Customization of an Open-Lung Ventilation Strategy to Treat a Case of Life-Threatening Acute Respiratory Distress Syndrome

David A Grooms RRT, Stephen H Sibole RRT, James R Tomlinson MD, Paul E Marik MD, and Robert L Chatburn MHHS RRT-NPS FAARC

The ARDS Network low-tidal-volume protocol is considered the standard of care for patients with acute lung injury (ALI) or acute respiratory distress syndrome (ARDS). The protocol is built on the foundation of low-tidal-volume ventilation, use of a combined PEEP and F_{IO_2} table, and managing alveolar end-inspiratory pressure by limiting the plateau airway pressure to ≤ 30 cm H_2O. Although this strategy, to date, is the only method that significantly improves ALI/ARDS survival, alternative methods of improving hypoxemia and minimizing ventilator-induced lung injury, in conjunction with low-tidal-volume ventilation, can be used for life-threatening ARDS. We present a case in which we customized the use of alveolar recruitment maneuvers by analyzing the hysteresis of the pressure-volume curve to assess lung recruitability, decremental PEEP to sustain lung recruitment, and careful use of plateau pressure ≥ 30 cm H_2O, which improved our patient's life-threatening hypoxemia within the first 36 min of arrival to our ICU. *Key words: acute lung injury; acute respiratory distress syndrome; positive end expiratory pressure; PEEP; lung recruitment; fraction of inspired oxygen; pressure-volume curve; ALI; ARDS; optimum PEEP; decremental PEEP trial*. [Respir Care 2011;56(4):514–519. © 2011 Daedalus Enterprises]

Introduction

Acute respiratory distress syndrome (ARDS) is a life-threatening condition in which an acute insult to the lungs causes inflammation, alveolar capillary permeability, alveolar flooding, low P_{aO_2}, and respiratory distress.[1] In its most severe form, ARDS is characterized by acute-onset hypoxemia (P_{aO_2}/F_{IO_2} ≤ 200 mm Hg) with bilateral infiltrates on the chest radiograph and the absence of left atrial hypertension.[2] Patients with ARDS usually require mechanical ventilatory support.

We present a case where the patient's poor oxygenation was restored by careful implementation of ventilator strategies not currently recommended for routine use, but that share a commonality with open-lung ventilation concepts.[3-6] Our strategy included:

- Alveolar recruitment maneuvers, with a quasi-static pressure-volume (P-V) curve with an end-inspiratory hold
- Analysis of the P-V curve hysteresis and recruitment volume
- PEEP is set in a decremental fashion following the recruitment maneuver
- Low-tidal-volume (low-V_T) ventilation of 6 mL/kg predicted body weight (PBW)
- Plateau pressure can be greater than 30 cm H_2O

We continually adjusted this strategy to improve arterial oxygenation while minimizing ventilator-induced lung injury (VILI).

David A Grooms RRT, Stephen H Sibole RRT, James R Tomlinson MD are affiliated with Sentara Norfolk General Hospital, Sentara Healthcare System, Norfolk, Virginia. Paul E Marik MD is affiliated with Eastern Virginia Medical School, Norfolk, Virginia. Robert L Chatburn MHHS RRT-NPS FAARC is affiliated with the Respiratory Institute, The Cleveland Clinic, and with Lerner College of Medicine, Case Western Reserve University, Cleveland, Ohio.

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Correspondence: David A Grooms RRT, Sentara Norfolk General Hospital, 600 Gresham Drive, Norfolk VA 23507. E-mail: dxgrooms@sentara.com.

