Measurement of Air Trapping, Intrinsic Positive End-Expiratory Pressure, and Dynamic Hyperinflation in Mechanically Ventilated Patients

Lluís Blanch MD PhD, Francesca Bernabé MD, and Umberto Lucangelo MD

Severe airflow obstruction is a common cause of acute respiratory failure. Dynamic hyperinflation affects tidal ventilation, increases airways resistance, and causes intrinsic positive end-expiratory pressure (auto-PEEP). Most patients with asthma and chronic obstructive pulmonary disease have dynamic hyperinflation and auto-PEEP during mechanical ventilation, which can cause hemodynamic compromise and barotrauma. Auto-PEEP can be identified in passively breathing patients by observation of real-time ventilator flow and pressure graphics. In spontaneously breathing patients, auto-PEEP is measured by simultaneous recordings of esophageal and flow waveforms. The ventilatory pattern should be directed toward minimizing dynamic hyperinflation and auto-PEEP by using small tidal volume and preserving expiratory time. With a spontaneously breathing patient, to reduce the work of breathing and improve patient-ventilator interaction, it is crucial to set an adequate inspiratory flow, inspiratory time, trigger sensitivity, and ventilator-applied PEEP. Ventilator graphics are invaluable for monitoring and treatment decisions at the bedside. *Key words: dynamic hyperinflation, intrinsic positive airway pressure, mechanical ventilation, positive end-expiratory pressure, work of breathing, hyperinflation, waveforms.* [Respir Care 2005;50(1):110–123. © 2005 Daedalus Enterprises]

Introduction

Acute respiratory failure requiring mechanical ventilatory support in patients with severe airflow obstruction has been one of the most frequent causes of admission to intensive care units for more than 40 years. Asthma and chronic obstructive pulmonary disease (COPD) are invariably associated with acute or chronic airflow obstruction

that imposes a substantial mechanical load on the respiratory system. Airflow obstruction develops when airway diameter is narrowed by bronchospasm, mucosal or interstitial edema, exudates of inflammatory cells, mucus, and (among patients with COPD) dynamic airway collapse during expiration.[1,2]

During severe airflow obstruction episodes, increased expiratory efforts simply raise alveolar pressure without improving expiratory airflow. In exacerbations of COPD and asthma, alveolar ventilation is preserved at the expense of increased work of breathing (WOB). If tidal volume (V_T) is high or if expiratory time is short because of a high respiratory rate, the lung cannot deflate to its usual resting equilibrium volume between breaths. Several pathophysiologic consequences result from the increase in lung volume and alveolar pressure: (1) end-expiratory lung volume exceeds predicted functional residual capacity (FRC), causing dynamic hyperinflation, (2) respiratory system compliance decreases, (3) the respiratory muscles progressively operate in an unfavorable part of their length-tension curve. Finally, breathing takes place in the upper and less compliant part of the lung pressure-volume relationship, near total lung capacity. In that setting, if exhaustion has not yet occurred, spontaneous breathing cannot be sustained for long, and the patient is at high risk of sudden respiratory arrest.[1,3–6]

Description of Dynamic Hyperinflation and Intrinsic Positive End-Expiratory Pressure

In normal subjects, lung volume at end-expiration approximates the relaxation volume of the respiratory system. However, in patients with airflow obstruction, the end-expiratory lung volume may exceed predicted FRC. Indeed, lung emptying is slowed and expiration is interrupted by the next inspiratory effort, before the patient has

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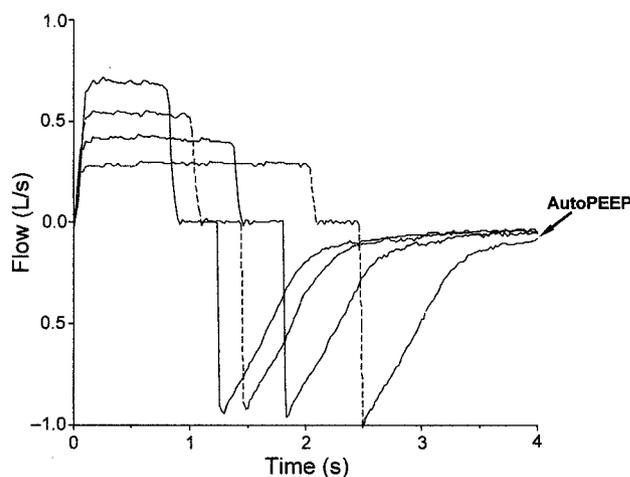

Fig. 1. Flow waveform showing air trapping by decreasing flow at equal tidal volume. Progressive reduction in expiratory time generates auto-PEEP when the expiratory time is not long enough to exhale all of the preceding tidal volume.

reached the static equilibrium volume.[3,4] This is termed *dynamic hyperinflation* and is affected by V_T, expiratory time, resistance, and compliance (Fig. 1).[4,7–9] This phenomenon, also called intrinsic positive end-expiratory pressure (auto-PEEP), was first described by Bergman[10] in 1972 and Jonson et al[11] in 1975. Its clinical implications and measurement technique during mechanical ventilation were further described by Pepe and Marini[9] in 1982.

External Factors

Most patients with asthma and COPD have dynamic hyperinflation and auto-PEEP during mechanical ventilation. However, dynamic hyperinflation and auto-PEEP can occur in the absence of expiratory flow limitation.[12] Under conditions of high minute volume ($\dot{V}_E$) and/or increased equipment expiratory resistance (eg, a mucus-narrowed endotracheal tube or heat-and-moisture exchanger),[13,14] the lungs do not have enough time to reach normal FRC, so expiratory flow driven by the difference in pressure between alveoli and the airway opening is still present at end-expiration, despite the fact that airways are open.[15]

Intrinsic Factors: Dynamic Airway Collapse

Elastic and resistive loads affect WOB. Elastic WOB increases when lung or chest wall compliance is reduced or when there is dynamic hyperinflation with auto-PEEP. COPD patients ventilated for exacerbations of airflow obstruction experience dynamic airway collapse and flow-limitation during tidal breathing.[12,16] Anatomical abnormalities in COPD include regional differences in airway caliber, loss of lung elasticity, and alterations in alveolar
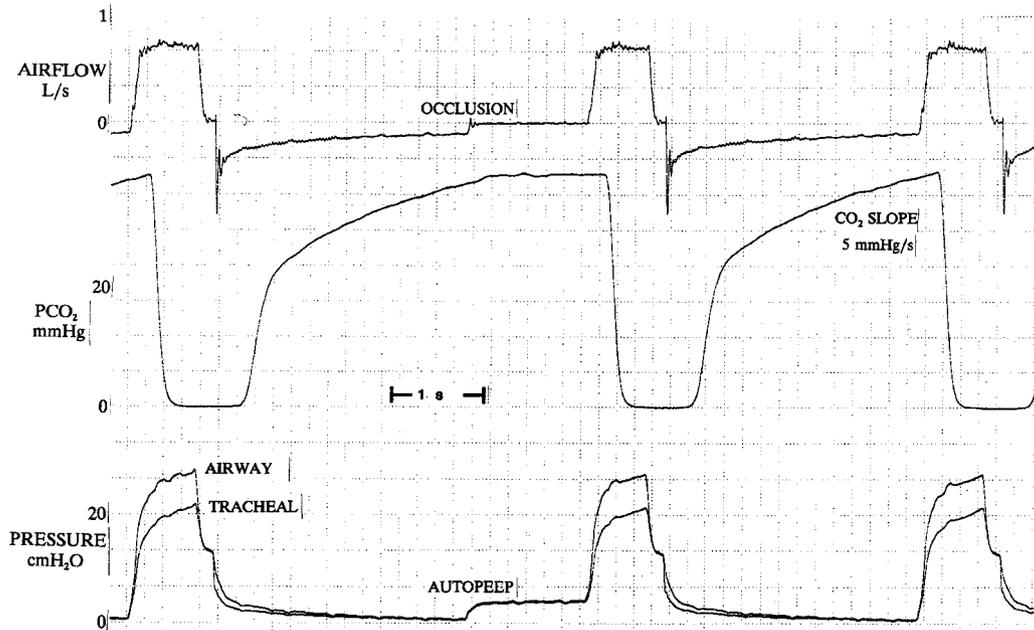
Fig. 2. Flow, carbon dioxide, tracheal pressure, and airway pressure in a patient with severe airflow obstruction. After a long expiratory time, intrinsic positive end-expiratory pressure (auto-PEEP) is still present (end-expiratory occlusion maneuver), indicating severe dynamic hyperinflation.

geometry. Compression and critical closure takes place in the small airways, and air trapping occurs distal to the site of critical closure.[4,9,12,17] In that setting, increasing expiratory effort raises pleural and alveolar pressure to the same extent, without improving expiratory airflow. Although flow limitation is usually an active process, it can occur during passive deflation (ie, during tidal ventilation) if alveolar pressure exceeds airway pressure in deformable small airways.[12] In patients receiving mechanical ventilation there is a significant correlation between expired-carbon-dioxide slope, respiratory-system resistance, and auto-PEEP, which suggests that dynamic hyperinflation originates from sequential emptying of slow hypercapnic units.[18] Carbon dioxide elimination is impaired by flow-resistance, and the degree of airway obstruction modulates the rate of P_{CO_2} increase during expiration (Fig. 2).

