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CURRENT TOPICS

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Measurement of functional residual capacity in the critically ill. Relevance for the assessment of respiratory mechanics during mechanical ventilation

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Introduction

During mechanical ventilation, respiratory mechanics are commonly assessed by studying the pressure-volume (PV) relationship, describing the elastic properties of the respiratory system, lungs and chest wall, and/or by measuring end-expiratory lung volume (EELV) or functional residual capacity (FRC). Recently a number of papers have been published on the inflation limb of the PV curve of the respiratory system, seeking its lower and upper inflection points to guide ventilator settings. It is apparent that a complete description of the elastic behavior of the respiratory system would require measurements made over the complete volume range, from residual volume (RV) to total lung capacitiy (TLC). In cooperative subjects, it is possible to measure the PV curve starting at RV, which influences the shape of the inflation, but not of the deflation, PV curves. Likewise, in an excised lung PV curves can be obtained from the degassed state and, this has a profound effect on the shape of the inflation limb of the PV curve, while the deflation limb remains unchanged. In other words, the shape of the inflation limb depends on the initial lung volume at which its determination starts. However, making measurements from RV is impractical and indeed dangerous in patients with acute lung injury. Therefore, measurements of PV curves are generally made starting from EELV at 0 cmH_2O airway pressure.

In normal subjects, EELV is synonymous with FRC, defined as the volume determined by the balance of static passive forces of the lung and chest wall. By definition, positive pressure ventilation in a sedated and paralyzed patient occurs above FRC. Therefore, with any setting on the ventilator, only the volume above the FRC can be modified according to the characteristics of the PV curve (i.e. compliance and hysteresis). In some patients the FRC is virtually at the RV, in others there is a substantial expiratory reserve volume. If the disease is associated with a highly compliant lung or chest wall, the FRC will be high and, conversely, if the lung or chest wall compliance is low, the FRC will be low. In the former case, one may not see an inflection point on the inflation limb of the PV curve, whereas it will probably be present in the latter. The position of the FRC within the TLC is thus “disease specific” and the problem is that, even FRC is measured with a gas dilution technique, it is difficult to assess it in relation to the TLC. Furthermore, in ALI/ARDS there is a significant portion of the intrathoracic gas volume occupied by tissue edema, fluids and inflammatory cells, as evidenced by computer tomographic studies, therefore lung gas volume measurements may not always be predictive of total thoracic volume. A further difficulty is that if, by some ventilatory strategy, one succeeds in increasing lung volume, one is never sure whether this is due to recruiting new gas exchange units (good) or overdistending already open units (bad). This issue was addressed in a recent paper by Gattinoni.

L Gattinoni, P Pelosi, PM Suter, A Pedoto, P Vercesi, A Lissoni (1998) Acute respiratory distress syndrome caused by pulmonary and extrapulmonary disease. Am J Respir Crit Care Med 158: 3–11

The investigators studied the differences in respiratory mechanics (elastance, partitioned into lung and chest wall components, and EELV) between ARDS originating from pulmonary (ARDSp) or from extrapulmonary (ARDSexp) disease. They found similar EELV at ZEEP (i.e. FRC) in both patient groups, but a different response to PEEP in terms of achieved volume recruitment. Elastance of the total respiratory system (Est,rs) was similar in both groups at ZEEP, but the elastance of the lung (Est,L) was elevated in ARDSp, whereas the elastance of the chest wall (Est,w) was elevated in ARDSexp. Increasing PEEP increased Est,rs and Est,L in ARDSp, but lowered Est,rs, Est,L, and Est,w in ARDSexp. The authors concluded that the prevalence of lung tissue consolidation in patients with ARDSp led to stiff lungs resulting in minimal PEEP-induced recruitment, whereas interstitial edema and alveolar collapse, as the predominant alteration of ARDSexp, allowed better recruitment with PEEP. Unfortunately, the effects of PEEP on gas exchange were not reported in this study.

VM Ranieri, N Brienza, S Santostasi, F Puntillo, L Mascia, N Vitale, R Giuliani, V Memeo, F Bruno, T Fiore, A Brienza, AS Slutsky (1997) Impairment of lung and chest wall mechanics in patients with acute respiratory distress syndrome. Am J Respir Crit Care Med 156: 1082–1091

A similar question on the importance of measurements of respiratory mechanics as a predictor of possible recruitment in patients with ARDS was raised by these authors, who compared the PV relationship in ventilated patients with ARDS following major abdominal surgery to patients with ARDS due to medical causes. FRC was not measured. In surgical ARDS, the inflation PV curves of the respiratory system and the lung showed an upward convexity, indicating that elastance increased with tidal volume (i.e. alveolar overdistention), whereas in patients with medical ARDS there was an upward concavity of the inflation PV curve, indicating a decrease in elastance (i.e. alveolar recruitment) during inflation. PEEP effects were not tested.

