

Adaptive Support Ventilation

An Appropriate Mechanical Ventilation Strategy for Acute Respiratory Distress Syndrome?

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Background: Adaptive support ventilation (ASV) allows the clinician to set a maximum plateau pressure (PP) and automatically adjusts tidal volume to keep PP below the set maximum.

Methods: ASV was compared to a fixed tidal volume of 6 ml/kg. ASV determined the respiratory rate and tidal volume based on its algorithms. Maximum airway pressure limit was 28 cm H₂O in ASV. Six sets of lung mechanics were simulated for two ideal body weights: 60 kg, Group I; 80 kg, Group II. Positive end expiratory pressure was 8, 12, and 16 cm H₂O, and target minute volume 120%, 150%, and 200% of predicted minute volume.

Results: ASV “sacrificed” tidal volume and minute ventilation to maintain PP in 9 (17%) of 54 scenarios in Group I and 20 (37%) of 54 scenarios in Group II. In Group I, the number of scenarios with PP of 28 cm H₂O or more was 14 for ASV (26%) and 19 for 6 ml/kg (35%). In these scenarios, mean PP were ASV 28.8 ± 0.86 cm H₂O (min 28, max 30.3) and 6 ml/kg 33.01 ± 3.48 cm H₂O (min 28, max 37.8) (*P* = 0.000). In group II, the number of scenarios PP of 28 cm H₂O or more was 10 for ASV (19%) and 21 for 6 ml/kg (39%). In these cases, mean PP values were ASV 28.78 ± 0.54 cm H₂O (min 28, max 29.6) and 6 ml/kg 32.66 ± 3.37 cm H₂O (min 28.2, max 38.2) (*P* = 0.000).

Conclusion: In a lung model with varying mechanics, ASV is better able to prevent the potential damaging effects of excessive PP (greater than 28 cm H₂O) than a fixed tidal volume of 6 ml/kg by automatically adjusting airway pressure, resulting in a decreased tidal volume.

OVER the past 10 yr, the approach to management of patients with acute lung injury and acute respiratory distress syndrome (ARDS) has dramatically changed. On the basis of data from Amato *et al.*¹ and the National Institutes of Health ARDS Network (ARDSnet),² it is clear

that tidal volume should be limited to a range of about 4 to 8 ml/kg predicted body weight and plateau pressure (PP) should be limited to less than 28 to 30 cm H₂O. Although the precise levels of tidal volume and PP are debated, it is clear that ventilation above these levels does result in adverse outcome.³ The National Institutes of Health ARDS Network protocol as a result has been widely recommended as the approach to manage ARDS patients. This protocol uses volume assist/control and targets a tidal volume of 6 ml/kg with a range of 4 to 8 ml/kg. Tidal volume is adjusted on the basis of patient comfort, pH, and maintaining PP of 30 cm H₂O. However, the bedside clinician must be alert to changes in respiratory mechanics and manually make adjustments to the ventilator settings to ensure variables are within target range.

Adaptive support ventilation (ASV) is a pressure-targeted form of closed loop ventilation that optimizes the relationship between tidal volume and respiratory frequency on the basis of lung mechanics as predicted by Otis.⁴ ASV uses a pressure ventilation format establishing a ventilatory pattern that minimizes work of breathing and auto positive end expiratory pressure (PEEP) while limiting peak airway pressure. In this regard, ASV is similar to pressure control ventilation and pressure-regulated volume control in its gas delivery format. It differs from pressure control and pressure-regulated volume control by its additional algorithmic control of the ventilatory pattern.⁵ ASV automatically determines the tidal volume and respiratory rate that best maintains the peak pressure below the target level.⁶ Thus, the ventilatory pattern established with ASV may be comparable to the ARDSnet Protocol and an appropriate mechanical ventilation strategy for ARDS patients. Pressure-regulated volume control is also algorithmically controlled by adjusting pressure to maintain a target tidal volume.

In this study, our aim was to evaluate the performance of ASV during simulated ARDS mechanics and to compare the ability of ASV to maintain PP below a set target as respiratory mechanics changed in comparison with a fixed tidal volume of 6 ml/kg using a lung simulator during controlled mechanical ventilation. Our hypothesis was that ASV would be better able to manage tidal volume delivery and ensure PP below a target level than a fixed tidal volume of 6 ml/kg in the setting of changing respiratory mechanics during controlled mechanical ventilation.

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Materials and Methods

We compared ASV to a fixed tidal volume of 6 ml/kg by using the IngMar Medical ASL5000 (IngMar Medical, Pittsburgh, PA) computerized lung simulator. The ASL5000 was used in its passive ventilation mode (controlled mechanical ventilation). Essentially, the Lung Model ASL5000 operates by controlling a piston within a cylinder with the use of a computerized, direct drive motor. Data used for the constant positioning of the piston is collected at a rate of 2,000 Hz. Lung compliance, defined by the user, governs the relationship between pressure and volume in the compartment. Similarly, resistance is set to govern the relationship between pressure and flow in and out of the compartment.