Lung Mechanics: Difference Between Asthma and COPD

Acute changes in lung mechanics from severe bronchospasm due to asthma attacks are similar to those in COPD exacerbations. However, the pathophysiology of asthma differs substantially from that of COPD. A main feature of advanced COPD is increased airway collapsibility due to destruction of the lung parenchyma and loss of lung elastic recoil, whereas the main features of asthma are increased thickness of airway walls (due to inflammation) and de-

creased collapsibility, despite considerable reduction in airway caliber.[19–22]

Hemodynamic Effects of Auto-PEEP

The hemodynamic consequences of auto-PEEP in an airflow-obstructed patient may be equal to or worse than the effects of a similar degree of PEEP applied to a patient with normal lungs. In the presence of highly compliant lungs, a high fraction of increased alveolar pressure is transmitted to the intrathoracic vessels. In their original description, Pepe and Marini[9] found that esophageal pressure decreased by at least 50% of the measured auto-PEEP when mechanical ventilation was discontinued. Increased mean intrathoracic pressure decreases venous return and reduces the preload of both ventricles. It also decreases left-ventricle compliance and may increase right-ventricle afterload because of high pulmonary vascular resistance. In clinical practice, pulmonary capillary wedge pressure has generally been considered a valid index of left-ventricle filling pressure, but in COPD the auto-PEEP-induced increase in intrathoracic pressure may falsely increase pulmonary capillary wedge pressure and right-atrial pressure, despite normal transmural pressure (pulmonary capillary wedge pressure minus esophageal pressure) preload, which can lead to mistakes in hemodynamic management. Rogers et al[23] reported on a patient who had severe COPD and developed refractory circulatory arrest, with sinus rhythm,
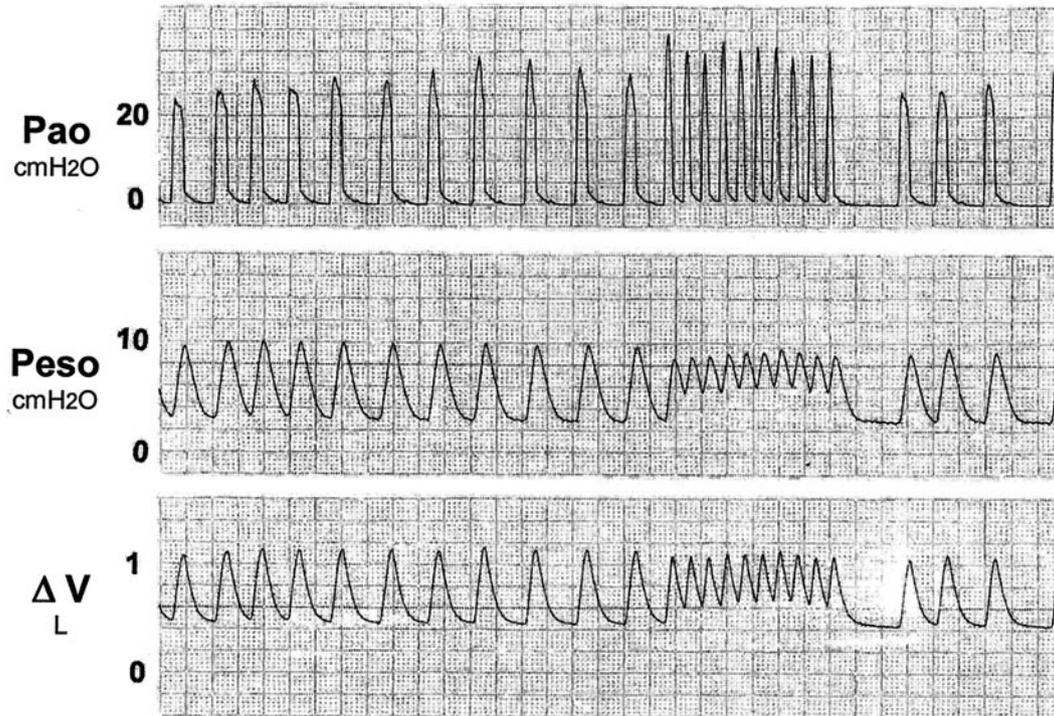
Fig. 3. Airway pressure (P_AO), esophageal pressure (P_eso), and lung volume waveforms in an experimental animal receiving manual (bag) ventilation during cardiopulmonary resuscitation. During rapid manual inflations, the expiratory time is shorter and lung volume and intrathoracic pressure is higher. ΔV = change in volume.

after intubation and positive-pressure ventilation. That case illustrated why the sudden increase of dynamic hyperinflation (due to a short expiratory time set on the ventilator) was responsible for the observed electromechanical dissociation (Fig. 3). Therefore, with severe airflow obstruction, a brief discontinuation of mechanical ventilation may be required to measure true pulmonary capillary wedge pressure[9] or to differentiate severe auto-PEEP from other causes of severe hypotension.[23]

Identification and Measurement of Auto-PEEP in Passive Patients

Simple observation of real-time graphics of airflow and airway pressure at the point of end-expiration is the key to identifying dynamic pulmonary hyperinflation in relaxed or well-adapted patients receiving mechanical ventilation. Whenever the end-expiratory flow is far from zero, the respiratory system is dynamically hyperinflated (Fig. 4). Single-breath flow-volume loops provide similar information.[24,25] The presence of airflow at end-expiration indicates that the alveolar pressure is higher than the atmospheric pressure or higher than the applied PEEP.[25,26] Auto-PEEP can be measured by performing an end-expiratory occlusion or by simultaneous observation or recording of
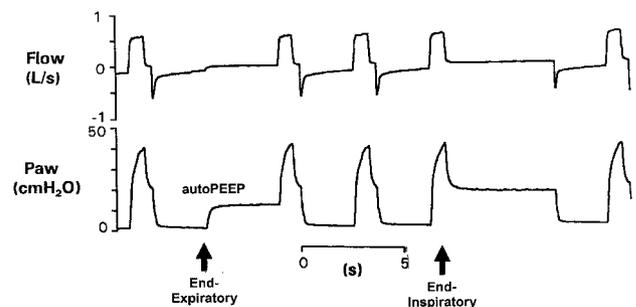

Fig. 4. Flow and airway pressure (P_aw) waveforms from a patient with chronic obstructive pulmonary disease, receiving mechanical ventilation. Rapid end-inspiratory and end-expiratory occlusions (arrows) allow assessment of alveolar pressures in static conditions. auto-PEEP = intrinsic positive end-expiratory pressure.

the airway pressure and airflow (see Fig. 4). Auto-PEEP measured with end-expiratory occlusion is called *static auto-PEEP* and is higher than auto-PEEP measured by simultaneous recording of airflow and airway pressure at end-expiration, which is called *dynamic auto-PEEP*. The difference is because dynamic auto-PEEP reflects the end-expiratory pressure of the lung units with short time constants and rapid expiration, while units with long time constants are still emptying.[25,27–29] The end-expiratory occlusion maneuver provides time to equilibrate lung units
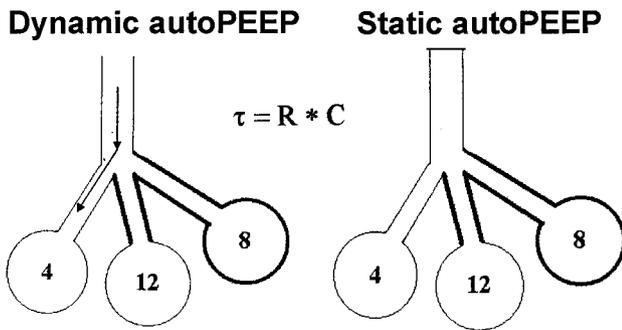
Fig. 5. Physiologic rationale behind the concepts of dynamic and static intrinsic positive end-expiratory pressure (auto-PEEP) during mechanical ventilation. With dynamic auto-PEEP, inspiratory flow begins when airway pressure is greater than end-expiratory alveolar pressure in lung regions that have shorter time constants (dynamic auto-PEEP = 4 cm H_2O). With static auto-PEEP, during end-expiratory occlusion, auto-PEEP corresponds to the mean value of all lung regions (static auto-PEEP = 8 cm H_2O). τ = time constant. R = resistance. C = compliance.

that have different regional auto-PEEP, and the value obtained after 2–3 seconds of end-expiratory occlusion is the mean value after equilibration, provided the airway is open (Figs. 5 and 6).[3,9] End-expiratory occlusion can be performed manually, using the software incorporated in the ventilator,[30] which can perform rapid occlusion exactly at the end of expiration.

Some ventilators can measure the dynamic-hyperinflation-induced trapped gas. In patients receiving ventilator-applied PEEP, the difference between the pressure obtained after an end-expiratory occlusion and the applied PEEP is the auto-PEEP. The measurement of static compliance of the respiratory system needs to be corrected for the presence of auto-PEEP, or the true value of static compliance will be underestimated (Fig. 7).[25,31]

The mechanics of the respiratory system can also be measured without the need for special maneuvers or particular flow patterns, by using the least squares fitting technique, with near-relaxed patients.[24,32]

The increase in lung volume due to applied PEEP or dynamic hyperinflation can be measured by passive exhalation, disconnecting the patient from the ventilator, or prolonging the expiratory time to FRC. At FRC, reconnecting the patient to the ventilator causes the opposite phenomenon: the inspired V_T will be greater than the exhaled V_T until lung volume stabilizes. In the absence of applied PEEP, trapped gas above FRC corresponds to the increase in end-expiratory lung volume due to dynamic hyperinflation. In the presence of applied PEEP, lung volume at end-expiration above FRC corresponds to the sum of end-expiratory lung volume due to dynamic hyperinflation plus the increase in lung volume induced by the applied PEEP (Fig. 8).[17,19,24]

Identification and Measurement of Auto-PEEP in Spontaneously Breathing Patients

Auto-PEEP can be present in a spontaneously breathing patient (ie, who is triggering the ventilator). In a spontaneously breathing patient, auto-PEEP results in less positive or more negative mean intrathoracic pressure than does fully controlled mechanical ventilation.[33] The main consequences are patient-ventilator asynchrony and increased WOB.[16,17,34–37] In spontaneously breathing patients, auto-PEEP is determined by simultaneously recording esophageal pressure and airflow tracings. Dynamic auto-PEEP is measured at end-expiration as the negative deflection of esophageal pressure to the point of zero flow (Fig. 9).[38]

