

Dynamic respiratory mechanics in acute lung injury/acute respiratory distress syndrome: research or clinical tool?

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Purpose of review

Classic static measurements of lung mechanics have been used mainly for research purposes, but have not gained widespread clinical acceptance. Instead, dynamic measurements have been used, but interpretation of results has been hampered by lack of clear definitions. The review provides an overview of possible definitions and a description of methods for evaluating lung mechanics in acute lung injury/acute respiratory distress syndrome patients.

Recent findings

Compliance measured using static techniques is significantly higher compared to measurements during ongoing ventilation. This indicates that lung mechanic properties depend on flow velocity during inflation and the time allowed for equilibration of viscoelastic forces. Thus, methods for evaluating lung mechanics should be clearly defined in terms of whether they are classically static, i.e. excluding resistance to flow and equilibration of viscoelastic forces, or truly dynamic, i.e. including flow resistance and unequilibrated viscoelastic forces. New techniques have emerged which make it possible to monitor lung mechanics during ongoing, therapeutic ventilation, 'functional lung mechanics', where the impact of flow resistance on tube and airway resistance has been eliminated, providing alveolar pressure/volume curves.

Summary

Functional lung mechanics obtained during ongoing ventilator treatment have the potential to provide information for optimizing ventilator management in critically ill patients.

Keywords

compliance, dynamic, lung mechanics, quasistatic, static

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Introduction

Ventilator-induced lung injury may be minimized by setting the tidal volume below the upper inflection point (UIP) of the static pressure/volume (P/V) curve so as to avoid overdistension, and setting the positive end-expiratory pressure (PEEP) above the lower inflection point (LIP) of the static P/V curve so as to prevent cyclic opening and collapse of alveoli [1–3]. In the clinical setting, measurements of static P/V curves have not gained widespread use because methods may be cumbersome and potentially dangerous (super-syringe technique), and demand interruption of ongoing ventilation. As a substitute, dynamic lung mechanics have been monitored, but the results have been difficult to interpret, partly because lung mechanic definitions have not been clearly defined [4*].

Definitions

We propose the following definitions of lung mechanics.

Classic static compliance (no-flow and equilibrated viscoelastic forces)

The classic definition of static conditions is that a sufficiently long end-inspiratory and end-expiratory pause is used not only to stop gas flow in the airways, but also to equilibrate viscoelastic forces of the lung. It has been shown that equilibration continues for 4–5 s after closure of the inspiratory valve during a prolonged end-inspiratory pause [5,6]. The tracheal pressure decreases around 2 cmH₂O during the 5 s.

Static compliance (no-flow and nonequilibrated viscoelastic forces)

The pressure fall immediately after closing the inspiratory valve of the ventilator occurs rapidly. This initial pressure drop is a result of obtaining no-flow conditions in the airways, and the time it takes is correlated to the endotracheal tube, patient airway resistance, breathing circuit compliance and flow immediately before closing the valve. The time constant can be calculated as $R \times C$,

where C is the compliance of the breathing circuit, and R is the resistance of the endotracheal tube and the airways. In a typical case, the breathing circuit has a compliance of 0.5×10^{-3} l/cmH₂O and the resistance of a tube is 6 cmH₂O/l/s, which gives a time constant of 3 ms. In this case, the flow will decrease by 95% in three time constants, i.e. around 10 ms. Thus, after a minimal time, the pressure in the ventilator and in the alveoli will be equilibrated, and static conditions are obtained in the sense that there are no-flow conditions in the airways. The viscoelastic forces will lag behind through the breath during tidal ventilation.

Quasistatic compliance (low-flow and quasi-equilibrated viscoelastic forces)

To minimize the influence of endotracheal tube and airway resistance, a low-flow inflation to reach a pressure of 40–45 cmH₂O was used [7]. Setting a very low respiratory rate and an inspiration: expiration ratio of 4:1 results in an inflation flow of below 5 l/min, which gives an inflation P/V curve that is almost negligibly right-shifted due to the resistance, but where the viscoelastic forces are not fully equilibrated.

Dynamic compliance (including flow resistance and nonequilibrated viscoelastic forces)

Dynamic compliance is obtained during ongoing ventilation, and includes flow resistance (endotracheal tube and airways) and viscoelastic forces that will not be equilibrated. Compliance measured during pressure control or support ventilation is true dynamic compliance as there is no end-inspiratory pause, and the peak pressure will include the influence of flow resistance and compliance will be falsely low.

Functional compliance and lung mechanics (excluding flow resistance but nonequilibrated viscoelastic forces)

According to Stahl *et al.* [8**], functional lung mechanics can be defined as measurements obtained during ongoing ventilation. Functional lung mechanics provide *alveolar* P/V curves irrespective of mode, where effects of tube and airway resistance are eliminated, but where viscoelastic forces are nonequilibrated. In this review we use 'functional/dynamic' to emphasize that functional lung mechanics are obtained during dynamic conditions.