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Table 1. Ventilator Settings and Blood Gas Values

	At Initiation of MV	9 h After Initiating MV	33 h After Initiating MV	35 h After Initiating MV*	45 min After Arrival	4 h After Arrival	10 h After Arrival	18 h After Arrival	24 h After Arrival	48 h After Arrival
Ventilation mode	VC-CMV	VC-CMV	VC-CMV	PC-CMV	PC-CMV	PC-CMV	PC-CMV	PC-CMV	PC-CMV	PC-CMV
V_T (mL/kg PBW)	8	6	6	6	6	6	6	6	6	6
Respiratory rate (breaths/min)	12	20	16	20	20	20	20	20	20	20
PEEP (cm H_2O)	5	15	15	15	22	22	22	20	14	12
Plateau pressure (cm H_2O)	23	30	30	30	35	34	33	31	27	25
F_{IO_2}	1	1	1	1	1	0.7	0.6	0.6	0.5	0.5
pH	7.44	7.45	7.34	7.17	7.22	7.32	7.27	7.26	7.35	7.45
P_{aCO_2} (mm Hg)	32	28	34	51	45	31	30	41	34	38
P_{aO_2} (mm Hg)	124	83	73	54	169	149	81	139	83	80
P_{aO_2}/F_{IO_2} (mm Hg)	124	83	73	54	169	213	135	231	166	160
Respiratory system compliance (mL/cm H_2O)	27	24	24	24	22	30	23	26	32	33

* 1 hour prior to transfer to our facility.
MV = mechanical ventilation
VC = volume control
PC = pressure control
CMV = continuous mandatory ventilation
PBW = predicted body weight

Case Report

A 33-year-old, 160-cm, 90 kg (body mass index 35 kg/m^2) female was admitted to an outside hospital for dehydration and malnutrition, after presenting to the emergency department with a general feeling of weakness. Her medical history included a Roux-en-Y gastric bypass procedure 11 years prior to this admission. She presented with progressive history of malabsorption (albumin 1.2 g/dL), constipation, rectal prolapse, anemia (hemoglobin 11 g/dL, hematocrit 33%), and shortness of breath. She was also non-responsive to empirical antibiotics and steroids as an out-patient. She had developed oral thrush with current steroid use and had stopped eating due to painful swallowing. In the 24 hours following admission her condition progressively worsened and she was witnessed aspirating. She was moved to the ICU for intubation and mechanical ventilation due to worsening hypoxemia. She was diagnosed with ARDS secondary to aspiration pneumonia. Chest radiograph after intubation revealed dense bilateral infiltrates consistent with edema. Arterial blood analysis showed severe hypoxemia on lung-protective ventilation per the ARDS Network protocol (Table 1). Initial management included low-V_T (6–8 mL/kg PWB), volume control continuous mandatory ventilation, incremental PEEP titrations to 15 cm H_2O, and plateau pressure not exceeding 30 cm H_2O. Her predicted body weight was calculated with the equation:

$$PBW\ (kg) = 45.5 + 2.3\ (height\ (in) - 60)$$

Difficulties in oxygenation and a deteriorating medical condition resulted in a change to pressure control continuous mandatory ventilation, while ensuring low-V_T ventilation, and, ultimately, transfer to our facility 48 hours after intubation.

Upon arrival the patient was cyanotic, with S_{pO_2} of 54%. Additional problems included hypovolemia, probable septic shock, and acute renal failure. Medical interventions at this time included sedation and a neuromuscular blocking agent, fluid boluses to maintain a minimum central venous pressure of 4–8 mm Hg,[7,8] and vasopressors to maintain a mean arterial pressure of ≥ 65 mm Hg. Steroids were not given, because her baseline cortisol level was 31.6 μg/dL.

Our modification of the initial ventilation strategy (pressure control continuous mandatory ventilation with V_T of 6 mL/kg PBW) included incorporation of alveolar recruitment maneuvers with PEEP adjustments based on a quasi-static P-V curve and decremental PEEP trials. Key points on the P-V curve include the lower inflection point, the additional recruitable volume (identified during the inspiratory pause), and the point of maximum hysteresis, which is the largest volume difference between the inspiratory and expiratory curves. These procedures were performed as follows.