Expiratory muscle contraction transmits an increase in pressure to the intrathoracic space, which further raises auto-PEEP. In these circumstances, the decrease in pleural (esophageal) pressure in early inspiration could be in part attributed to expiratory-muscle relaxation rather than to inspiratory-muscle contraction. Consequently, the part due to expiratory-muscle contraction (determined from an abdominal pressure signal) needs to be subtracted from the drop in esophageal pressure (Fig. 10).[25,29,33,39,40] Interestingly, the expiratory-muscle component of auto-PEEP becomes negligible at high auto-PEEP in patients with COPD.[25] In spontaneously breathing patients receiving mechanical ventilation, the patient makes an active inspiratory effort against a positive alveolar pressure (auto-PEEP) at the same time that the expiratory muscles relax. Ventilator triggering takes place when auto-PEEP has been counterbalanced.[16,33,41]

Ventilatory Strategy

Once intubation has been performed, attention should be directed to avoiding high auto-PEEP. Sedation may lower mean arterial pressure, but positive-pressure ventilation in airflow-obstructed patients can also compromise venous return, and intubation may be followed by cardiovascular collapse. Accordingly, the initial ventilator settings should be directed toward avoiding high mean intrathoracic pressure and auto-PEEP. The patient should be disconnected from the ventilator to check for a rise in blood pressure in cases of ventilator-related hypotension.[9,42]

Defining the appropriate ventilatory strategy for patients with airflow obstruction requires understanding the relationship between hyperinflation and the rate of lung emptying. Hubmayr et al[43] showed how insufficient expiratory flow produces dynamic hyperinflation during total ventilatory support. Assuming a 1-L V_T initiated from the static equilibrium volume at a respiratory rate of 20 breaths/min
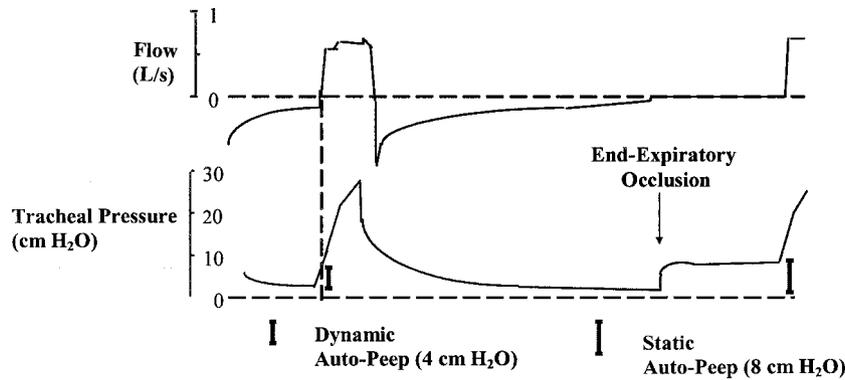
Fig. 6. Flow and tracheal pressure waveforms, showing the determination of dynamic intrinsic positive end-expiratory pressure (auto-PEEP) at the beginning of inspiration and static auto-PEEP after a prolonged end-expiratory occlusion.
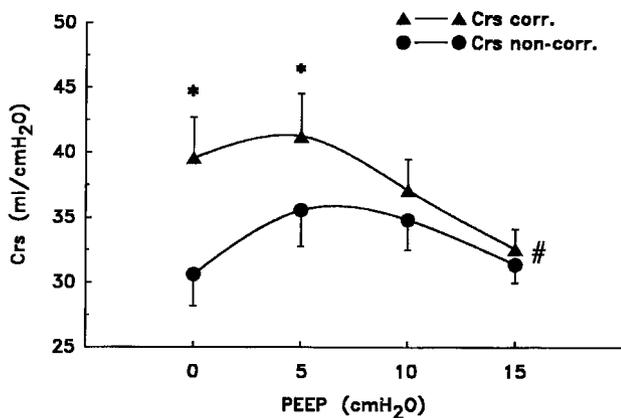

Fig. 7. Effect of intrinsic positive end-expiratory pressure (auto-PEEP) on static respiratory system compliance (C_{RS}) in a population of patients ($n = 10$) with acute respiratory distress syndrome, receiving mechanical ventilation. At lower PEEP, the C_{RS} is underestimated unless auto-PEEP is corrected for with the appropriate equation. This effect is less evident at high PEEP, where the phenomenon of expiratory flow limitation is partially abolished. corr = corrected. non-corr = not corrected.

Fig. 8. Airway pressure (P_{aw}) and lung volume (Vol) waveforms from a patient with acute respiratory distress syndrome, ventilated with applied positive end-expiratory pressure (PEEP) of 15 cm H_2O. After PEEP removal and a prolonged expiration, the lung-volume-increase induced by PEEP can be measured. At functional residual capacity the application of PEEP increases lung volume in each breath, until baseline stabilization (see text). ΔV = change in volume.

and a duty cycle of 0.33 gives the patient 2 seconds to exhale. If airflow is obstructed and mean maximum expiratory flow is only 0.25 L/s, the patient can exhale only 0.5 L (half of the previous V_T), so the next breath will take place at a higher lung volume. According to the flow-volume relationship of that patient, a higher mean expiratory flow can be achieved at the new lung-volume, but it will be insufficient to empty the lungs adequately. The steady-state condition, in which the time available for expiration (2 s) is adequate to exhale 1 L would be reached when the increase in lung volume resulted in a maximum mean expiratory flow of 0.5 L/s (Fig. 11).[42,43] The problem would be avoided by selecting a V_T of 0.5 L. The ventilatory pattern should minimize both dynamic hyperinflation and mean intrathoracic pressure, which increase the risk of barotrauma and cardiovascular compromise.

Flow, Tidal Volume, and Respiratory Rate in Asthma and COPD

Optimal ventilatory patterns can be achieved with different combinations of V_T, respiratory rate, and inspiratory flow. Tuxen and Lane[44] studied the effects of the ventilatory pattern on the degree of hyperinflation, airway pressure, and hemodynamics in patients with severe airflow obstruction. They found that dynamic hyperinflation could increase end-inspiratory lung volume by as much as 3.6 $\pm$ 0.4 L above the apneic FRC when V_T was increased and/or when expiratory time was decreased, either by an increase

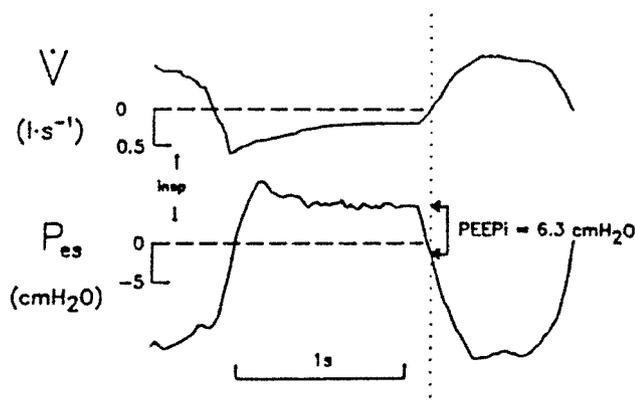Fig. 9. Flow ($\dot{V}$) and esophageal pressure (P_{es}) waveforms, illustrating the method to identify intrinsic positive end-expiratory pressure (auto-PEEP) during unsupported spontaneous ventilation. Auto-PEEP was measured as the negative deflection of P_{es} from the onset of inspiratory effort to the point of zero flow. (From Reference 38, with permission.)

in respiratory rate (and hence $\dot{V}_E$) or by a decrease in inspiratory flow (at a constant $\dot{V}_E$). Pulmonary hyperinflation was associated with increased alveolar, central venous, and esophageal pressure, as well as with systemic hypotension. Tuxen and Lane found that, at constant $\dot{V}_E$, mechanically ventilated flow-obstructed patients exhibited the lowest degree of dynamic hyperinflation when ventilated at high inspiratory flow and long expiratory time. Small V_T and higher respiratory rate seemed preferable to higher V_T at a lower respiratory rate. Above all, $\dot{V}_E$ was the main determinant of hyperinflation. The main goal of the ventilatory pattern was to ensure low $\dot{V}_E$ and an expiratory time long enough to allow lung-emptying,[45,46] together with high peak flow, at the expense of increased peak airway pressure. Although high inspiratory flow exposes robust proximal bronchi to greater pressure, the increase in peak flow reduces alveolar hyperinflation, so there is less hypotension.[21,44] Finally, measured auto-PEEP may underestimate end-expiratory alveolar pressure in severe asthma, and marked pulmonary hyperinflation may be present despite low measured auto-PEEP, especially at low respiratory rates. This phenomenon may be due to widespread airway closure that prevents accurate assessment of alveolar pressure at end-expiration.[47]

Current recommendations[48–52] indicate that the ventilation strategy for patients with acute asthma should favor relatively small V_T and higher inspiratory flow, to preserve expiratory time and minimize hyperinflation, barotrauma, and hypotension. That objective can be achieved with an inspiratory flow of 80–100 L/min, V_T of 6–10 mL/kg, peak airway pressure approaching 40–45 cm H_2O, and alveolar plateau pressure not higher than 25–30 cm H_2O. The respiratory rate should be 8–12 breaths/min, to achieve the least possible hyperinflation (auto-PEEP < 10

cm H_2O), and to maintain pH in an acceptable range, if possible. For COPD exacerbations the indications for invasive mechanical ventilation and the ventilatory strategies are similar to those for asthma, but patients with COPD often have less structural airflow obstruction than patients with asthma, at the point when they require ventilatory support. In most cases, patients can be rested adequately with V_T of 9–10 mL/kg and a respiratory rate of 14–16 breaths/min in assisted/control mode. In both COPD and asthma, ventilator-trigger sensitivity should be minimal.[2,6,42]

Particular Features of Acute Respiratory Distress Syndrome

In patients who have acute respiratory distress syndrome (ARDS), the factors associated with auto-PEEP and dynamic hyperinflation (in the absence of expiratory flow limitation) are marked increase in expiratory resistance and the use of high $\dot{V}_E$. Recently, Koutsoukou et al,[53] using a negative-expiratory-pressure technique and flow-volume diagrams, showed that expiratory flow limitation and auto-PEEP were present at zero PEEP in semirecumbent patients with ARDS (Fig. 12). Auto-PEEP values ranged from 0.4 to 7.7 cm H_2O, suggesting that the majority of patients with ARDS have small-airway closure and concomitant auto-PEEP. Patients with ARDS present with decreased lung volume,[54,55] and breathing at low lung volume promotes airway closure and air trapping, with further reduction in the expiratory flow reserve. Interestingly, applied PEEP and inhaled bronchodilators abolish the expiratory-flow-limitation.[53,56,57]

The ARDS Network study[58] found that V_T of 6 mL/kg (compared to V_T of 12 mL/kg) reduced mortality by 22% among patients with ARDS. The ARDS Network low-V_T strategy implies the use of increasing ventilatory support (elevated respiratory rate) to maintain carbon dioxide clearance at normal levels. To date, 3 studies—that did not precisely replicate the ARDS Network study—have shown that an increase in respiratory rate (to avoid V_T-reduction hypercapnia-increase) may induce substantial gas trapping and auto-PEEP in patients with ARDS (Fig. 13).[59–61] Therefore, it is necessary to pay special attention to monitoring graphic displays of pressure and flow[62] with ARDS patients who have expiratory flow limitation and who are ventilated with short expiratory times, in order to detect inadvertent high total PEEP.