J Hammer, A Numa, CJL Newth (1998) Total lung capacity by N2 washout from high and low lung volumes in ventilated infants and children. Am J Respir Crit Care Med 158: 526–531

These investigators tried to measure FRC, as a relative lung volume, in relation to TLC, both lung volumes being measured by gas dilution. The study included 50 critical ill infants with a variety of lung diseases. The results show that determination of TLC and FRC is reliable and helpful in estimating the degree of lung hyperinflation, by calculation of the FRC/TLC ratio. The authors concluded that lung volumes and their ratio discriminated the patients with respect to the underlying pathophysiology. They postulate that the combined measurements of FRC and TLC might be helpful in the ventilatory management of restrictive and obstructive patients. PEEP effects were not assessed.

Discussion

Gattinoni's paper quite clearly shows that there are marked differences between ARDS of pulmonary (ARDSp) and extrapulmonary (ARDSexp) origin, the crucial difference being the chest wall compliance. This makes a substantial difference in the response to volume recruitment measures, PEEP being effective in recruiting ARDSexp, but not in ARDSp. This is probably one reason why there are such conflicting results in many previous ARDS studies. These authors took this one bold step further. At each PEEP level they measured the EELV above FRC, and then compared EELV with the measured FRC multiplied by the compliance. The underlying assumption is that the specific compliance in ARDS is normal. They found their measured volume greater than their computed volume in ARDSexp and concluded that they had recruited new alveoli, whereas this did not occur in ARDSp.

There are two problems with this ingenious approach. The first is technical: the patients with ARDSexp were aged 55.9 on average and at that age in the supine position, sedated and paralyzed, the FRC is well below closing volume with extensive terminal airway closure at ZEEP, which makes a helium dilution FRC highly dubious. Patients with ARDSp were 17.3 years younger and would therefore have less closure. Secondly, their calculation is based on the assumption that the specific elastance in ARDS is normal. As the fundamental message of this paper is that there is a major difference in the elastance of patients with ARDSp and ARDSexp, this assumption may be erroneous. This is a landmark paper, but the same conclusions could have been reached without the troublesome and dubious measurement of helium dilution lung volume. The case could have been made with arterial blood gases. Recruitment should have increased PaO_2 substantially more than simple overdistention.

The findings from Ranieri's study are somewhat in contradiction with those of the Gattinoni paper. Ranieri's medical ARDS patients, who would belong to Gattinoni's ARDSp group with some exceptions, showed an upward concavity of the inflation PV curve, indicating recruitment during inflation, whereas Gattinoni's ARDSp patients did not exhibit lung recruitment with PEEP. It is not easy to explain all the factors contributing to this discrepancy, but it is clear that the different maneuvers, measurement techniques and assumptions used by the two groups may have led to these controversial results.

We conclude that:

1. It is exceedingly difficult to measure the gas volume of FRC with any accuracy in ARDS.
2. Even if it was possible, its position cannot be easily related to a place in the total lung capacity. (The study by Hammer et al. is perhaps a first step in this direction).
3. That being so, the inflation limb of the PV curve is highly sensitive to the initial volume conditions.

Because of these difficulties, both in measuring volume and in the meaning of the inflation limb, why measure them, and why not use the deflation limb which is much more stable? This issue was first addressed in high frequency oscillation (HFO) by introducing a recruitment maneuver (sustained inflation) and then reducing the airway pressure, allowing the lung to slide down the deflation limb of the PV curve and stopping above the closing volume (Kolton et al. (1992) Anesth Analg 61:323–332). Since then the power of this strategy has been very clearly demonstrated and forms the basis of current successful HFO strategies in neonates. This strategy seems to be equally effective in small tidal volume (Vt) conventional ventilation (Rimensberger et al. Crit Care Med: in press). Unlike the patchy chaotic behavior of the lung on inflation, during deflation there is a symmetrical and consistent decrease in size of all the alveoli until closing volume is reached. Similar to the inflation limb, the deflation limb of the PV curve has a sigmoidal shape with an asymptote in the upper third (where the lung is overdistended) a middle third (which is the most compliant section of the deflation limb) and a lower third (where lung closing will occur). The ventilator cycle (Vt excursion) has to be placed within the middle third in order to keep the lung open as homogeneously as possible during ventilation.