Barotrauma: Detection, Recognition, and Management*

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ARDS = adult respiratory distress syndrome; CT = computed tomography; FIo2 = fractional inspired oxygen concentration; MAP = mean airway pressure; PaO2 = mean alveolar pressure; PCV = pressure-controlled ventilation; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure

Barotrauma is an important and potentially lethal complication of mechanical ventilation. All physicians working with patients receiving mechanical ventilation must be familiar with the different clinical manifestations of barotrauma, the recognition of these manifestations, and their management. Perhaps the most important aspect of management is the use of ventilatory strategies that may prevent or limit the development of barotrauma. This portion of the symposium will first review different types of lung injury related to barotrauma, including one type that has only recently been recognized (systemic gas embolism), and another type that has only recently been attributed to barotrauma (diffuse lung injury). Next, the pathogenesis of these manifestations of barotrauma will be reviewed as this underlies the rationale of newer ventilatory strategies.

Clinical Manifestations

Extra-alveolar Gas

The most widely recognized form of barotrauma is the presence of extra-alveolar air. The strict definition of this phenomenon is that gas presents in different tissue spaces after rupturing from the alveoli. Based on work originally performed by Macklin and Macklin in the 1940s, it is thought that gas in the alveoli first ruptures across the boundary between the alveoli and the bronchovascular sheath. The gas then dissects within this sheath toward the mediastinum from which it decompresses through other fascial planes producing the radiographic and clinical manifestations of pneumothorax, subcutaneous emphysema, subpleural air cysts, pneumomediastinum, and pneumoperitoneum.

The incidence of pneumothorax in patients receiving mechanical ventilation is cited to be between 4 and 15 percent, although in patients with the adult respiratory distress syndrome (ARDS), status asthmaticus, and aspiration pneumonia, the incidence may be significantly higher. Gammon and colleagues recently published a study in which they retrospectively reviewed the films and medical records of 139 patients receiving ventilation in their ICU over a 10-month time period. While the incidence of pneumothoraces in the entire group was 14 percent, similar to earlier reports, the incidence in patients with ARDS was 60 percent, while none was observed in patients with congestive heart failure or patients intubated for neurologic disease.

The consequences of a pneumothorax in a patient receiving positive pressure ventilation can include impaired gas exchange, but, perhaps more importantly, adverse hemodynamic effects. Intrathoracic extra-alveolar air may increase intrathoracic pressure, decreasing venous return to the right side of the heart. Compression of the lung and pulmonary vessels may increase afterload to the right side of the heart, and geometric changes in the heart itself may decrease myocardial performance. Studies in animals on positive pressure ventilation demonstrate that there is an almost linear decrease in cardiac output as the volume of an experimentally induced pneumothorax is increased. A significant fall in cardiac output may occur without a corresponding decrease in oxygenation. Therefore, changes in arterial blood gases may not be sensitive indicators of a hemodynamically important pneumothorax. These data also support the clinical maxim that even a small pneumothorax must be evacuated in a patient receiving positive pressure ventilation as it may be causing hemodynamic effects or it could rapidly progress to one that would.

Unfortunately, it is difficult to make a radiographic diagnosis of a pneumothorax on portable x-ray films taken in the ICU setting. The traditional radiographic hallmark of a pneumothorax—an apicolateral collection of air with the visceral pleura visible as a thin white line in the upper hemithorax—may not be present on portable supine films of patients with pneumothoraces. Free air will often be located in the anterior costophrenic sulcus as this is the most superior portion of the pleural space in the supine patient. In addition, concurrent lung disease may lead to different distributions of free air in the pleural space than in patients with relatively normal lungs, or to loculated gas collections if there is associated pleural disease. "Less common" radiographic patterns for pneumothorax may, in fact, be the most common findings in ICU patients. Tocino and colleagues retrospectively determined the location of gas collections on the portable chest radiographs of patients in the ICU. The majority of pneumothoraces were located either in the anteromedial (38 percent) or subpulmonic (26 percent) areas. Only 22 percent of the pneumothoraces were located in the traditional apicolateral location. For this reason, the clinician must be alert to subtle radiographic signs of pneumothoraces in these other locations: (1) relative hyperlucency over the upper abdominal quadrants; (2) deep costophrenic angle (the deep sulcus sign); and (3) the visualization of the anterior costophrenic sulcus that results in a curvilinear change in density over the upper quadrant.