Methods for quantification of lung mechanics

There are a number of methods for quantification of lung mechanics.

Classic static techniques

Disconnecting the patient from the ventilator, connecting the patient to the super syringe and then stepwise inflating the patient to a pressure of 40–50 cmH₂O followed by a stepwise deflation, at each step recording

the pressure after a 5- to 6-s pause, is a lengthy, cumbersome and sometimes dangerous procedure. For adequate interpretation, measurements need to be corrected for temperature, humidity and last, but not least, the oxygen consumption of the patient [9,10], which has a profound effect on the measurements as it takes up to 2 min to perform a complete P/V curve. The difficulties encountered with the super-syringe technique led to the development of more automatic methods for P/V curves, with no need for disconnection of the patient. Several methods based on interrupter techniques have been presented [11,12]. In contrast to the super-syringe technique, such methods have the advantage of each volume step measurement being independent of the previous measurements and the P/V curves showed very little hysteresis as compared to the P/V curves obtained by the super syringe.

Conventional two-point compliance calculated from pressure values obtained after prolonged (more than 4 s) end-inspiratory and end-expiratory pauses can be regarded as classic static compliance.

Static techniques

Conventional two-point compliance during volume control ventilation with a short end-inspiratory pause, often misnamed dynamic compliance (tidal volume/end-inspiratory pressure – end-expiratory pressure), calculated during ongoing ventilation can be regarded as static in the no-flow sense, as the end-inspiratory pause may be short (less than 300 ms) and the viscoelastic forces will not be equilibrated [13]. It is noteworthy that an end-inspiratory pause can only be implemented in volume control ventilation. In pressure control and especially pressure support ventilation, there may be flow ongoing at the end of inspiration leading to a falsely high end-inspiratory pressure value, resulting in an underestimation of compliance.

Quasistatic techniques

Low-flow inflations have been used in a number of studies to obtain an inspiratory P/V curve with flows ranging from 3 to 15 l/min [7,14,15]. The correct flow rate for low-flow inflation is difficult to determine as a too low flow will be affected by oxygen uptake and a too high flow will include resistance from airways, especially the endotracheal tube. As it takes up to 5 s for the viscoelastic forces to equilibrate [5], the low-flow inflation technique cannot give classic static P/V curves [7,14].

Dynamic techniques

The Stress Index method [16,17] is not a method that directly results in a conventional P/V curve as it calculates the shape of the inspiratory pressure–time curve during ongoing volume control and constant flow ventilation according to the formula: airway pressure = $a \times \text{time}^b + c$, where coefficient b (stress index) describes the shape of the curve; $b < 1$ indicates tidal recruitment and $b > 1$ indicates

hyperinflation. In principle, this method is a true dynamic technique as it includes flow resistance of the endotracheal tube and airways, but no equilibration of viscoelastic forces. The advantage of the Stress Index is that it is based on easily available data for computation of the index. The main disadvantage is that it requires volume control ventilation and only considers the inspiratory part of the breath. There may also be some doubts as to whether airway resistance is constant during inspiration.

Lung mechanics obtained during dynamic conditions – functional lung mechanics

Two techniques are consistent with the definition of functional lung mechanics as described above:

- (1) The Slice method [18,19] is a three-step procedure where the tracheal pressure is first calculated from the ventilator pressure and flow, and an algorithm for the endotracheal tube resistance and then a tracheal pressure volume loop are obtained. For reasonable precision, the P/V loop is divided into six slices and multiple linear regression applied to each slice to give a compliance value for each slice from bottom to top of the tidal volume. Thus, this method has the capacity of calculating volume-dependent compliance breath by breath, i.e. fast compliance. The advantage of the method is that it is based on easily available data for computation, and can be used in both volume and pressure control ventilation. The disadvantage is that tube resistance may differ from the algorithm values in clinical practice and that the end parts of the breath – at the bottom and at the top – are difficult to calculate with good precision. Also, any inflection point will be prepositioned between the slices irrespective of where they are in reality.
- (2) The Dynostatic Algorithm (DSA) [20–22] is based on direct tracheal pressure measurements to obtain a tracheal P/V loop. Assuming that the expiratory and inspiratory resistances at the same inspiratory and expiratory volume are reasonably similar, alveolar pressure can be calculated using the equation of motion at a number of isoplanes of the tracheal pressure volume loop and an alveolar P/V curve can be obtained displaying the fast volume-dependent compliance breath by breath. The DSA is independent of tube resistance and changes in airway resistance during inspiration and expiration. The P/V curve can show the correct position of any inflection points as it is based on at least 20 isovolume planes for each breath. It can be used in both volume and pressure control mode. The disadvantage is that it demands a tracheal pressure line inserted through the tube, but this is also an advantage as the pressure in the trachea can be measured without interrupting ventilation, i.e. peak tracheal pressure and intrinsic PEEP caused by

flow limitations of the endotracheal tube can be monitored continuously.