Study Setup

The Galileo Ventilator (Hamilton Medical, Bonaduz, Switzerland) was used to ventilate the passive ASL5000 during both the ASV mode (pressure ventilation) and a fixed tidal volume of 6 ml/kg (volume control). The Hamilton Medical standard adult circuit for use with the Galileo was employed. The study was conducted without the inclusion of an active humidifier to avoid water contamination of the lung model.

Six unique lung mechanics scenarios were applied to each of two predicted patient weights. In Group I, 60-kg body weight-simulated patient, compliance (ml/cm H₂O) and resistance (cm H₂O/L/s) combinations of 45 and 5 (C45 R5), 30 and 5 (C30 R5), 15 and 5 (C15 R5), 45 and 10 (C45 R10), 30 and 10 (C30 R10), and 15 and 10 (C15 R10), respectively, were used. In Group II, 80-kg body weight-simulated patient, compliance (ml/cm H₂O) and resistance (cm H₂O/L/s) combinations of 50 and 5 (C50 R5), 35 and 5 (C35 R5), 20 and 5 (C20 R5), 50 and 10 (C50 R10), 35 and 10 (C35 R10), and 20 and 10 (C20 R10), respectively, were used. These settings were based on the spectrum of lung mechanics reported in patients with ARDS/acute lung injury.^{1,2,7-12} The lung model was connected directly to the circuit wye, and no endotracheal tube was included in the set up. During this evaluation, the ASL5000 acted as a single-compartment lung model.

Each evaluation was performed with a PEEP of 8, 12, and 16 cm H₂O. The target minute volume was set to 120%, 150%, and 200% of predicted healthy normal minute volume being equal to 0.1 l/kg ideal body weight.^{13,14} These settings were also based on the spectrum of minute volumes reported in patients with ARDS/acute lung injury.^{1,2,7-12} With a fixed tidal volume of 6 ml/kg, tidal volume was kept constant at 6 ml/kg in volume ventilation resulting in respiratory rates to 20, 25, or 33 and inspiratory:expiratory ratios of approximately 1:3, 1:2 and 1:1.25. Inspiratory time was set at 0.8 s.^{2,10} Flow wave form was square and peak flow was set to ensure that active delivery of the tidal volume occurred over the entire inspiratory time.¹⁵ ASV determined the respiratory rate and tidal volume based on its algorithms. The pressure limit alarm was set at 38 cm H₂O (10 cm H₂O higher than the desired peak pressure) in ASV to ensure that peak pressure was maintained no more than 28 cm H₂O. The Galileo maintains a 10 cm H₂O window of pressure above the target pressure where alarms are activated if pressure exceeds the target level. Overall, 108 unique testing conditions were simulated for each approach; two body weights times six lung mechanics settings times three PEEP levels times three target minute ventilation levels.

Variables Evaluated

The following variables were evaluated for both ASV and a fixed tidal volume of 6 ml/kg: PP, respiratory rate, target tidal volume, delivered tidal volume, and minute ventilation. Respiratory rate and target tidal volume were obtained directly from the ventilator display. PP was determined by establishing a 1.0-s end inspiratory pause and obtaining the reading directly from the ventilator display. Delivered tidal volume and minute ventilation were displayed by the ASL5000. AutoPEEP was obtained by determining the difference between the PEEP level measured in the airway and in the lung compartment of the ASL5000 at end exhalation. The major performance variable used to compare the two approaches was the number of test scenarios in which the PP exceeded the pressure limit.

Table 1. Target Tidal Volumes, Mean Delivered Tidal Volumes, and Mean Respiratory Rates in Both Groups across All 108 Scenarios

	Target Tidal Volume, ml/kg			Delivered Tidal Volume, ml/kg			Respiratory Rate, breaths/min		
	Median	25th–75th	Min–max	Median	25th–75th	Min–max	Median	25th–75th	Min–max
Group I (60 kg)									
ASV	6.27	4.42–7.27	3.95–9.0	6.27	4.42–7.24	3.33–9.0	25	20.5–33	15–45
6 ml/kg	6.0	6.0–6.0*	6.0–6.0	6.08	6.08–6.25	5.9–6.42	25	20–33	20–33
Group II (80 kg)									
ASV	5.43	4.44–7.05	4.41–8.3	5.24	3.97–7.05‡	2.68–8.3	27	20–34.5	15–45
6 ml/kg	6.0	6.0–6.0†	6.0–6.0	6.13	6.13–6.25	6.0–6.25	25	20–33	20–33

* $P = 0.000$ vs. delivered tidal volume 6 ml/kg Group I; † $P = 0.000$ vs. delivered tidal volume 6 ml/kg Group II; ‡ $P = 0.049$ vs. delivered tidal volume 6 ml/kg Group II.

ASV = adaptive support ventilation.