The Role of Applied PEEP

To initiate inspiratory flow during patient-triggered breaths, the patient must first counterbalance auto-PEEP. Because that counterbalancing pressure is provided by the inspiratory muscles, auto-PEEP acts as a threshold load for
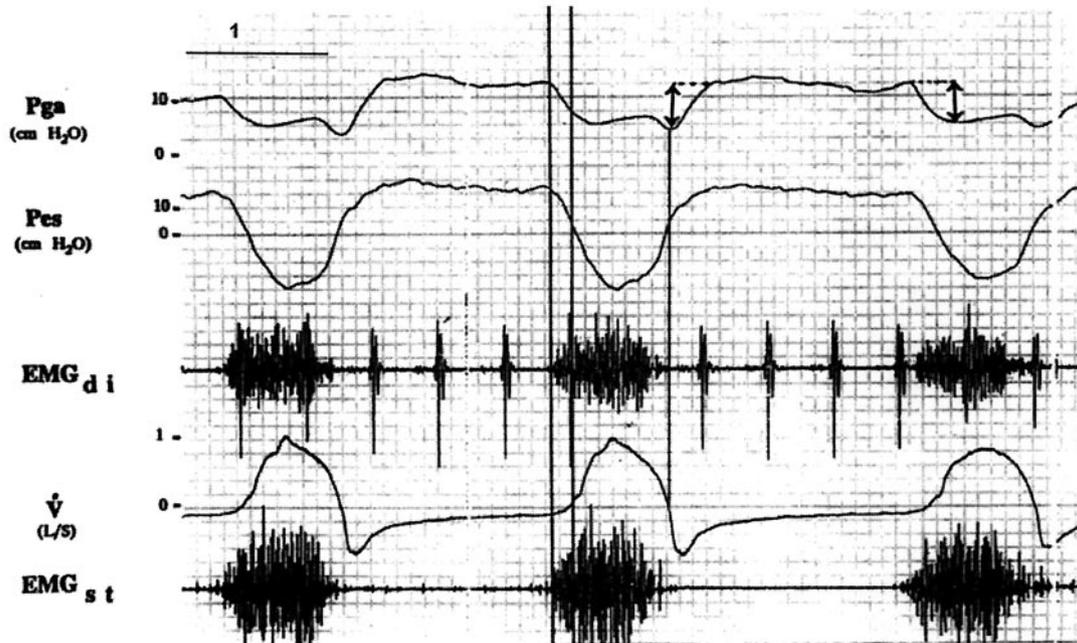
Fig. 10. Increase in intrinsic positive end-expiratory pressure (auto-PEEP) due to expiratory muscle activity in patients receiving mechanical ventilation. Gastric pressure (P_{ga}), esophageal pressure (P_{es}), flow ($\dot{V}$), and electromyographic activity of the diaphragm (EMG_{di}) and sternocleidomastoid muscle (EMG_{st}) show expiratory muscle recruitment (large increase in P_{ga} during expiration) and absence of time lag between expiratory muscle relaxation and inspiratory muscle activity (first vertical line), and the time lag between that activation and the onset of inspiratory flow (second vertical line). (From Reference 40, with permission.)
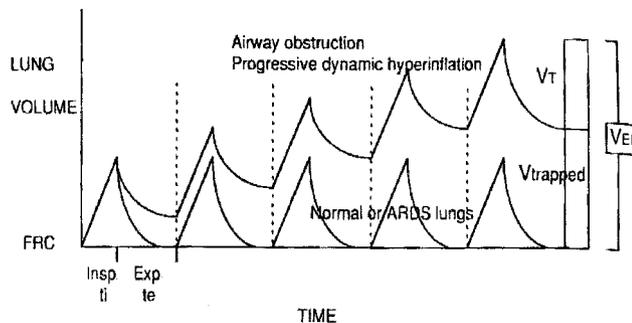

Fig. 11. Mechanical ventilation in normal lungs versus lungs with acute respiratory distress syndrome (ARDS). The curves show return of lung volume to functional residual capacity (FRC) during expiration, before the arrival of the next tidal volume (V_T). In a patient with airway obstruction, slow expiratory flow causes incomplete exhalation, resulting in progressive dynamic hyperinflation until a lung volume is reached at which the entire V_T is exhaled. Air trapping at end-expiration or at end-inspiration (V_{EI}) can cause barotrauma and cardiovascular compromise (see text). Insp t_i = inspiratory time. Exp t_e = expiratory time. (From Reference 42, with permission.)

Fig. 12. Flow-volume loops of control and negative-expiratory-pressure test breath with zero end-expiratory pressure (ZEEP), showing expiratory flow-limitation (EFL) at end-expiration. Application of positive end-expiratory pressure (PEEP) of 6.5 cm H_2O reversed the expiratory flow-limitation. INSP = inspiration. EXP = expiration. (From Reference 53, with permission.)

each inspiratory effort. To alleviate the breathing efforts that auto-PEEP imposes on the respiratory muscles, end-expiratory alveolar pressure can be counterbalanced with applied PEEP. To initiate a ventilator breath, pleural pressure must first reverse the positive recoil pressure present at end-expiration, and the ventilator's trigger sensitivity

must be set appropriately.[16,41,63] Severely hyperinflated patients with poor muscle function may exhibit some ineffective inspiratory efforts between ventilator-aided breaths. In that situation, applied PEEP (usually about 80% of the baseline auto-PEEP) improves inspiratory-muscle effectiveness.[16,17,19,41,64] Applied PEEP similar to the level of auto-PEEP should have no effect on alveolar pressure.[4] Patients ventilated for COPD exacerbation experience dy-

Fig. 13. Physiologic variables in a patient with acute respiratory distress syndrome (ARDS) receiving mechanical ventilation according to the ARDS Network's traditional-tidal-volume (V_T) strategy and low-V_T strategy.[58] The increasing respiratory rate used with the low-V_T strategy resulted in higher functional residual capacity (FRC) than the traditional-V_T strategy and increased total positive end-expiratory pressure (PEEP$_{total}$) above the nominal PEEP set on the ventilator. P_{aw}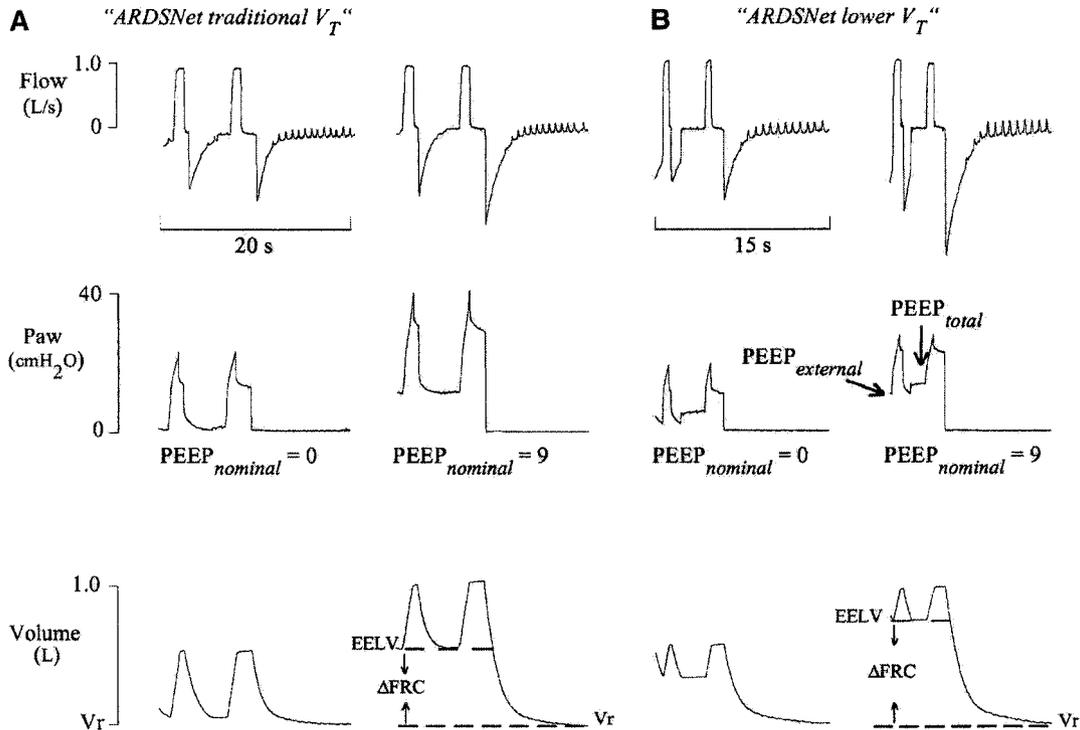 = airway pressure. PEEP$_{external}$ = PEEP applied by the ventilator (same as PEEP$_{nominal}$). EELV = end-expiratory lung volume. V_r = resting volume. (From Reference 59, with permission.)