Soon after the patient was admitted to our ICU, we generated an automated, low-flow quasi-static P-V curve, using the PV Tool II on the Galileo ventilator (Hamilton Medical, Bonaduz, Switzerland). Automated P-V curves are also commercially available on the Viasys Avea and Dräger Evita XL ventilators. In the absence of automated

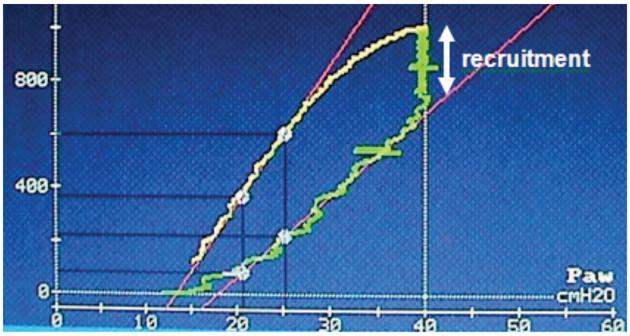

Fig. 1. Initial airway pressure (P_{aw}) versus volume curve, beginning from a baseline PEEP of 15 cm H_2O, increasing to a recruiting pressure of 40 cm H_2O. Pressure is automatically increased by 3 cm H_2O per second during the maneuver. The inspiratory curve is green. The expiratory curve is yellow. The red lines indicate the inspiratory and expiratory chord compliance through the white points on the curves.

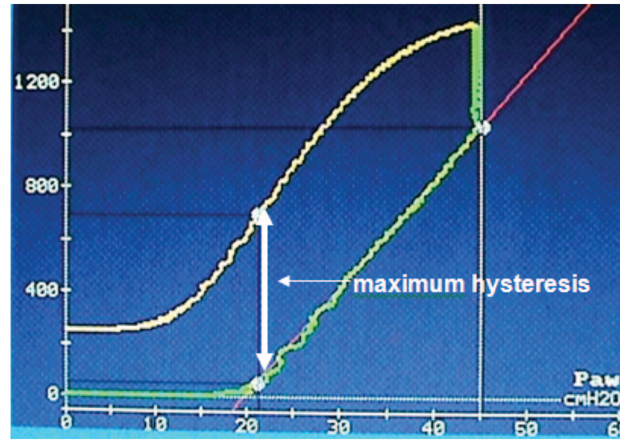

Fig. 2. Second airway pressure (P_{aw}) versus volume curve, beginning from a baseline PEEP of 0 cm H_2O increasing to a recruiting pressure of 45 cm H_2O. The pressure-volume curve hysteresis is greatest around 22 cm H_2O.

P-V curves, one can use any commercially available ventilator to perform this, as previously described.[9] The maneuver was performed beginning from a baseline PEEP of 15 cm H_2O, increasing to a recruiting pressure of 40 cm H_2O, followed by a decrease to baseline PEEP. A recruiting pressure of 40 cm H_2O was chosen because of: a suspicion of stiff chest wall mechanics due to her obesity; our understanding of previously reported literature, which suggested the safe use of such recruiting pressures with minimal adverse hemodynamic effects[10-15]; and limiting the recruitment V_T to around 1,000 mL, based on static compliance, which we calculated as:

$$\text{Static compliance } 24 \text{ mL/cm } H_2O \times 40 \text{ cm } H_2O = 960 \text{ mL expected recruited volume}$$

We also used an end-inspiratory pause of 23 seconds during the maneuver, for a total maneuver time of 40 seconds (Fig. 1). The pressure is automatically increased by 3 cm H_2O per second during the maneuver (other ventilators control flow rather than pressure during automated P-V curve maneuvers).[16] In Figure 1 the inspiratory curve is shown in green and the expiratory curve in yellow. The red lines indicate inspiratory and expiratory chord compliances through the white points on the curves. The inspiratory curve compliance was 24 mL/cm H_2O. The expiratory curve compliance was 44 mL/cm H_2O. The white points were chosen in order to superimpose the red lines over the linear slopes of the curves, to identify the point at which the curve's trajectory deviates from the red lines. This deviation can be interpreted as the pressure at which alveolar behavior changes, indicating recruitment or derecruitment. The black lines project off of the white dots to indicate values of both pressure and volume.