Despite careful review of the supine chest film, it is possible for pneumothoraces to be missed without the use of other imaging modalities or techniques. Several studies have reported that CT scans of the chest may have a greater
sensitivity to detect pneumothoraces in ICU patients than portable chest radiographs. In one study, the investigators performed CT scan cuts through the chest in patients with multiple trauma who were having a head CT scan per-
formed. Twenty one pneumothoraces were visualized in 15 of the 25 patients by either chest radiograph or CT scan. However, 11 of the pneumothoraces (52 percent) were detected by CT scan alone. Of note, three pneumothoraces were missed by CT scans because the cuts were not extended down into the subpulmonic area in these patients.

Unfortunately, it is not always practical or safe to transport critically ill patients for a CT scan to exclude an occult pneumothorax, particularly when the patient is hemody-
namically unstable. Are there methods of improving the sensitivity of portable chest radiographs taken in the ICU? Recently, Carr and colleagues investigated the sensitivity of the lateral decubitus chest radiograph for experimentally induced pneumothoraces in human cadavers. Lateral decu-
bitus films for pneumothoraces are technically easier than those taken to detect pleural fluid as the attention is on the superior hemithorax and not the dependent hemithorax which may be obscured by the bed or other objects. Pneumothoraces were induced in the cadavers with a catheter in the right pleural space. Supine, erect, and left lateral decubitus films were taken at baseline and at each increment in injected volume. Computed radiography was also performed simultaneously. All films were interpreted randomly and in a blinded fashion by five radiologists who graded the films on a five-point scale for the presence or absence of a pneumothorax. The lateral decubitus film was superior to that of both the erect and supine films in sensitivity and could detect a pneumothorax as small as 50 ml. Conventional screen-film radiography provided similar sensitivity as computed radiography in all positions. It is uncertain if lateral decubitus films would reliably detect loculated as opposed to free air collections. Therefore, a study in patients is required to confirm the results of these findings. Nonetheless, these results suggest that lateral decubitus films may be the next radiographic exam to obtain after a supine or erect chest radiograph when there is a high index of suspicion for a pneumothorax.

Other forms of extra-alveolar air may themselves not be life threatening but may herald the development of pne-
mothoraces. Extra-alveolar air in the pulmonary parenchyma (pulmonary interstitial emphysema, subpleural air cysts) or in the mediastinum may rupture through fascial planes into the pleural space and lead to hemodynamically significant pneumothoraces. In a retrospective review by Gammon et al of patients receiving mechanical ventilation, mediastinal emphysema was the initial manifestation of extra-alveolar air in 21 percent of the patients. Once again, the subgroup of ARDS patients had the highest incidence (62 percent). Subsequent pneumothoraces occurred in 42 percent of these patients within 3 days (50 percent of the patients with ARDS mediastinal emphysema). Prophylactic chest tubes in this series of patients would have been unnecessary in a large proportion of patients. Moreover, one cannot be certain that the chest tube will be located in the appropriate position. If the pneumothorax is loculated it may remain unevacuated by a previously placed but inade-
quately positioned chest tube. It may be more appropriate to carefully monitor patients with mediastinal emphysema and be prepared to emergently place directed chest tubes if a pneumothorax develops.

Other complications of extra-alveolar air in the pulmonary parenchyma can occur. Albeda and colleagues reported that in their series of five patients with subpleural air cysts, two patients developed secondary infections in the cysts. One of these patients subsequently died of Pseudomonas sepsis; Pseudomonas was cultured from purulent material present in the cysts at autopsy.