namic airway collapse and flow limitation. Under those conditions, critical closure of the airways occurs. Applying PEEP at a magnitude similar to auto-PEEP causes no impairment in expiratory airflow or increments in alveolar pressure or lung volume. The physiology of this phenomenon is explained by the analogy of the waterfall (Fig. 14).[4,17,19] Furthermore, counterbalancing auto-PEEP with a set, applied PEEP has no effect on gas exchange and does not impair hemodynamics or right-ventricular function in patients with COPD.[19,65]

In contrast to COPD patients, applying PEEP during total ventilatory support of a patient who has dynamic hyperinflation with fixed airflow obstruction due to severe asthma and without airway collapse may produce potentially dangerous increases in lung volume, airway pressure, and intrathoracic pressure, causing circulatory compromise.[66] Although some clinical studies[67,68] have reported improved airway function (without untoward effects) with continuous positive airway pressure or with noninvasive ventilation and PEEP among patients with acute asthma, the use of PEEP during total ventilatory support of a patient with acute asthma is controversial. Furthermore, with a sedated, well-adapted, nonhypoxemic COPD patient who is receiving controlled mechanical ventilation and exhibiting auto-PEEP, applied PEEP gives no clinical benefit,
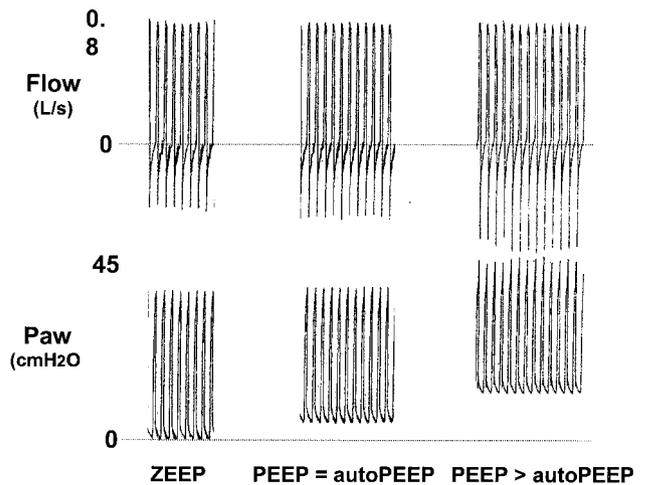
Fig. 14. Flow and airway pressure (P_{aw}) waveforms from a patient with flow obstruction due to chronic obstructive pulmonary disease. Applying positive end-expiratory pressure (PEEP) that is equal to the static intrinsic PEEP (auto-PEEP) does not increase lung volume (as measured by absence of modification of peak P_{aw} and expiratory flow). Increasing applied PEEP above auto-PEEP elevates intrathoracic pressure (high P_{aw}), which increases lung volume (increased peak expiratory flow). ZEEP = zero end-expiratory pressure.

unless clinical conditions other than dynamic hyperinflation favor its application.

During acute airflow obstruction, to select an adequate ventilatory pattern and optimal PEEP, it may help the clinician to measure peak pressure, alveolar (plateau) pressure, and auto-PEEP, to calculate the respiratory system's compliance and resistance, and to periodically control end-expiratory lung volume.[69,70]

Dynamic Hyperinflation and Patient/Ventilator Interaction

The term *patient-ventilator interaction* describes the various events that occur during patient-triggered ventilation and how those events influence patient-ventilator synchrony and, thus, patient comfort. Once mechanical ventilation has begun, optimal patient-ventilator interaction must be accomplished to link the ventilator's output to the patient's requirements. Adequate selection of inspiratory flow, inspiratory time, and trigger sensitivity is critical for reducing the patient's WOB.[36,37,63]

The WOB is determined by the patient's ventilatory drive and muscle strength. Synchrony with a patient-triggered breath depends on the ventilator's ability to meet the patient's flow demand. The ventilator's peak flow setting must be greater than the patient's inspiratory flow demand, or the patient is forced to work against the resistance of the ventilator circuit and against his own internal impedance to flow and chest expansion.[71,72] Marini et al[73] demonstrated that WOB during assisted mechanical ventilation may equal that found during spontaneous breathing if the inspiratory flow setting is inadequate. To avoid high inspiratory effort and reduce patient-ventilator asynchrony, the pressure necessary to trigger the ventilator must be minimal. As mentioned above, the difficulty that auto-PEEP causes in triggering the ventilator represents an elastic threshold load and often manifests as intermittent failure of patient effort to trigger the ventilator. With dynamic hyperinflation, only the most vigorous efforts trigger the ventilator, and ineffective inspiratory-muscle contractions can be observed. This is a common phenomenon in patients with airflow obstruction, and it can cause muscle fatigue, impair the muscles, and increase dyspnea. Therefore, auto-PEEP must be reduced by increasing the time available for expiration or by reducing $\dot{V}_E$.[36,37,74,75] Another approach is to add applied PEEP, as described above. Among patients with severe obstruction, the incidence of ineffective triggering does not differ between the pressure-triggered and flow-triggered systems built into modern ventilators.[37,76]

The pressure and flow waveforms displayed on the ventilator monitor can alert the clinician if the patient's inspiratory effort is insufficient to trigger the ventilator (Fig. 15). This is particularly important at high levels of venti-lator assistance. Breaths that precede nontriggering efforts have shorter respiratory cycle times and expiratory times, so elastic recoil pressure builds up within the thorax, in the form of auto-PEEP.[77,78] A full description of the factors that affect patient-ventilator interactions is beyond the scope of this review. However, dynamic hyperinflation can be generated or aggravated by certain manipulations of the ventilator settings (Fig. 16). Inadequate increase in inspiratory flow causes immediate and persistent tachypnea, which shortens expiratory time.[77,79,80] Further, the switch from inspiration to expiration on the ventilator should match the patient's breathing pattern. Neural inspiratory time is often shorter or longer than the inflation time set on the ventilator. That type of asynchrony is very uncomfortable; it causes ineffective triggering or double-triggering, and it aggravates dynamic hyperinflation, increasing the burden on the respiratory muscles.[35,36,78,81,82] Clinical observation of the patient and of the flow and pressure waveforms is the best and simplest way to optimize patient-ventilator interaction.

Auto-PEEP and Weaning Failure

Failure of the respiratory-muscle pump is probably the most common cause of failure to wean from mechanical ventilation.[83,84] Indeed, in comparison to COPD patients who tolerate spontaneous breathing trials and are successfully extubated, COPD patients who fail spontaneous breathing trials exhibit immediate rapid and shallow breathing and progressive worsening of pulmonary mechanics, with inefficient carbon dioxide clearance.[85] Deterioration in respiratory system mechanics in patients who fail spontaneous breathing trials is characterized by an increase in auto-PEEP and inspiratory resistance and a decrease in dynamic lung compliance. Thus, inefficient carbon dioxide clearance in the failing group appears to be a consequence of worsening of pulmonary mechanics, with increased energy expenditure and rapid shallow breathing, because the decrease in V_T increases dead space.[85]