Table 2. Target Tidal Volumes, Delivered Tidal Volumes, and Respiratory Rates in Adaptive Support Ventilation (ASV) Scenarios Where the Target Tidal Volume and Minute Ventilation Could Not Be Met

	n	Target Tidal Volume, ml/kg			Delivered Tidal Volume, ml/kg			Respiratory Rate, breaths/min		
		Median	25th–75th	Min–max	Median	25th–75th	Min–max	Median	25th–75th	Min–max
Group I (60 kg)	9	4.4	(4.4–4.4)*	4.4–7.37	4.07	(3.61–4.22)	3.33–6.73	34	(27–45)	27–45
Group II (80 kg)	20	4.44	(4.42–4.44)**	4.41–6.89	3.76	(3.29–4.22)	2.68–6.06	35	(30.25–45)	27–45

* $P = 0.003$ vs. delivered tidal volume; ** $P = 0.000$ vs. delivered tidal volume.

Data Analysis and Statistics

Data were expressed as median (25th–75th percentile) with minimum and maximum where indicated. Statistical analyses were performed with Mann–Whitney U Test by using SPSS software (Statistical Package for the Social Sciences, version 15.0; SPSS Inc.; Chicago, IL). A value for $P < 0.05$ was considered statistically significant.

Results

There was no significant difference between ASV and a fixed tidal volume of 6 ml/kg in both groups with respect to target tidal volume and respiratory rate (table 1). Delivered tidal volumes were similar in Group I. However, during ASV in Group II, delivered tidal volumes were smaller compared to a fixed tidal volume of 6 ml/kg ($P = 0.049$).

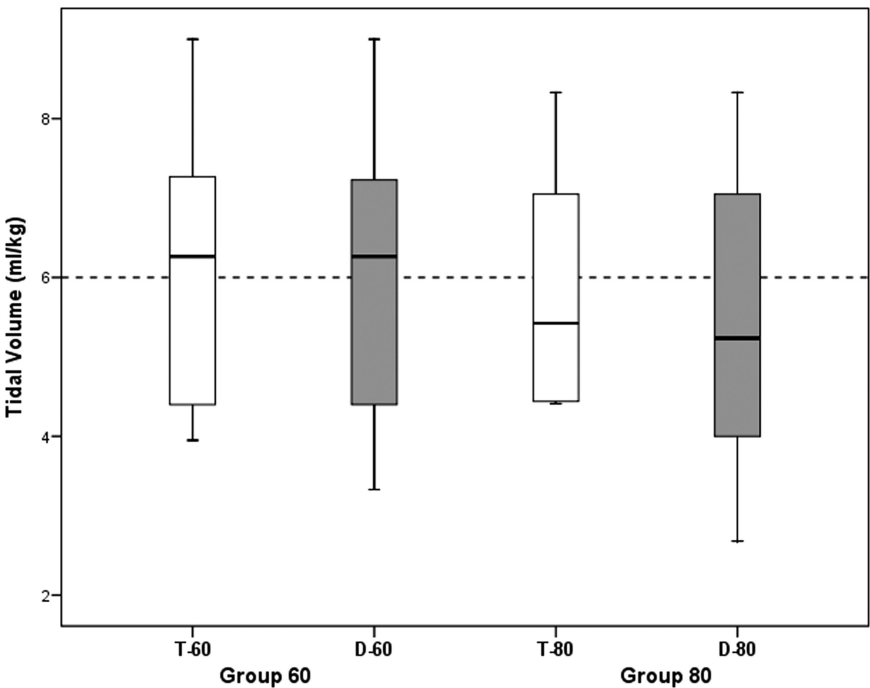
ASV sacrificed delivered tidal volumes and minute ventilation to maintain PP in 9 (16.7%) of 54 simulated scenarios in Group I and 20 (37%) of 54 simulated scenarios in Group II (table 2). Among the 9 sacrificed scenarios in Group I, 90–99% of the target tidal volume and minute ventilation were met in 5 scenarios, 80–89% were met

in 3 scenarios, and 70–79% were met in 1 scenario. Among the 20 sacrificed scenarios in Group II, 90–99% of the target tidal volume and minute ventilation were met in 5 scenarios, 80–89% were met in 8 scenarios, 70–79% were met in 4 scenarios, and 60–69% were met in 3 scenarios. For both groups, in these delivered tidal volume and minute ventilation sacrificed scenarios, delivered tidal volumes with ASV were significantly lower than the fixed tidal volume of 6 ml/kg. Respiratory rates were significantly higher in ASV for sacrificed delivered tidal volume and minute ventilation settings.

Figure 1 illustrates the effect of patient ideal body weight on tidal volume. As noted, no differences were observed. The variables that had the greatest effect on tidal volume during ASV were compliance and resistance. These differences are illustrated in figure 2. PEEP level also affected delivered tidal volume during ASV (fig. 3). ASV delivered tidal volume, however, was not affected by the target minute volume (fig. 4).

Measured AutoPEEP levels were minimal during all evaluations. During ASV autoPEEP varied between 0 and 2.0 cm H₂O; during a fixed tidal volume of 6 ml/kg, autoPEEP varied between 0 and 3.5 cm H₂O and was only

Fig. 1. Target versus delivered tidal volumes during adaptive support ventilation (ASV), no differences observed. All data medians (25th–75th, min–max). T-60 (open column) = targeted tidal volume in 60-kg group; D-60 (gray column) = delivered tidal volume in 60-kg group; T-80 (open column) = targeted tidal volume in 80-kg group; D-80 (gray column) = delivered tidal volume in 80-kg group.