Systemic Gas Embolism

It is possible for extra-alveolar air to enter the systemic circulation if there is a bronchovenous communication and an adequate pressure gradient. Gas that has ruptured from alveolar compartments into the bronchovascular sheath may preferentially enter the pulmonary venous system if paren-
chymal infiltrates block the decompression of this gas into other tissue planes, and if the vascular structures have been disrupted by a necrotizing process or shear forces. The clinical manifestations occur because of entry of gas into the systemic circulation and subsequent occlusion of the vascular supply to multiple organs. Marini and Culver described the simultaneous onset of livido reticularis over the right anterior hemithorax, focal neurologic changes with seizures, and myocardial infarction in two young patients with ARDS, high peak airway pressures, and tension air cyst formation. The distribution of the tissue injury could be explained by microembolization of gas into large vessels that would preferentially receive buoyant gas in the supine position: right internal thoracic artery, the right carotid artery, and the right coronary artery. In one patient, gas in the left atrium was visualized by a transthoracic echocardiogram without evidence of an atrial septal defect at autopsy.

Systemic gas embolization is a well recognized complica-
tion in neonates with the neonatal respiratory distress syndrome, as well as in diving accidents or when there is accidental injection of air into a central vein. These cases in adult patients with ARDS suggest that this diagnosis should be considered when patients with other evidence of extra-alveolar air develop unexplained myocardial or cere-
bral injury. It is possible, though unproven, that more subtle abnormalities in acutely ill patients receiving mechanical ventilation are related to systemic gas embolization.

Diffuse Lung Injury

Forms of barotrauma that occur from the rupture of alveoli and the extravasation of alveolar gas may not be the only manifestation of tissue injury. In 1976, Teplitz reported his experience as a pathologist doing autopsies on burn victims at the United States Army Surgical Research Unit during the time when routine clinical blood gas monitoring became available in the early 1960s. Prior to 1963, he rarely saw evidence of hyaline membrane formation in patients dying with pulmonary edema. After 1963, when the aggressive ventilatory management of gas exchange abnormalities was instituted, he frequently observed hyaline membrane for-
mation in these patients. It was his hypothesis that ARDS was nothing more than the iatrogenic complication of ventilatory management for noncardiogenic pulmonary edema. He could not distinguish, however, if these histo-
pathologic changes were related to the ventilatory management, the increased inspired oxygen concentrations, or to the natural history of this complication in patients who received aggressive life support.

Subsequently, numerous investigators have demonstrated that diffuse lung edema and tissue histopathologic changes indistinguishable from that of ARDS can occur in normal animals ventilated with moderately high peak airway pressures (30 to 50 cm H2O).38-40 Webb and Tierney38 demonstrated that pulmonary edema and hypoxemia would occur in normal rats ventilated at peak inspiratory pressures (PIP) of 30 cm H2O. Interestingly, applied PEEP at 10 cm H2O decreased the level of injury. Kolobow and colleagues40 demonstrated at autopsy that normal sheep ventilated at a PIP of 50 cm H2O developed, within 35 h, severely reduced static lung compliance, decreased FRC, hypoxemia, and grossly abnormal lungs. In a related study,40 sheep ventilated with high tidal volumes developed not only lung injury but hypotension and renal failure similar to that seen in patients with multiple organ system failure.

Although not yet supported by data from patients, the implication of these studies is that lung edema may be perpetuated or extended by the very technique designed to compensate for it. These studies have provoked a re-examination of the underlying pathogenesis of barotrauma, and the ventilatory strategies applied to certain patient groups predisposed to this complication.

**Pathogenesis of Barotrauma**

Peak inspiratory pressures over 40 to 50 cm H2O are associated with an increased risk of alveolar rupture during mechanical ventilation, and the incidence of barotrauma exceeds 40 percent in patients exposed to a PIP above 70 cm H2O.41 Other data suggest an association of barotrauma with the requirement for high levels of PEEP.42 As reviewed above, certain types of lung injury—notably ARDS—appear to increase the risk of barotrauma. However, how these factors interact, and their relative contributions to the risk of barotrauma are not completely understood.

Early investigations3 into the pathophysiology of pneumothoraces demonstrated that alveolar disruption appeared to occur in alveoli bordering the bronchovascular sheath when there was an excessive pressure gradient across this boundary. Subsequent studies suggested that alveolar volume was also an important factor.43 In fact, high airway pressures can be applied to the respiratory system without injury if excessive lung inflation is prevented. For example, Dreyfuss and colleagues44 reported that rats had impressive alveolar flooding and microvascular injury when exposed to 20 min of peak airway pressures of 45 cm H2O. This degree of injury, however, could be prevented if the chests of the animals were strapped.