The point of maximum hysteresis, as described by Demory et al[3] and Koefoed-Neilsen et al,[17] was initially observed to be greatest around 30–35 cm H_2O, but was thought to be high because of performing the maneuver at a PEEP of 15 cm H_2O. However, there was an increase in end-inspiratory recruitable volume of greater than 300 mL (white arrow in Fig. 1). Recruitment is observed as an increase in lung volume (vertical green line) at the end-inspiratory hold (40 cm H_2O). The fact that this particular maneuver is a pressure controller rather than a flow controller allows volume to accumulate in this manner at constant pressure if recruitable lung is available. S_{pO_2} increased immediately after the maneuver, from 54% to 75%, with the previous ventilator settings (PEEP 15 cm H_2O, F_{IO_2} 1.0), but over the subsequent 2 minutes S_{pO_2} decreased to 70%.

A second recruitment maneuver was performed, with an end-inspiratory pause of 20 seconds and a recruiting pressure to 45 cm H_2O (Fig. 2). A start and end pressure of 0 cm H_2O was used to obtain a better analysis of the alveolar pressures at which recruitment and derecruitment occurred. Following the second recruitment maneuver, S_{pO_2} improved to 93%, still with the prior ventilator settings. Analysis of the P-V curve indicated that the point of maximum hysteresis was an alveolar pressure of approximately 22 cm H_2O (see Fig. 2), indicating a potential optimal PEEP. During the subsequent 15 min, with a PEEP of 15 cm H_2O, S_{pO_2} decreased from 93% to 88%, again suggesting alveolar derecruitment.

A third recruitment maneuver was performed with pressure control continuous mandatory ventilation, a PEEP of 45 cm H_2O, and an inspiratory pressure of 5 cm H_2O (ie, peak airway pressure 50 cm H_2O), for 45 seconds. This maneuver was simply done to re-recruit alveoli that had collapsed as a result of persistently setting the PEEP at 15 cm H_2O following the recruitment maneuvers. The inspiratory-time setting was set long enough to allow inspiratory flow to decay to zero, which allowed for the safe assumption that plateau pressure was equal to peak airway pressure. S_{pO_2} immediately increased to 99%. This response suggested the potential for a higher PEEP setting. To minimize potential de-recruitment of newly opened lung units, we proceeded with a decremental PEEP maneuver. Thus, with the inspiratory pressure remaining at 5 cm H_2O, PEEP was decreased in 5 cm H_2O increments every minute, down to a PEEP of 22 cm H_2O.

Hemodynamic variables (heart rate and blood pressure) were stable prior to and remained unchanged during and after all the recruitment maneuvers. Following the final PEEP adjustment, inspiratory pressure was increased to 13 cm H_2O to restore V_T to 6 mL/kg PBW. Peak airway pressure was 35 cm H_2O, with inspiratory flow decaying to zero, indicating pressure equilibration between circuit and alveolar pressure. An inspiratory hold confirmed that plateau pressure was indeed 35 cm H_2O. S_{pO_2} was sustained at 99% throughout the PEEP titrations. Within the next 4 hours we reduced F_{IO_2} to 0.7 with S_{pO_2} remaining above 99%. Serial chest radiographs showed improved aeration. During the next 48 hours further F_{IO_2} reductions were achieved and PEEP was decreased based on serial P-V curves (see Table 1). The patient was successfully extubated on day 5 after arrival at our facility, and was discharged from the hospital on day 19.

Discussion

This case demonstrates how several ventilation strategies can be woven together in the face of a deteriorating clinical condition. These interventions are not generally recommended for routine use, and should be given careful consideration. Although there are data in the literature regarding each of these techniques (none of which show a survival benefit), there are no studies comparing these various tactics to one another for management of severe hypoxemia. In contrast, if used appropriately, they can assist in individualizing the ventilator settings to the patient's lung mechanics, while providing lung protection. Culturally, we have incorporated the ARDS Network protocol into clinical practice because it decreases mortality[1] and provides simplicity that helps reduce ALI/ARDS practice variation. However, clinicians, at times, are reluctant to consider alternative approaches if desirable goals are not met within the protocol. In particular, most clinicians rely solely on lung-protective ventilation and the ARDS Network PEEP/F_{IO_2} table, but in some cases, simply raising the F_{IO_2} and/or PEEP are not adequate to improve oxygenation, which warrants the use of other tactics. Tactics in addition to those we used in the patient described above include prone positioning, inhaled vasodilators, high-frequency ventilation, and PEEP guided by esophageal manometry. We did not consider the latter tactics in the patient described above, because they require additional personnel or equipment, whereas the tactics we used did not. This case study demonstrates how analysis of an automated P-V curve, followed by recruitment maneuvers, a decremental PEEP strategy, and a V_T of 6 mL/kg PBW while allowing plateau pressure to exceed 30 cm H_2O because of obesity-related stiff chest wall mechanics, were used to safely individualize the ventilation care plan while providing lung protection and restoring normoxia.