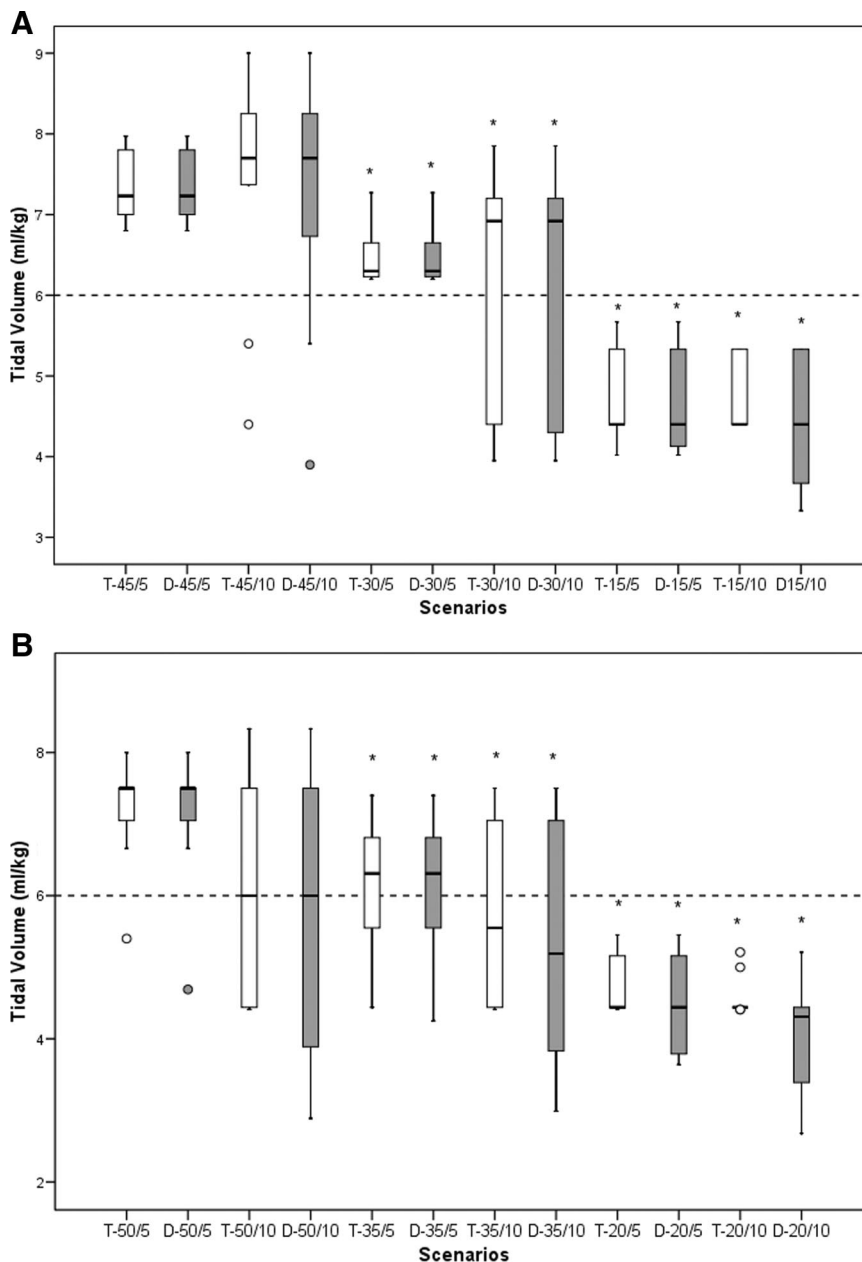


Fig. 2. The effect of compliance and resistance on targeted (T; white column) and delivered (D; gray column) tidal volume during adaptive support ventilation (ASV). (A) 60-kg group. 45/5 = compliance of 45 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 45/10 = compliance of 45 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹; 30/5 = compliance of 30 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 30/10 = compliance of 30 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹; 15/5 = compliance of 15 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 15/10 = compliance of 15 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹. (B) 80-kg group. 50/5 = compliance of 50 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 50/10 = compliance of 50 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹; 35/5 = compliance of 35 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 35/10 = compliance of 35 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹; 20/5 = compliance of 20 ml/cm H₂O, resistance of 5 cm H₂O · l⁻¹ · s⁻¹; 20/10 = compliance of 20 ml/cm H₂O, resistance of 10 cm H₂O · l⁻¹ · s⁻¹. Changes in resistance settings had no significant effect on T and D. However, as the compliance decreased, both T and D decreased significantly. All data are medians (25th–75th, min-max) with outliers (o). * *P* < 0.05.