This relationship of lung injury to hyperinflation has led some investigators to suggest that "barotrauma" might be more appropriately termed "volutrauma," and that the relevant pressure is not peak airway pressure or PEEP level, but the transalveolar pressure.45 In fact, Dreyfuss et al44 could reproduce lung injury in his rat model by using negative pressure ventilators that created similar transalveolar pressures. Because the normal lung is inflated to total lung capacity with transalveolar pressures of 35 cm H2O, there is an emerging consensus that peak alveolar pressures (or transthoracic pressure) exceeding 35 to 40 cm H2O may increase the risk of tissue rupture. Above this pressure, normal alveoli are almost certainly overdistended, and fragile alveoli may rupture.

High transalveolar pressures and alveolar overdistention are unlikely to be the only causative factors in barotrauma. In neonates, significant barotrauma can occur during high frequency ventilation even with modest peak and mean alveolar pressures. In animal models of ARDS, large tidal volumes contributed to increased lung edema even if peak airway pressures, end-inspiratory lung volume, and pulmonary capillary wedge pressures were held constant.46 These and other data suggest that a variety of factors influence the risk of barotrauma: maximal distending pressures, mean airway pressure, the "mechanical stress of hyperventilation," tissue fragility, secretion retention, surfactant depletion, shear forces, and the duration of ventilation.

The role of underlying lung injury as a risk factor for barotrauma can be illustrated by examining the underlying characteristics of the lung in patients with early ARDS. Diffuse lung injury is one of the defining characteristics of ARDS. However, despite the widespread tissue injury and the diffuse infiltrates present on the frontal chest radiograph, there does not appear to be a homogeneous distribution of radiographic abnormalities, gas exchange abnormalities, or mechanical alterations. When performed within the first 10 days of disease onset, CT scans demonstrate marked heterogeneity in the radiographic density of the lung.47 Analyses of gas exchange using inert gas techniques demonstrate that, despite the marked increases in shunt and dead space, a significant proportion of lung units retain normal ventilation to perfusion (V/Q) ratios.48 Another indication that many lung units are uninvolved, or at least are mechanically normal, is that the compliance of the lung corrected for aerated lung volume (the specific compliance) is comparable to that of anesthetized normal subjects.49 Thus, the functioning lung in ARDS is not so much stiff as it is small. The ventilator must apply high pressures to the airway to deliver a tidal volume of "standard size" (10 to 12 ml/kg) into these small lungs. These high applied pressures can lead to hyperinflation of regions of the lung that have relatively normal lung units, putting them at risk for overdistention, rupture, or injury.

**Ventilatory Strategies to Decrease Barotrauma**

The ideal ventilatory strategy would relieve the patient of an excessive breathing workload, assure adequate gas exchange to support organ function, and recruit collapsed or flooded alveoli without injuring normally compliant lung units. Unfortunately, the goal of achieving adequate gas exchange to support organ function may conflict with the goal of limiting regional hyperinflation. For example, the conventional ventilatory strategy in ARDS patients is to use tidal volumes of 10 to 15 ml/kg and respiratory rates adjusted to normalize pH and PaCO2. Positive end-expiratory pressure is applied as necessary to achieve acceptable O2 saturations at nontoxic inspired oxygen concentrations. In some ARDS patients, this strategy will be associated with peak transthoracic pressures exceeding 50 cm H2O—well within the range that may cause alveolar overdistention and...
tissue injury.

Pressure-Targeted Ventilation (Permissive Hypercapnia)

Newer ventilatory strategies in ARDS patients use a "pressure-targeted" approach in that they limit peak distending pressures applied to the respiratory system rather than targeting a normal PaCO₂ or pH. Common objectives of these strategies are to maintain some minimum effective level of positive alveolar pressure throughout the respiratory cycle, thereby preventing collapse of unstable lung units; and to prevent peak alveolar (plateau) pressures from exceeding 35 cm H₂O.¹⁰