Components of the ventilator circuit, including endotracheal tubes, can increase resistance to airflow and the resistive component of the WOB during spontaneous breathing trials. The important factors are the size of the tube, deposition of secretions in the tube, kinking/curvature of the tube, and the presence of elbow-shaped parts or a heat-and-moisture exchanger in the circuit. Moreover, the components of the ventilator circuit can add dead space. Those factors increase muscle work load and reduce alveolar ventilation for a given $\dot{V}_E$.[13,86–88] During spontaneous breathing trials, clinicians should be aware that the aforementioned instrumental elements may be unsuitable for difficult-to-wean patients.
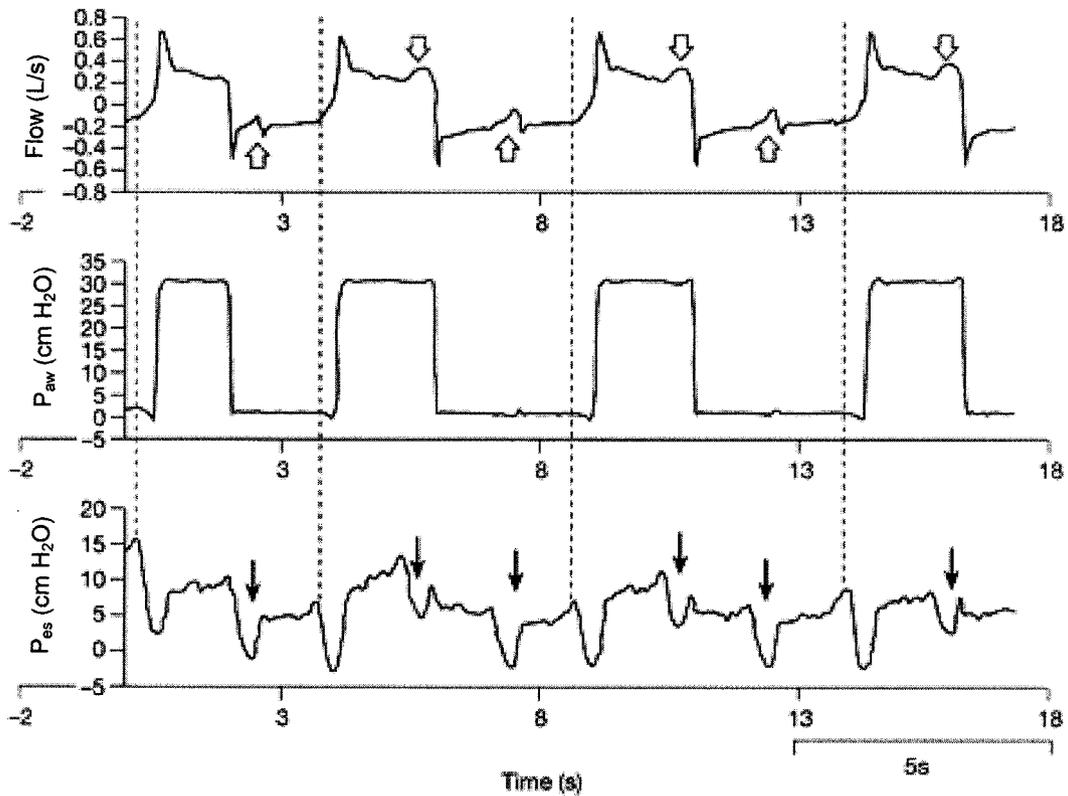
Fig. 15. Flow, airway pressure (P_{aw}), and esophageal pressure (P_{es}) waveforms from a patient with severe chronic obstructive pulmonary disease, receiving pressure-support ventilation. Ineffective inspiratory efforts occur during both mechanical inspiration and expiration and can be easily identified on the flow waveforms (arrows). (From Reference 37, with permission.)
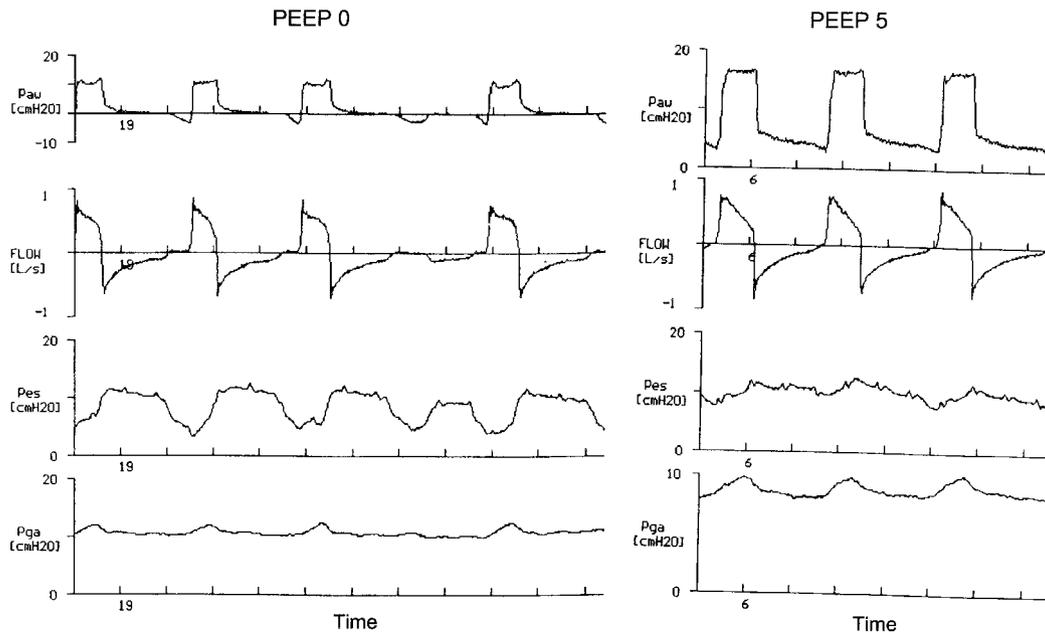
Fig. 16. Airway pressure (P_{aw}), flow ($\dot{V}$), esophageal pressure (P_{es}), and gastric pressure (P_{ga}) waveforms from a representative patient with chronic obstructive pulmonary disease, receiving mechanical ventilation with zero positive end-expiratory pressure (PEEP) (left panel) and with PEEP of 5 cm H_2O (right panel). Inspiratory esophageal swings and work of breathing were maximal during ventilation with zero PEEP. Moreover, one ineffective inspiratory effort was identified. Applying PEEP markedly reduced inspiratory efforts, intrinsic PEEP, and patient-ventilator asynchrony. (Adapted from Reference 74, with permission.)

Summary

Dynamic hyperinflation and auto-PEEP are common problems in patients receiving full or partial ventilatory support, as well as in those ready to be weaned from the ventilator. The clinician needs to fully understand the physiology of dynamic hyperinflation and auto-PEEP, so as to choose appropriate ventilator settings. Ventilator graphics are invaluable for monitoring and treatment decisions with patients receiving mechanical ventilation.

REFERENCES

1. Marcy TW, Marini JJ. Modes of mechanical ventilation. In: Simmons DH, Tierney DF, editors. Current pulmonology. St Louis: Mosby Year Book; 1992:43–90.
2. Derenne JP, Fleury B, Pariente R. Acute respiratory failure of chronic obstructive pulmonary disease. Am Rev Respir Dis 1988;138(4):1006–1033.
3. Gottfried SB, Rossi A, Milic-Emili J. Dynamic hyperinflation, intrinsic PEEP, and the mechanically ventilated patient. Intensive Crit Care Digest 1986;5:30–33.
4. Tobin MJ, Lodato RF. PEEP, auto-PEEP, and waterfalls (comment). Chest 1989;96(3):449–451.
5. Hall JB, Wood LDH. Liberation of the patient from mechanical ventilation. JAMA 1987;257(12):1621–1628.
6. Schmidt GA, Hall JB. Acute or chronic respiratory failure: assessment and management of patients with COPD in the emergency setting. JAMA 1989;261(23):3444–3453.
7. Kondili E, Alexopoulou C, Prinianakis G, Xirouchaki N, Georgopoulos D. Pattern of lung emptying and expiratory resistance in mechanically ventilated patients with chronic obstructive pulmonary disease. Intensive Care Med 2004;30(7):1311–1318.
8. Fleury B, Murciano D, Talamo C, Aubier M, Pariente R, Milic-Emili J. Work of breathing in patients with chronic obstructive pulmonary disease in acute respiratory failure. Am Rev Respir Dis 1985;131(6):822–827.
9. Pepe PE, Marini JJ. Occult positive end-expiratory pressure in mechanically ventilated patients with airflow obstruction: the auto-PEEP effect. Am Rev Respir Dis 1982;126(1):166–170.
10. Bergman NA. Intrapulmonary gas trapping during mechanical ventilation at rapid frequencies. Anesthesiology 1972;37(6):626–633.
11. Jonson B, Nordström L, Olsson SG, Akerback D. Monitoring of ventilation and lung mechanics during automatic ventilation: a new device. Bull Physiopathol Respir (Nancy) 1975;11(5):729–743.
12. Marini JJ. Should PEEP be used in airflow obstruction? (editorial) Am Rev Respir Dis 1989;140(1):1–3.
13. Iotti GA, Olivei MC, Palo A, Galbusera C, Veronesi R, Comelli A, et al. Unfavorable mechanical effects of heat and moisture exchangers in ventilated patients. Intensive Care Med 1997;23(4):399–405.
14. Campbell RS, Davis K Jr, Johannigman JA, Branson RD. The effects of passive humidifier dead space on respiratory variables in paralyzed and spontaneously breathing patients. Respir Care 2000;45(3):306–312.
15. Scott LR, Benson MS, Pierson DJ. Effect of inspiratory flowrate and circuit compressible volume on auto-PEEP during mechanical ventilation. Respir Care 1986;31(11):1075–1079.
16. Smith TC, Marini JJ. Impact of PEEP on lung mechanics and work of breathing in severe airflow obstruction. J Appl Physiol 1988;65(4):1488–1499.
17. Gottfried SB. The role of PEEP in the mechanically ventilated COPD patient. In: Marini JJ, Roussos C, editors. Ventilatory failure. Berlin: Springer-Verlag; 1991:392–418.
18. Blanch L, Fernandez R, Saura P, Baigorri F, Artigas A. Relationship between expired capnogram and respiratory system resistance in critically ill patients during total ventilatory support. Chest 1994;105(1):219–223.
19. Ranieri VM, Giuliani R, Cinnella G, Pesce C, Brienza N, Ippolito EL, et al. Physiologic effects of positive end-expiratory pressure in patients with chronic obstructive pulmonary disease during acute ventilatory failure and controlled mechanical ventilation. Am Rev Respir Dis 1993;147(1):5–13.
20. Pride NB, Macklem PT. Lung mechanics in disease. In: Fishman AP, editor. Handbook of physiology. The respiratory system. Mechanics of breathing, vol. 3, part 2. Bethesda: American Physiological Society 1986:659–692.
21. Hall JB, Wood LDH. Management of the critically ill asthmatic patient. Med Clin North Am 1990;74(3):779–796.
22. McFadden ER Jr. Acute severe asthma. Am J Respir Crit Care Med 2003;168(7):740–759.
23. Rogers PL, Schlichtig R, Miró A, Pinsky M. Auto-PEEP during CPR: an "occult" cause of electromechanical dissociation? Chest 1991;99(2):492–493.
24. Iotti GA, Braschi A. Measurements of respiratory mechanics during mechanical ventilation. Rhazurns, Switzerland: Hamilton Medical Scientific Library; 1999.
25. Rossi A, Polese G, Brandi G, Conti G. Intrinsic positive end-expiratory pressure (PEEPi). Intensive Care Med 1995;21(6):522–536.
26. Brochard L. Intrinsic (or auto-) PEEP during controlled mechanical ventilation. Intensive Care Med 2002;28(10):1376–1378.
27. Younes M. Dynamic intrinsic PEEP (PEEP$_i$,dyn). Is it worth saving? (editorial) Am J Respir Crit Care Med 2000;162(5):1608–1609.
28. Hernandez P, Navalesi P, Maltais F, Gursahaney A, Gottfried SB. Comparison of static and dynamic measurements of intrinsic PEEP in anesthetized cats. J Appl Physiol 1994;76(6):2437–2442.
29. Zakynthinos SG, Vassilakopoulos T, Zakynthinos E, Roussos C. Accurate measurement of intrinsic positive end-expiratory pressure: how to detect and correct for expiratory muscle activity. Eur Respir J 1997;10(3):522–529.
30. Gottfried SB, Reissman H, Ranieri VM. A simple method for the measurement of intrinsic positive end-expiratory pressure during controlled and assisted modes of mechanical ventilation. Crit Care Med 1992;20(5):621–629.
31. Broseghini C, Brandolese R, Poggi R, Bernasconi M, Manzin E, Rossi A. Respiratory resistance and intrinsic positive end-expiratory pressure (PEEPi) in patients with the adult respiratory distress syndrome (ARDS). Eur Respir J 1988;1(8):726–731.
32. Iotti GA, Braschi A, Brunner JX, Smits T, Olivei M, Palo A, Veronesi R. Respiratory mechanics by least squares fitting in mechanically ventilated patients: applications during paralysis and during pressure support ventilation. Intensive Care Med 1995;21(5):406–413.
33. Brochard L. Intrinsic (or auto-) positive end-expiratory pressure during spontaneous or assisted ventilation. Intensive Care Med 2002;28(11):1552–1554.
34. Fabry B, Guttmann J, Eberhard L, Bauer T, Haberthur C, Wolff G. An analysis of desynchronization between the spontaneously breathing patient and ventilator during inspiratory pressure support. Chest 1995;107(5):1387–1394.
35. Rossi A, Appendini L. Wasted efforts and dyssynchrony: is the patient-ventilator battle back? (editorial) Intensive Care Med 1995;21(11):867–870.
36. Tobin MJ, Jubran A, Laghi F. Patient-ventilator interaction. Am J Respir Crit Care Med 2001;163(5):1059–1063.
37. Kondili E, Prinianakis G, Georgopoulos D. Patient-ventilator interaction. Br J Anaesth 2003;91(1):106–119.