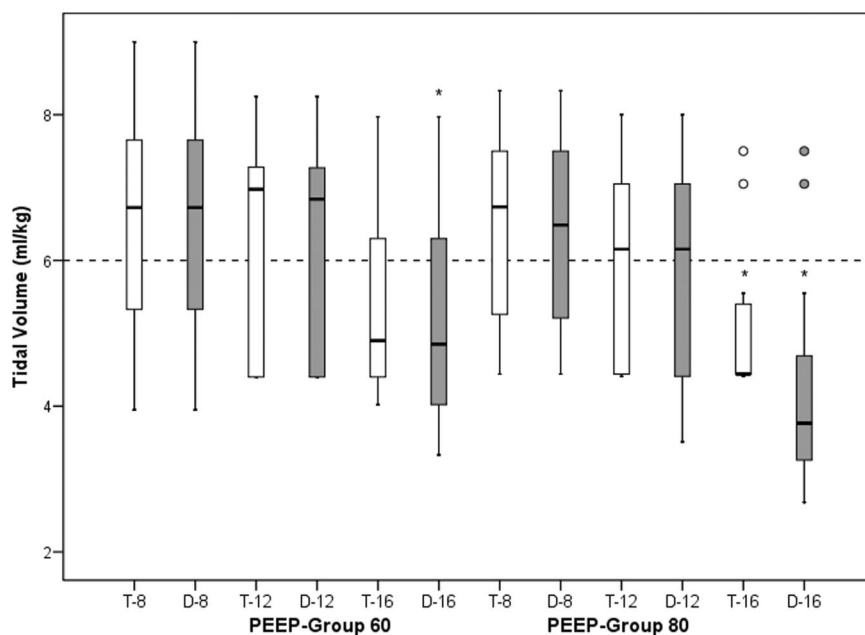
present when respiratory rate was greater than 30 breaths/min. The highest levels of autoPEEP were determined in the 80-kg group when the compliance was 15 ml/cm H₂O and resistance was 10 cm H₂O · l⁻¹ · s⁻¹ and target minute volume was set at 200% of predicted healthy normal minute volume.

In 22 (75.9%) of the total 29 delivered tidal volume and minute ventilation sacrificed scenarios, PEEP was set at 16 cm H₂O, in 5 (17.2%) at 12 cm H₂O, and in 2 (6.9%) at 8 cm H₂O. In 22 (75.9%) out of 29 scenarios, resistance was 10 cm H₂O · l⁻¹ · s⁻¹, and in 7 scenarios it was 5 cm H₂O · l⁻¹ · s⁻¹. In 13 (44.8%) out of the 29 scenarios, compliance was set at its lowest setting (15 ml/cm H₂O in Group I and 20 ml/cm H₂O in Group II), in 8 (27.6%) scenarios at a moderate setting (30 ml/cm

H₂O in Group I, 35 ml/cm H₂O in Group II), and in 8 (27.6%) scenarios at the highest setting (45 ml/cm H₂O in Group I, 50 ml/cm H₂O in Group II). In 15 scenarios (51.7%) target minute ventilation was set at 200% of the healthy normal minute volume, in 7 scenarios at 150% (24.1%), and in 6 scenarios (20.7%) at 120%.

PP were similar in ASV and a fixed tidal volume of 6 ml/kg in both groups (Group I: ASV median 25.2 [21.78–28.03, range 16.5–30.3] cm H₂O, fixed tidal volume of 6 ml/kg median 23.5 [19.38–29.9, range 15.5–37.8] cm H₂O; Group II: ASV median 24.95 [22.45–27.8, range 17.8–29.6] cm H₂O, fixed tidal volume of 6 ml/kg median 26 [21.35–30.8, range 17.30–38.2] cm H₂O; fig. 5). However, the number of simulated scenarios in which the PP was over the pressure limit (at least 28 cm H₂O)

Fig. 3. Effect of positive end expiratory pressure (PEEP) on targeted (T; *white column*) versus delivered (D; *gray column*) tidal volumes during adaptive support ventilation (ASV). In general, as PEEP increased, both T and D decreased. At PEEP of 16 cm H₂O, D was significantly lower than T in the 80-kg group. All data are medians (25th–75th, min-max) with outliers. * $P < 0.05$. 8 = PEEP of 8 cm H₂O; 12 = PEEP of 12 cm H₂O; 16 = PEEP of 16 cm H₂O.