The ventilation strategy for ARDS has changed over the last decade. The focus has shifted from normalizing the arterial blood gas values with high V_T, to a strategy that minimizes both alveolar stretch due to excessive V_T (volutrauma) and the repetitive opening and collapse of diseased alveoli (atelectrauma). This approach aims to reduce inflammatory cytokine and neutrophil elastase production (biotrauma).[18] The first focus has been addressed with reduced V_T and plateau pressure, whereas the second may be achieved with the use of recruitment maneuvers to open collapsed lung units, and high PEEP.[6]

Several methods for performing recruitment maneuvers exist,[13-15,19,20] but, without computed tomography, most fail to use the pressure-volume relationship of the lung to quantify lung recruitability and/or lung de-recruitment.[10] Demory and colleagues in a "preliminary and exploratory" study, used quasi-static P-V curves to estimate lung recruitability.[3] They found a significant relationship between the maximum hysteresis (the difference between the inspiratory and expiratory volumes at a given alveolar pressure) and the volume increase during a recruitment maneuver. Koefoed-Nielsen also found, in a porcine lung injury model, that PEEP set at 90% of maximum hysteresis gave similar oxygenation, higher quasi-static compliance of the respiratory system, fewer hyperaerated areas, and less cardiovascular depression than did PEEP set at the lower inflection point or the point of maximum curvature.[17] This relationship, if confirmed, may assist in identifying patients who would benefit from a recruitment maneuver. However, careful consideration should be given to the use of recruitment maneuvers, because in certain patients they may be poorly tolerated (hemodynamic instability, pulmonary emphysema). The P-V curves from our patient indicated the potential benefits of a recruitment maneuver followed by a modified decremental PEEP strategy. Also, further assessment of Figures 1 and 2 shows a commonality that may explain why our patient persistently de-recruited on PEEP of 15 cm H_2O following the recruitment maneuvers. Despite the end-exhalation pressure at which the recruitment maneuvers began (zero vs 15 cm H_2O), initial recruitment is not observed until alveolar pressure exceeds 17–18 cm H_2O, in both curves. Prior to each recruitment maneuver we analyzed the expiratory flow pattern and performed a manual expiratory hold to assess for intrinsic PEEP, and found no intrinsic PEEP, so this could represent the chest wall pressure that must be overcome to recruit alveoli. Therefore, if the end-expiratory alveolar pressure falls below 17–18 cm H_2O, alveoli may be unable to sustain persistent opening, leading to VILI and worsening hypoxemia.

Hickling[4] and Girgis et al[5] have proposed that PEEP should be set in a decremental fashion following lung recruitment. This method is simply a PEEP trial that adjusts PEEP from a higher level to a lower level.[5] The minimum PEEP is the PEEP required to maintain the oxygenation benefit of the recruitment maneuver. Minimum PEEP maintains the lung above the point of maximum hysteresis on the deflation part of the P-V curve. During the initial care of our patient we observed desaturation each time the PEEP was restored to 15 cm H_2O following the recruitment maneuver, which suggests lung derecruitment due to decreased end-expiratory alveolar pressure. We performed a modified decremental PEEP trial, decreasing PEEP by 5 cm H_2O every minute, down to a PEEP of 22 cm H_2O (based on P-V curve hysteresis).