38. Haluszka J, Chartrand DA, Grassino AE, Milic-Emili J. Intrinsic PEEP and arterial PCO_2 in stable patients with chronic obstructive pulmonary disease. Am Rev Respir Dis 1990;141(5 Pt 1):1194–1197.

39. Ninane V, Yernault JC, de Troyer A. Intrinsic PEEP in patients with chronic obstructive pulmonary disease: role of expiratory muscles. Am Rev Respir Dis 1993;148(4 Pt 1):1037–1042.

40. Lessard MR, Lofaso F, Brochard L. Expiratory muscle activity increases intrinsic positive end-expiratory pressure independently of dynamic hyperinflation in mechanically ventilated patients. Am J Respir Crit Care Med 1995;151(2 Pt 1):562–569.

41. Fernandez R, Benito S, Blanch L, Net A. Intrinsic PEEP: a cause of inspiratory muscle ineffectivity. Intensive Care Med 1988;15(1):51–52.

42. Tuxen DV. Permissive hypercapnic ventilation. Am J Respir Crit Care Med 1994;150(3):870–874.

43. Hubmayr RD, Abel MD, Rehder K. Physiologic approach to mechanical ventilation. Crit Care Med 1990;18(1):103–113.

44. Tuxen DV, Lane S. The effects of ventilatory pattern on hyperinflation, airway pressures, and circulation in mechanical ventilation of patients with severe air-flow obstruction. Am Rev Respir Dis 1987; 136(4):872–879.

45. Georgopoulos D, Mitrouska I, Markopoulou K, Patakas D, Anthonisen NR. Effects of breathing patterns on mechanically ventilated patients with chronic obstructive pulmonary disease and dynamic hyperinflation. Intensive Care Med 1995;21(11):880–886.

46. Leatherman JW, McArthur C, Shapiro RS. Effect of prolongation of expiratory time on dynamic hyperinflation in mechanically ventilated patients with severe asthma. Crit Care Med 2004;32(7):1542–1545.

47. Leatherman JW, Ravenscraft SA. Low measured auto-positive end-expiratory pressure during mechanical ventilation of patients with severe asthma: hidden auto-positive end-expiratory pressure. Crit Care Med 1996;24(3):541–546.

48. Perret C, Feihl F. Respiratory failure in asthma: management of the mechanically ventilated patient. In: Vincent JL, editor. Yearbook on intensive care and emergency medicine. Berlin: Springer-Verlag; 1992:364–371.

49. Darioli R, Perret C. Mechanical controlled hypoventilation in status asthmaticus. Am Rev Respir Dis 1984;129(3):385–387.

50. Georgopoulos D, Kondili E, Prinianakis G. How to set the ventilator in asthma. Monaldi Arch Chest Dis 2000;55(1):74–83.

51. Corbridge TC, Hall JB. The assessment and management of adults with status asthmaticus. Am J Respir Crit Care Med 1995;151(5):1296–1316.

52. Papiris S, Kotanidou A, Malagari K, Roussos C. Clinical review: severe asthma. Crit Care 2002;6(1):30–44.

53. Koutsoukou A, Armaganidis A, Stavrakaki-Kallergi C, Vassilakopoulos T, Lymberis A, Roussos C, Milic-Emili J. Expiratory flow limitation and intrinsic positive end-expiratory pressure at zero positive end-expiratory pressure in patients with adult respiratory distress syndrome. Am J Respir Crit Care Med 2000;161(5):1590–1596.

54. Gattinoni L, Bombino M, Pelosi P, Lissoni A, Pesenti A, Fumagalli R, Tagliabue M. Lung structure and function in different stages of severe adult respiratory distress syndrome. JAMA 1994;271(22):1772–1779.

55. Puybasset L, Cluzel P, Chao N, Slutsky AS, Coriat P, Rouby JJ. A computed tomography scan assessment of regional lung volume in acute lung injury. The CT Scan ARDS Study Group. Am J Respir Crit Care Med 1998;158(5 Pt 1):1644–1655.

56. Armaganidis A, Stavrakaki-Kallergi K, Koutsoukou A, Lymberis A, Milic-Emili J, Roussos C. Intrinsic positive end-expiratory pressure in mechanically ventilated patients with and without tidal expiratory flow limitation. Crit Care Med 2000;28(12):3837–3842.

57. Koutsoukou A, Bekos B, Sotiropoulou C, Koulouris NG, Roussos C, Milic-Emili J. Effects of positive end-expiratory pressure on gas exchange and expiratory flow limitation in adult respiratory distress syndrome. Crit Care Med 2002;30(9):1941–1949.

58. The Acute Respiratory Distress Syndrome Network. Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000;342(18):1301–1308.

59. de Durante G, del Turco M, Rustichini L, Cosimini P, Giunta F, Hudson LD, et al. ARDSNet lower tidal volume ventilatory strategy may generate intrinsic positive end-expiratory pressure in patients with acute respiratory distress suyndrome. Am J Respir Crit Care Med 2002;165(9):1271–1274.

60. Vieillard-Baron A, Prin S, Augarde R, Desfonds P, Page B, Beauchet A, Jardin F. Increasing respiratory rate to improve CO_2 clearance during mechanical ventilation is not a panacea in acute respiratory failure. Crit Care Med 2002;30(7):1407–1412.

61. Richard JC, Brochard L, Breton L, Aboab J, Vandelet P, Tamion F, et al. Influence of respiratory rate on gas trapping during low volume ventilation of patients with acute lung injury. Intensive Care Med 2002;28(8):1078–1083.

62. Branson RD, Davis K Jr, Campbell RS. Monitoring graphic displays of pressure, volume and flow: the usefulness of ventilator waveforms. World Federation of Critical Care 2004; February:8–12.

63. Marini JJ. Patient-ventilator interaction: rational strategies for acute ventilatory management. Respir Care 1993;38(5):482–493.

64. Petrof BJ, Legare M, Goldberg P, Milic-Emili J, Gottfried SB. Continuous positive airway pressure reduces work of breathing and dyspnea during weaning from mechanical ventilation in severe chronic obstructive pulmonary disease. Am Rev Respir Dis 1990;141(2):281–289.

65. Baigorri F, de Monte A, Blanch L, Fernández R, Vallès J, Mestre J, et al. Hemodynamic responses to external counterbalancing of auto-positive end-expiratory pressure in mechanically ventilated patients with chronic obstructive pulmonary disease. Crit Care Med 1994; 22(11):1782–1791.

66. Tuxen DV. Detrimental effects of positive end-expiratory pressure during controlled mechanical ventilation of patients with severe air-flow obstruction. Am Rev Respir Dis 1989;140(1):5–9.

67. Martin JG, Shore S, Engel LA. Effect of continuous positive airway pressure on respiratory mechanics and pattern of breathing in induced asthma. Am Rev Respir Dis 1982;126(5):812–817.

68. Fernández MM, Villagrá A, Blanch L, Fernández R. Non-invasive mechanical ventilation in status asthmaticus. Intensive Care Med 2001;27(3):486–492.

69. Hess DR, Kacmarek RM. Essentials of mechanical ventilation. New York: McGraw-Hill; 2002.

70. Rossi A, Polese G, Milic-Emili J. Monitoring respiratory mechanics in ventilator-dependent patients. In: Tobin MJ, editor. Principles and practice of intensive care monitoring. New York: McGraw-Hill; 1998:553–596.

71. Marini JJ. Monitoring during mechanical ventilation. Clin Chest Med 1988;9(1):73–100. *Erratum in: Clin Chest Med 1988 Jun;9(2):following x.*

72. Truwit JD, Marini JJ. Evaluation of thoracic mechanics in the ventilated patient. Part II: Applied mechanics. J Crit Care 1988;3(3):199–213.

73. Marini JJ, Rodriguez RM, Lamb V. The inspiratory workload of patient-initiated mechanical ventilation. Am Rev Respir Dis 1986; 134(5):902–909.

74. Mancebo J, Albaladejo P, Touchard D, Bak E, Subirana M, Lemaire F, et al. Airway occlusion pressure to titrate positive end-expiratory pressure in patients with dynamic hyperinflation. Anesthesiology 2000;93(1):81–90.

75. Sinderby C, Navalesi P, Beck J, Skrobic Y, Comtois N, Friberg S, et al. Neural control of mechanical ventilation in respiratory failure. Nat Med 1999;5(12):1433–1436.