Once the diagnosis of ARDS is established, we initiate conventional volume-cycled ventilation with the assist-control mode using tidal volumes of 7 to 10 ml/kg. Next, PEEP, at a minimum level of 5 to 7 cm H₂O, is applied in an effort to recruit nonaerated alveoli and to prevent airway closure and alveolar collapse at end-expiration. Increments of PEEP are added as needed to reduce fractional inspired oxygen concentration (FIO₂) requirements, but a PEEP level of 15 cm H₂O is rarely exceeded as this will further increase peak distending pressures. We aggressively control respiratory infections, work to clear secretions, and reposition the patient frequently (if tolerated) to maximize volume recruitment and minimize alveolar collapse. Tidal volume is adjusted to maintain peak plateau pressures at, or less than, 35 cm H₂O. Occasionally, in a patient with a very stiff chest wall, higher maximal alveolar pressures may be acceptable because the corresponding transalveolar pressure will be less. To limit cycling pressures and lung injury, it may be desirable and necessary to use relatively small tidal volumes (5 to 8 ml/kg).

In some patients, it will not be possible to maintain a normal PaCO₂ and still stay within acceptable pressure limits. In these patients, the PaCO₂ is allowed to rise gradually despite the development of a respiratory acidosis, a strategy termed "permissive hypercapnia."" While acute hypercapnia has potential deleterious effects, including intracellular acidosis, increased pulmonary vascular resistance, increased cerebral blood flow, and increased sympathetic activity, the gradual development of hypercapnia allows for compensatory changes to occur. Hypercapnia has been relatively well tolerated in animal experiments,¹¹ in humans during anesthesia,¹² and in some patient groups where this strategy has been employed either by clinicians (status asthmaticus)¹³ or by the patients themselves (COPD with chronic hypercapnia).

Hickling and colleagues¹⁴ used a pressure-targeted strategy in a series of 50 patients with severe ARDS (defined as having a lung injury score ≥2.5). Patients were ventilated with tidal volumes as low as 350 ml (5 ml/kg) to maintain peak inspiratory pressure less than 30 to 40 cm H₂O. The maximum PaCO₂ in these patients averaged 59 mm Hg, but exceeded 90 mm Hg in four patients, three of whom survived. The survival rate was higher than that predicted by APACHE II scores (corrected for hypercapnia), and eight surviving patients had a "ventilator score" (determined by age, oxygenation, and peak inspiratory pressures) that had previously been associated with 100 percent mortality.¹⁵ The study, however, did not include a concurrent control group. A separate investigation¹⁶,¹⁷ compared extracorporeal CO₂ removal to a pressure-targeted ventilation strategy in ARDS patients who met the extracorporeal membrane oxygenation (ECMO) study criteria. There were no differences in survival between the two treatment groups, but survival in both groups was significantly better than that previously reported in patients meeting these same criteria who were managed with conventional ventilatory strategies. Once again, there was not a concurrent group treated with conventional ventilation. Controlled studies of pressure-targeted ventilation versus conventional ventilation are needed to confirm these preliminary findings.

Pressure-Controlled Ventilation

Some investigators advocate the use of pressure-controlled ventilation (PCV) in patients with ARDS as a means of improving gas exchange while limiting barotrauma.¹⁸,¹⁹ During PCV, a rectangular ("square") wave of set pressure is applied at the airway opening for a defined duration (expressed usually as a fraction of the total respiratory cycle, or as a ratio in relation to expiratory time). Inspiratory flow is initially high, reflecting the large gradient between alveolar and airway pressure, then decelerates as this pressure gradient falls. There are several potential advantages to this mode. First, the set pressure represents a maximum pressure that alveolar pressure cannot exceed under conditions of passive ventilation, thereby preventing uncontrolled and dangerous increases in alveolar pressure. Second, gas exchange may improve under conditions of decelerating flow; rapid expansion of alveoli may facilitate collateral ventilation or improve gas exchange by other mechanisms.