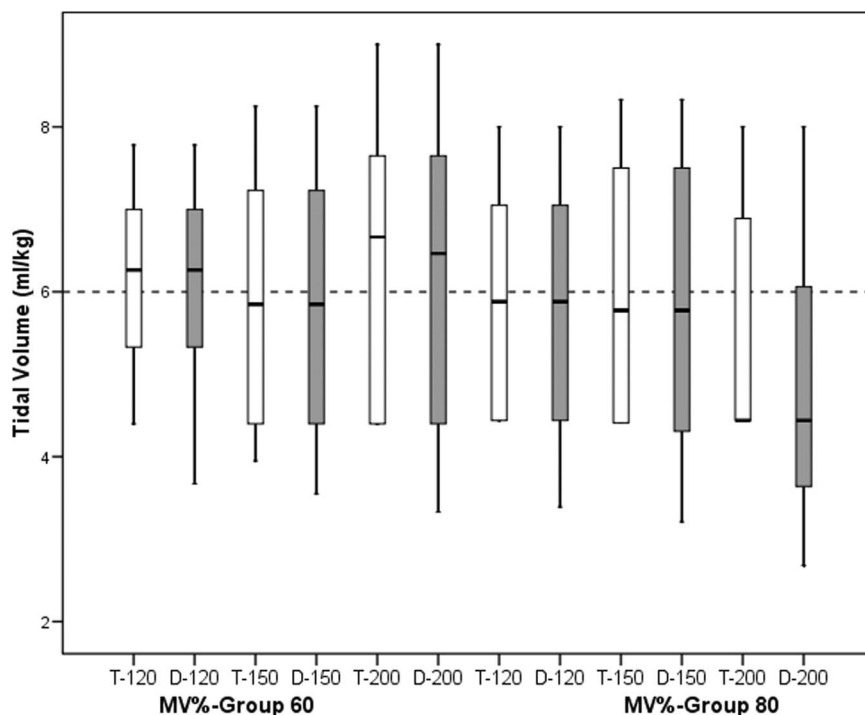
was 24 (22%) with ASV as compared to 40 (37%) for a fixed tidal volume of 6 ml/kg ($P < 0.02$). In Group I, the number of simulated scenarios in which the PP measured over the pressure limit (at least 28 cm H₂O) was 14 for ASV (25.9%) and 19 for a fixed tidal volume of 6 ml/kg (35.2%). In these simulated scenarios, PP was significantly different between ASV median 28.45 (28.1–29.3, range 28.0–30.3) and a fixed tidal volume of 6 ml/kg median 33.5 (29.1–37.1, range 28–37.8) ($P = 0.000$). In Group II, the number of simulated scenarios where PP was over the pressure limit (at least 28 cm H₂O) was 10 for ASV (18.5%) and 21 for a fixed tidal

volume of 6 ml/kg (38.8%). In these cases, PP was again significantly different between ASV (Group II: ASV median 28.65 [28.45–29.38, range 28–29.6] and a fixed tidal volume of 6 ml/kg median 33.2 [29.65–35.55, range 28.2–38.2]; $P = 0.000$; fig. 6).

Discussion

The findings of this study can be summarized as follows. (1) In a lung model, ASV is at least equivalent to a fixed tidal volume of 6 ml/kg in maintaining PP below

Fig. 4. Effect of minute ventilation (MV) target on targeted (T; *white column*) versus delivered (D; *gray column*) tidal volume during adaptive support ventilation (ASV). All data are medians (25th–75th, min-max). No significant differences were observed. 120 = minute volume of 120%; 150 = minute volume of 150%; 200 = minute volume of 200%.



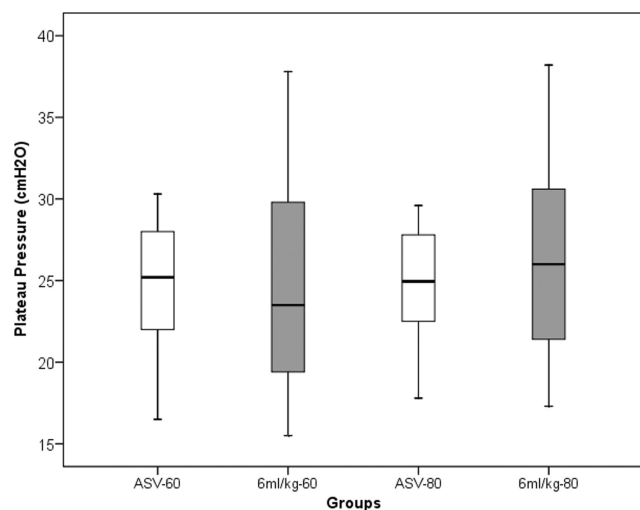


Fig. 5. Plateau pressures (PP) were similar in adaptive support ventilation (ASV; white column) and a fixed tidal volume of 6 ml/kg (gray column) settings in both groups. Group I: ASV median 25.2 (21.78–28.03, range 16.5–30.3), 6 ml/kg median 23.5 (19.38–29.9, range 15.5–37.8); Group II: ASV median 24.95 (22.45–27.8, range 17.8–29.6), 6 ml/kg median 26 (21.35–30.8, range 17.30–38.2). Data are medians (25th–75th, min-max). 60 = 60-kg Group I; 80 = 80-kg Group II.

target level during changing respiratory mechanics and maintains lower PP than a fixed tidal volume of 6 ml/kg in low-compliance, high-PEEP, high-target minute volume simulated scenarios during controlled mechanical ventilation. (2) Actual delivered tidal volume in ASV varied to a low of 2.6 ml/kg to avoid exceeding the PP limit. (3) During ASV, minute volume was sacrificed when tidal volume and respiratory rates reached their defined limits. There are a number of differences be-