76. Sassoon CS, Foster GT. Patient-ventilator asynchrony. Curr Opin Crit Care 2001;7(1):28–33.

77. Leung P, Jubran A, Tobin MJ. Comparison of assisted ventilator modes on triggering, patient effort, and dyspnea. Am J Respir Crit Care Med 1997;155(6):1940–1948.

78. Tobin MJ. Advances in mechanical ventilation. N Engl J Med 2001; 344(26):1986–1996.

79. Fernandez R, Mendez M, Younes M. Effect of ventilator flow rate on respiratory timing in normal humans. Am J Respir Crit Care Med 1999;159(3):710–719.

80. Lagui F, Karamchandani K, Tobin MJ. Influence of ventilator settings in determining respiratory frequency during mechanical ventilation. Am J Respir Crit Care Med 1999;160(5 Pt 1):1766–1770.

81. Yamada Y, Du HL. Analysis of the mechanisms of expiratory asynchrony in pressure support ventilation: a mathematical approach. J Appl Physiol 2000;88(6):2143–2150.

82. Mancebo J. Triggering and cycling off during pressure support ventilation: simplicity or sophistication? (editorial) Intensive Care Med 2003;29(11):1871–1872.

83. Marini JJ. Weaning from mechanical ventilation (editorial). N Engl J Med 1991;324(21):1496–1498.

84. Vassilakopoulos T, Zakynthinos S, Roussos Ch. Respiratory muscles and weaning failure. Eur Respir J 1996;9(11):2383–2400.

85. Jubran A, Tobin MJ. Pathophysiologic basis of acute respiratory distress in patients who fail a trial of weaning from mechanical ventilation. Am J Respir Crit Care Med 1997;155(3):906–915.

86. Pelosi P, Solca M, Ravagnan I, Tubiolo D, Ferrario L, Gattinoni L. Effects of heat and moisture exchangers on minute ventilation, ventilatory drive, and work of breathing during pressure-support ventilation in acute respiratory failure. Crit Care Med 1996;24(7):1184–1188.

87. Le Bourdelles G, Mier L, Fiquet B, Djedaini K, Saumon G, Coste F, Dreyfuss D. Comparison of the effects of heat and moisture exchangers and heated humidifiers on ventilation and gas exchange during weaning trials from mechanical ventilation. Chest 1996;110(5):1294–1298.

88. Epstein SK, Ciubotaru RL. Influence of gender and endotracheal tube size on preextubation breathing pattern. Am J Respir Crit Care Med 1996;154(6 Pt 1):1647–1652. *Erratum in: Am J Respir Crit Care Med 1997 Jun;155(6):2115.*

Discussion

Bigatello: I'm sure I'm not the only one in the audience who is very interested in the value of auto-PEEP in the ARDS Network trial patients, and you mentioned the study by de Durante et al,[1] who applied the ARDS Network's ventilation criteria to a new group of patients and *did* detect some auto-PEEP. I seem to remember that a subset of the ARDS Network trial centers looked for auto-PEEP, though I don't think those data are published. Now I'm not sure which one is right.

Do you have an opinion about that? Of course, whether these patients have auto-PEEP makes a big difference in our thinking about the ARDS Network trial ventilator settings. What is very surprising is that these patients did so well with a lower PEEP than what we generally use, but the reality may be that Durante et al are right and those patients *did* have a higher PEEP than the set PEEP. So do you have any insight about who's right?

REFERENCE

1. de Durante G, del Turco M, Rustichini L, Cosimini P, Giunta F, Hudson LD et al. ARDS Network lower tidal volume ventilatory strategy may generate intrinsic positive end-expiratory pressure in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2002;165(9): 1271–1274.

Blanch: I have 2 comments on that. First, there are actually 3 papers that indicate that auto-PEEP can occur at the respiratory rates used in the treatment arm of the ARDS Network trial.[1–3]

Second, in patients with ARDS, flow limitation has also been shown using low-flow negative aspiration during expiration.[4] Therefore, flow limitation can be present in a substantial number of patients with ARDS. In fact, older age, smoking history, or other unknown lung diseases may co-exist in patients with ARDS that would favor airflow limitation and be exacerbated by high respiratory rate. Smoking history is not a usual exclusion criteria in big mechanical ventilation trials. Moreover, patients with ARDS may have secretions and airway collapse at low PEEP levels.

Finally, applied PEEP counterbalances autoPEEP, and airflow limitation is relieved in the majority of patients and, consequently, auto-PEEP is not usually found at high PEEP levels. That's why total PEEP might not coincide with applied PEEP in ARDS patients ventilated at high respiratory rates.

REFERENCES

1. de Durante G, del Turco M, Rustichini L, Cosimini P, Giunta F, Hudson LD, et al. ARDS Network lower tidal volume ventilatory strategy may generate intrinsic positive end-expiratory pressure in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2002;165(9): 1271–1274.

2. Vieillard-Baron A, Prin S, Augarde R, Desfonds P, Page B, Beauchet A, Jardin F. Increasing respiratory rate to improve CO_2 clearance during mechanical ventilation is not a panacea in acute respiratory failure. Crit Care Med 2002;30(7):1407–1412.

3. Richard JC, Brochard L, Breton L, Aboab J, Vandelet P, Tamion F, et al. Influence of respiratory rate on gas trapping during low volume ventilation of patients with acute lung injury. Intensive Care Med 2002;28(8): 1078–1083.

4. Koutsoukou A, Armaganidis A, Stavrakaki-Kallergi C, Vassilakopoulos T, Lymberis A, Roussos C, Milic-Emili J. Expiratory flow limitation and intrinsic positive end-expiratory pressure at zero positive end-expiratory pressure in patients with adul-

trespiratory distress syndrome. Am J Respir Crit Care Med 2000;161(5):1590–1596.

MacIntyre: John Marini taught me that there are only 3 factors that determine auto-PEEP. Number one is minute ventilation—it doesn't matter whether it's from respiratory rate or tidal volume. Minute ventilation. Number two is the I-E [inspiratory-expiratory] ratio. Number three is the expiratory time constants. And that's it.

So it doesn't surprise me that if you take patients who have a little bit different time constants—maybe they do have as little as you're suggesting; maybe there is a little more airway obstruction in the European population than in the American population because of smoking habits. The ARDS Network study did not tightly limit the I-E ratio, and you can certainly manipulate the I-E ratio to produce more or less risk of air trapping. And if you drive up the respiratory rate and the minute ventilation, you get air trapping in ARDS patients.

You're right: the ARDS Network trial did not mandate measurement of auto-PEEP, but there were a couple of centers that did it informally, and on occasion they found auto-PEEP, but it was not a common occurrence. I think it was a slightly different patient population and perhaps slightly different ventilator settings that produced the different results that have been published.[1]

REFERENCE

1. de Durante G, del Turco M, Rustichini L, Cosimini P, Giunta F, Hudson LD, et al. ARDS Network lower tidal volume ventilatory strategy may generate intrinsic positive end-expiratory pressure in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 2002;165(9): 1271–1274.

Blanch: I agree with you that it is a mistake to believe that prolonging the expiratory time may relieve auto-PEEP, when the main factor is minute ventilation. However, when additional resistance was measured in the context of incremental levels of PEEP, additional resistance markedly increased at PEEP of 10 cm H_2O or higher. That increase can be caused by a viscoelastic effect or by a pendelluft effect among lung regions that have different time constants. Certainly, pendelluft is associated with auto-PEEP, but that is just a physiologic comment.

Bigatello: Pelosi et al[1] studied increased resistance in ARDS patients. They partitioned in early airway resistance and the late viscoelastic resistance. I think it was all viscoelastic component. That high volume might be what causes that slight resistance increase in ARDS.

REFERENCE

1. Pelosi P, Cereda M, Foti G, Giacomini M, Pesenti A. Alterations of lung and chest wall mechanics in patients with acute lung injury: effects of positive end-expiratory pressure. Am J Respir Crit Care Med 1995; 152(2):531–537.

Harris: Marcel Amato has some unpublished data about PEEP in obstructive lung disease that shows that lung volume and expiratory lung volume can actually decrease with increased PEEP in certain situations of obstructive lung disease. Presumably that's because if you overcome auto-PEEP, you can increase expiratory flow and decrease relaxation lung volume. I'm wondering if you have any data or experience with that?

Blanch: Yes. We studied whether applying PEEP to COPD patients who had auto-PEEP improved CO_2 elimination, and we found that applying PEEP improved expiratory resistance and expired CO_2 slope.[1] PEEP can open and stabilize closed airways, favoring expiratory flow rich in CO_2.

REFERENCES

1. Blanch L, Lucangelo U, Fernández R, Baigorri F, De Monte A, Saura P, Romero P, Artigas A. [Efecto de la PEEP sobre la mecánica pulmonar y el capnograma espiratorio en pacientes con enfermedad pulmonar obstructiva crónica ventilados mecánicamente.] Med Intensiva 1995;19: 304–312. *Article in Spanish.*

Dhand: There are data that even in patients with ARDS there is an increase in the airway resistance.[1,2] This is responsive to bronchodilators, and it is the initial or the minimal resistance that improves after the administration of bronchodilators. I don't think that you should totally discount airway involvement in ARDS. I think there are several reasons for the airways to be obstructed in patients with ARDS. With the level of inflammation going on in the lung, it would be very easy to imagine that the small airways would probably be more than in a similar kind of inflammatory process, and that the lung involvement in ARDS is not totally restricted to the alveolar region. Therefore, having auto-PEEP in some patients, I think, would be fairly reasonable.

REFERENCES

1. Wright PE, Carmichael LC, Bernard GR. Effect of bronchodilators on lung mechanics in the acute respiratory distress syndrome (ARDS). Chest 1994;106(5):1517–1523.
2. Morina P, Herrera M, Venegas J, Mora D, Rodriguez M, Pino E. Effects of nebulized salbutamol on respiratory mechanics in adult respiratory distress syndrome. Intensive Care Med 1997;23(1):58–64.