As with any pressure-limited mode of ventilation, the volume actually delivered varies with respiratory system compliance and resistance. Furthermore, any level of inadvertent end-expiratory pressure generated by dynamic hyperinflation will exert a direct (and possibly undetected) opposing pressure. Therefore, careful monitoring of exhaled volume and minute ventilation is mandatory. Increments of applied PEEP will also decrease delivered tidal volume unless the set pressure is also increased. If minute ventilation is inadequate, it may seem logical to raise respiratory frequency. However, minute ventilation does not increase linearly with frequency during PCV and actually reaches a plateau.²⁰ Alveolar ventilation reaches a peak value and then actually falls with further increments of frequencies.²¹ Finally, not all ventilators designed for adult patients are able to provide PCV, and not all clinicians are familiar with its use and complexities.

Extended Inspiratory Time Ventilatory Modes (Inverse Ratio Ventilation)

During positive pressure ventilation of a passive subject, mean airway pressure (MAP) is the pressure measured at the airway opening averaged over the entire respiratory cycle, and reflects the average pressure applied by the ventilator. Under these same conditions, mean alveolar pressure (Pα) is the average pressure acting to distend the alveoli against the combined recoil of lung and chest wall. In the setting of lung edema, Pα corresponds directly to alveolar recruitment, shunt reduction, and blood oxygenation. Although Pα cannot be measured directly during the
tidal cycle, it is closely related to changes in the MAP of the patient receiving passive ventilation. As a result, MAP is a major determinant of oxygenation as well as a key determinant of hemodynamic compromise. The MAP, in turn, is a function of the minute ventilation, the amount of applied PEEP, and the pattern of applied airway pressure. One approach to refractory hypoxemia in ARDS patients may be to augment MAP by extending the inspiratory time rather than by increasing applied PEEP.

The inspiratory time can be extended, and MAP increased in small increments during volume-controlled ventilation by decreasing the inspiratory flow rate, by adding an end-inspiratory pause, or by changing to a decelerating flow waveform. Alternatively, PCV can be used with protracted inspiratory times. In concept, prolongation of the inspiratory time should maintain tidal volume and increase MAP at lower levels of PEEP and peak distending pressures, provided that excessive gas trapping does not occur. Sustained elevations in airway pressure may recruit lung units more effectively than transient increases. Sustained alveolar inflation also appears to decrease dead space, perhaps by enhancing the efficacy of collateral ventilation or by facilitating the mixing of gas in well and poorly perfused regions.

Eventually, as expiratory time is shortened, autoPEEP (dynamic hyperinflation) will develop. Unlike the situation with patients who have dynamic airway collapse, PEEP and autoPEEP are generally additive in ARDS patients. As end-expiratory alveolar pressure increases, either peak alveolar pressure will rise during volume-controlled ventilation, or tidal volume will fall during PCV. The total end-expiratory pressure (determined by end-expiratory port occlusion) must be monitored and maintained between 10 and 15 cm H2O by altering the level of applied PEEP or the inspiratory time.

There are several real or theoretic problems that can occur with this ventilatory strategy. As expiratory time falls, there may be air-trapping in lung units with high expiratory resistance, and these disadvantaged lung units may become overdistended. Thus, increases in MAP and inspiratory time may exacerbate or extend barotrauma. The second potential problem with extended inspiratory time ventilation is that cardiac output may fall as MAP increases. A third problem is that many patients do not tolerate extended inspiratory times without sedation, and in some cases, neuromuscular paralysis. This is particularly important in volume-controlled ventilation as alveolar pressures will increase dangerously if the respiratory frequency is excessive.

For these reasons, the ventilator should be adjusted to provide the shortest inspiratory time and the lowest MAP associated with adequate oxygenation. Many patients do not require actual inversion of their I:E ratio. Unfortunately, many patients do not achieve sufficient benefit from this strategy to justify its hazards. Although there are many anecdotal reports, there are no controlled studies comparing survival in ARDS patients treated with extended inspiratory time ventilation to those treated with conventional ventilation.

Conclusions

The hazards of excessive applied pressures and, perhaps more directly, regional hyperinflation extend beyond pneumothoraces to other forms of lung and systemic injury. Newer ventilatory strategies such as pressure targeted ventilation with permissive hypercapnia attempt to limit overdistension of relatively normal lung units. Preliminary studies suggest, but as yet do not confirm, that this approach may reduce the incidence of barotrauma. Until there is more investigational and clinical experience, these methods must be applied cautiously and with full awareness of their possible hazards.

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