A recent approach demonstrated significant improvement in oxygenation and static lung compliance using esophageal pressure (measured via esophageal balloon) to guide PEEP adjustment to minimize end-expiratory transpulmonary pressure.[21] This method was not initially considered in our patient, because we wanted to minimize the number of invasive procedures (eg, placement of esophageal balloon) until she was medically stable, and at the time we were unaware of studies on the association of esophageal pressure and lung recruitability. V_T of 6 mL/kg PBW was restored after the decremental PEEP process, resulting in a plateau pressure of 34–35 cm H_2O. Figure 3 illustrates our algorithm.

Acceptance of a plateau pressure exceeding 30 cm H_2O appeared appropriate in our patient. Recently, Meade et al[6] examined the mortality effect of an open-lung approach that combines V_T, recruitment maneuvers, high PEEP, and plateau pressure less than 40 cm H_2O, compared to an established low-V_T ventilation strategy in patients with moderate to severe lung injury. They found an equivalent mortality rate, but the open-lung strategy was better in secondary end points, related to hypoxemia and fewer rescue therapies. For our patient we perceived that approach as acceptable because of an established understanding that, at times, plateau pressure and V_T are not primary surrogates for lung stress and strain.[22] Maximum tidal transalveolar pressure (stress), and actual tissue stretch (strain) are the primary cause of VILI. Talmor et al[21] used esophageal-pressure-guided PEEP for ARDS management. Despite the finding that plateau pressure reached as high as 35 cm H_2O, end-inspiratory P_{tp} never exceeded 24 cm H_2O and did not differ significantly from the control group. This suggests that alveolar stress may remain tolerable

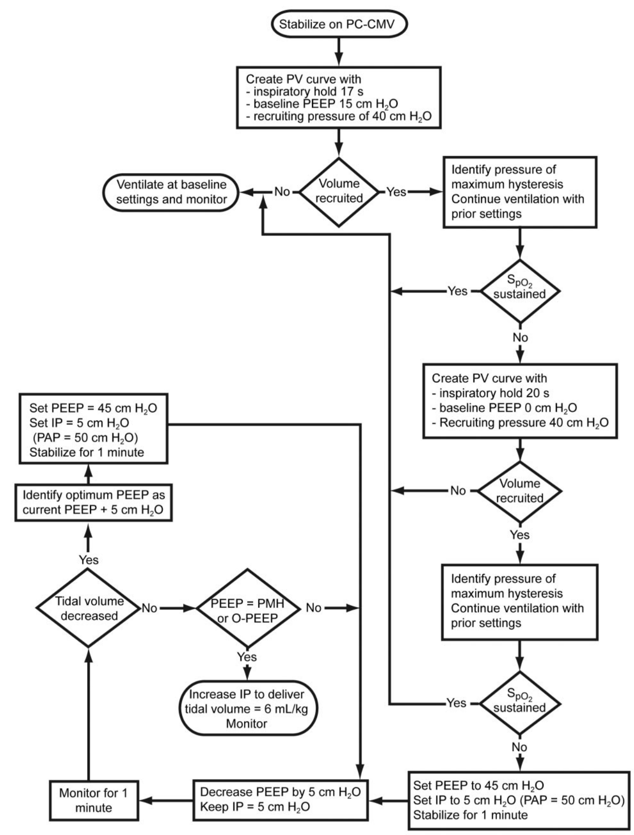

Fig. 3. The PEEP optimization algorithm we used with this patient. PC-CMV = pressure control continuous mandatory ventilation. PV = pressure-volume. IP = inspiratory pressure above PEEP, O-PEEP = optimum PEEP, PMH = pressure of maximum hysteresis. PAP = peak airway pressure.

despite increasing plateau and pleural pressure generated by an opposing stiff chest wall.

Although the ARDS Network protocol was designed to streamline our approach to ventilating ARDS patients, and has a survival benefit, it does not discourage the use of rescue therapies in life-threatening situations. The tactics discussed above improved our patient's oxygenation while minimizing VILI. These tactics are not recommended for routine use, because no evidence of a mortality benefit has been demonstrated. Careful consideration of clinical indications and contraindications must be given to their application. However, if carefully utilized, they can provide additional information for individualizing the ventilator settings to safely oxygenate and ventilate a patient in relation to the patient's lung mechanics. At present, these rescue therapies should remain as alternatives until the patient's clinical picture warrants their use.

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