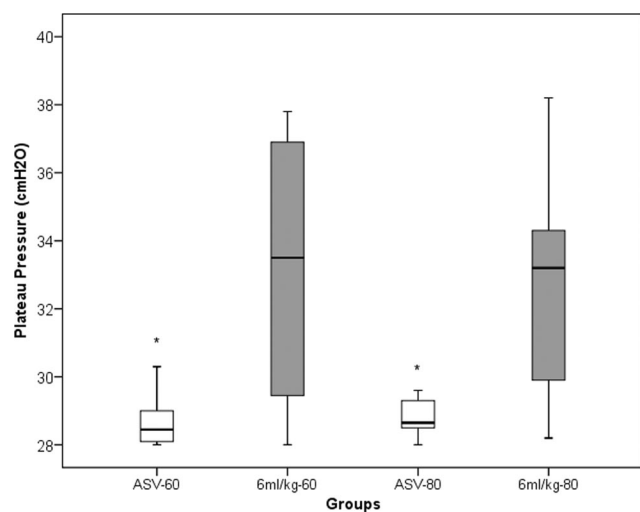


Fig. 6. In the simulated scenarios where the plateau pressures (PP) was greater than the pressure limit (at least 28 cm H₂O) mean PP were significantly higher for 6 ml/kg in both groups. Group I: adaptive support ventilation (ASV; white column) median 28.45 (28.1–29.3, range 28.0–30.3), 6 ml/kg (gray column) median 33.5 (29.1–37.1, range 28–37.8); Group II, ASV median 28.65 (28.45–29.38, range 28–29.6), 6 ml/kg median 33.2 (29.65–35.55, range 28.2–38.2). Data are medians (25th–75th, min-max). * $P = 0.000$ 60 = 60-kg Group I; 80 = 80-kg Group II.

tween ASV and the application of a fixed tidal volume of 6 ml/kg. Current recommendations for ventilator management of ARDS calls for volume-targeted ventilation, and ASV uses pressure-targeted ventilation. ASV automatically adjusts tidal volume and respiratory rate to maintain the peak pressure and minute ventilation targets, while the recommended approach requires intervention by a clinician to make any adjustment. The use of pressure *versus* volume ventilation in the management of ARDS has been debated,^{6,15–18} but no definitive data exist to support the use of either approach. The National Institutes of Health ARDS Network² used volume ventilation in both arms of all of its studies. On the other hand, Amato *et al.*¹ used pressure-targeted ventilation in the treatment arm of their original lung protective ventilation in ARDS study *versus* volume ventilation in the control arm. The treatment arm resulted in better outcome. The only evidence available supports the use of pressure ventilation. In the current study, ASV was able to adjust target tidal volume (4.4 to 9.0 ml/kg predicted body weight) and respiratory rate (15 to 45 breaths/min) to approximate the National Institutes of Health ARDS Network protocol (tidal volume 4–8 ml/kg predicted body weight). However, in those instances where the plateau limit was reached, tidal volume was reduced even further to avoid exceeding the limit by more than 2.3 cm H₂O. Essentially, ASV automatically adjusts these variables in a manner that would be required of a clinician at the bedside during the application of the National Institutes of Health ARDS Network protocol. The National Institutes of Health ARDS Network protocol defines a tidal volume range of 4 to 8 ml/kg predicted body weight, but it requires a clinician to make the change. AutoPEEP was not a major issue affecting the PP, although it ranged from 0 to 2 cm H₂O during ASV and from 0 to 3.5 cm H₂O during the ARDSnet protocol.

On the basis of the defined algorithms for ASV, we expected that the target PP would never be exceeded. As indicated, however, PP was exceeded in 24 of the 108 scenarios evaluated but by only a maximum of 2.3 cm H₂O. This less than 10% variance in the PP may have simply been a result of measurement error or the measurement of a transient pressure overshoot or the presence of low level autoPEEP. During a fixed tidal volume of 6 ml/kg the PP exceeded the target by up to 10.2 cm H₂O (fig. 6).

The minimum targeted tidal volume allowed by the ASV algorithm is 4.4 ml/kg predicted body weight (by design, two times the anatomical dead space, approximated at 2.2 ml/kg). However, the target tidal volume was further decreased if the PP limit (28 cm H₂O) was met. In eight scenarios delivered tidal volume was less than 3.5 ml/kg. In each case, however, the PP was above the target level, and visual and audio alarms were activated with the reduced tidal volume displayed. What is an acceptable minimal tidal volume in ARDS? Clearly,

because of consolidation and atelectasis, actual anatomic dead space is not 2.2 ml/kg; however, physiologic dead space to tidal volume ratios are increased in ARDS.^{19–21} This reduction in tidal volume in ASV in the presence of excessive PP essentially ensures the development of permissive hypercapnia, which may or may not be advisable in a given patient. As a result, the clinician must determine if the potential wide range of tidal volume change and P_{CO_2} /pH change is acceptable for the particular patient before the application of ASV. In addition, the ASV algorithm allowed tidal volume to increase to 9 ml/kg, which may be excessive and cause overdistention. Consideration of limiting the maximum tidal volume to 8 ml/kg as recommended by the National Institutes of Health ARDS Network should be made. However, in all settings where the tidal volume reached 9 ml/kg, PP was considerably less than 28 cm H₂O.

As tidal volume decreased in ASV, the respiratory rate increased but the increase in rate is limited by the selected minute volume and rate. The greater the minute volume selection, the greater the allowed increase in the rate. This is consistent with the basic algorithm for ASV, but it prevents the increase in rate needed to achieve the minute ventilation target when the plateau limit is reached. This is because the ASV algorithm is based on Otis' least work of breathing concept.⁴ Thus, on the basis of the patients' lung mechanics, the algorithm determines the respiratory rate and tidal volume resulting in least work at the set minute ventilation. The algorithm, however, does not allow the rate to increase if tidal volume is decreased because the pressure limit is reached.

