing has been found previously during spontaneous breaths assisted with ATC.²⁶ This reduction of inspiratory effort with ATC seems to be relatively high. However, even in patients with obstructive lung disease and high airway resistance, R_{ct} can be the major component of total resistance.³¹ If V_E and, consequently, inspiratory flow is high, the share of total resistance that R_{ct} constitutes further increases because of the nonlinear dependency of R_{ct} on gas flow. This may explain the marked reduction of the inspiratory effort in the presence of ATC in our patients who had a high V_E and respiratory rate. In agreement with our findings,

ATC has been observed to provide better unloading from the undesirable load because of R_{ct} than constant pressure support or CPAP in patients with increased ventilatory demand.⁶ Furthermore, investigations in healthy volunteers^{9,19} suggest that the comfort of breathing depends on both the inspiratory and expiratory assistance during ATC.

In our patients, spontaneous breathing assisted with ATC during APRV was not associated with a decrease of CI, although ΔP_{es} was significantly lower. Periodic decrease in intrathoracic pressure during spontaneous inspiration with APRV has been suggested to improve venous return and CI.³² Apparently, during APRV with ATC, spontaneous respiratory activity decreased intrathoracic pressures sufficiently to cancel out the cardiovascular depression caused by higher airway pressures and reduction in ΔP_{es} .

The results of this study demonstrate that despite the observed nonideal regulation of dynamic pressure support, ATC during APRV in our patients with ALI unloaded considerably the inspiratory muscle load and increased alveolar ventilation without compromising cardiorespiratory function. Transient lowering of P_{aw} during expiration with ATC did not promote alveolar collapse in these patients. Further studies are warranted to evaluate these and previous observations with respect to clinical relevance.

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