Respiratory rate depends on the expiratory time constant and minimum tidal volume calculated as $2 \times$ dead space (ideal body weight \times 2.2). In the low-compliance scenarios, the expiratory time constant decreased accordingly, and target minute ventilation was met by a combination of high respiratory rates and low tidal volumes with lower PP. In scenarios where target minute ventilation could not be met, tidal volume was limited by the PP limit, and maximum rate was limited by the ASV algorithm. In these settings, patients may be better served if the algorithm allowed respiratory rate to increase to a level only limited by the development of auto-PEEP.

The basic application of ASV has four safety limits: too low a frequency to prevent apnea, too high a frequency to prevent autoPEEP, too low a tidal volume to prevent tachypnea or insufficient alveolar ventilation, and too high a tidal volume to prevent volutrauma or barotrauma.²² On the basis of the ventilator's assessment of the patient's compliance and expiratory time constant and the clinician's selection of target PP and minute ventilation, a target frequency and tidal volume resulting in the least work of breathing is identified. Adjustments of inspiratory pressure and frequency are made to achieve the

target tidal volume and frequency within the limits defined.

It should be appreciated that ASV is similar to pressure control ventilation and pressure regulated volume control.⁵ Individual breaths are indistinguishable, and ASV provides a breath by using the same gas delivery pattern as pressure control and pressure-regulated volume control. However, the comparison ends when response to changing lung mechanics is compared. With pressure control, a pressure target and backup rate are set and only change on the basis of clinician adjustment. When lung mechanics change, pressure control does not determine the ventilator pattern that results in the least work of breathing. In most applications of pressure control, the tidal volume does decrease as the lung becomes stiffer but the rate only increases if the patient is actively breathing. In pressure-regulated volume control, the tidal volume is maintained constant by varying the pressure level. This is a concern if the lung and chest compliance decreases, which would increase the pressure applied to maintain the target tidal volume.

Earlier studies on ASV concentrated on weaning from mechanical ventilation predominantly in postoperative patients, and ASV was found to simplify ventilator management reducing the time to extubation.^{23–27} Recently, studies have focused on the role of ASV in the mechanical ventilation of patients with acute respiratory failure. Arnal *et al.*²⁸ reported on the use of ASV in 243 patients with various lung conditions (normal lung, chronic obstructive pulmonary disease, acute lung injury/ARDS, chest wall stiffness). They concluded that ASV selected different tidal volume-respiratory rate combinations on the basis of respiratory mechanics in these passively ventilated patients. Arnal *et al.*²⁹ also reported on the use of ASV in 45 ARDS patients and observed that in 60% of the patients ASV automatically selected a tidal volume below 8 ml/kg predicted body weight and adjusted tidal volume as the patients' lung mechanics changed over time. In the light of emerging evidence, the debate of whether or not adaptive pressure control modes, including ASV, should be used for all patients receiving mechanical ventilation is still ongoing.⁵

Limitations

There are a number of limitations to this study. (1) This study was not performed on patients; as a result, the data cannot be directly extrapolated to patients. However the use of a lung simulator allowed us to precisely vary lung mechanics and define the precise responses of this mode of ventilation. (2) The study was only performed during controlled mechanical ventilation; as a result, we cannot precisely predict how ASV would perform during assisted ventilation. However, it is expected that this would depend on the level of ventilatory demand. In patients with weak ventilatory demands, ASV would be expected to perform similar to what we observed. How-

ever, if ventilatory demand is high, large tidal volumes may be delivered, even if the peak airway pressure is markedly diminished. Data in spontaneously breathing patients requiring mechanical ventilation are needed to verify the function of ASV in assisted ventilation. (3) Tests were performed by using two ideal body weights (60–80 kg); these weights clearly do not represent the spectrum of patients presenting with ARDS. However, we have no indications that the mode of ventilation would operate differently within its defined ideal body weight range. (4) The ASL5000 acted as a single lung compartment. The complexities of the multiple compartments in the human lung were not simulated in this model. (5) An endotracheal tube was not used; the ventilator wye was directly connected to the lung model. However the total system resistance was equal to that reported in acute lung injury/ARDS patients.^{1,2,7–12} (5) Finally, the dynamics of change over time as respiratory mechanics change in real patients²⁰ cannot be adequately assessed in a simulation study.

Conclusion

ASV maintains lower PP than a fixed tidal volume of 6 ml/kg in low-compliance, high-PEEP, high-target minute volume simulated scenarios. ASV does sacrifice tidal volume and minute volume to maintain PP and respiratory rate targets. In a lung model with varying compliance, ASV is better able to prevent the potential damaging effects of excessive PP (greater than 28 cm H₂O) than a fixed tidal volume of 6 ml/kg by automatically adjusting airway pressure resulting in a decreased tidal volume. However, clinical trials are necessary to determine if this potentially beneficial effect will affect patient outcome.

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