Both the Slice method and the DSA are methods for functional volume-dependent compliance monitoring, which give P/V curves that disregard effects of the viscoelastic forces. This may lead to an underestimation of the level of a LIP in comparison with LIP determined with a slow inflation inspiratory P/V curve, as the time that the alveolar pressure is below the LIP during tidal breathing is much shorter: in a typical case 1.5 s as compared to over 6 s during slow inflation (Fig. 1). Taking into account that the time needed for alveolar or terminal bronchiolar collapse may be up to 4 s [23], the LIP during normal tidal breathing may not be seen even when the PEEP level is below a LIP determined with a slow inflation method (Fig. 2).

Time-dependent lung mechanics

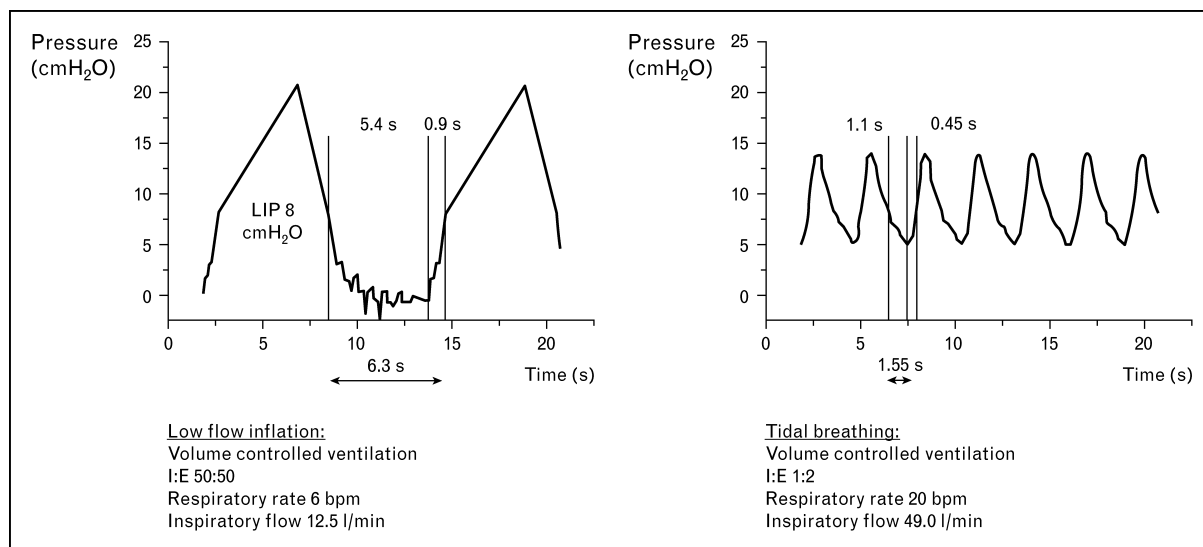
Lung mechanics are obviously time dependent and the method used for quantification may affect the results.

Fast and slow compliance

In 1999, classic static inflation–deflation P/V curves were presented with dynamic tidal ventilation P/V loops inscribed [24]. These loops indicated that at the same lung volume or pressure level, lung compliance was different when inflation was rapid, such as during tidal ventilation, as compared to a classic static procedure. In a mathematical model study on incremental vs. decremental PEEP trials, the phenomenon with lower compliance during tidal breathing than during slow inflations was further described [25], pointing at a weak spot in the use of classic and quasistatic P/V curves – they did not give the same information about lung mechanics that is present during tidal ventilator treatment. The time factor that seems to be an important factor for the mechanical behavior of the lung could be identified and slowly distensible compartments quantified by a PEEP step maneuver [26*,27]. The presence of slowly distensible lung units was more common in acute respiratory distress syndrome (ARDS) patients than in patients with mild lung injury.

Re-expansion of atelectasis during anesthesia may take up to 5 s [28] and could explain why tidal recruitment is less than PEEP-induced recruitment. In a study on oleic acid-induced lung injury in dogs, classic static P/V curves obtained with the super-syringe method and dynamic P/V curves during ventilation with a respiratory rate of 15 breaths/min and a tidal volume of 350 ml were compared [29]. This interesting study showed that the LIP was right-shifted during dynamic conditions and probably did not represent the same phenomenon as the static LIP. The dynamic P/V curve above the LIP showed a

Figure 1 Alveolar pressure vs. time in an acute lung injury patient during slow inflation (left) and during tidal breathing (right)

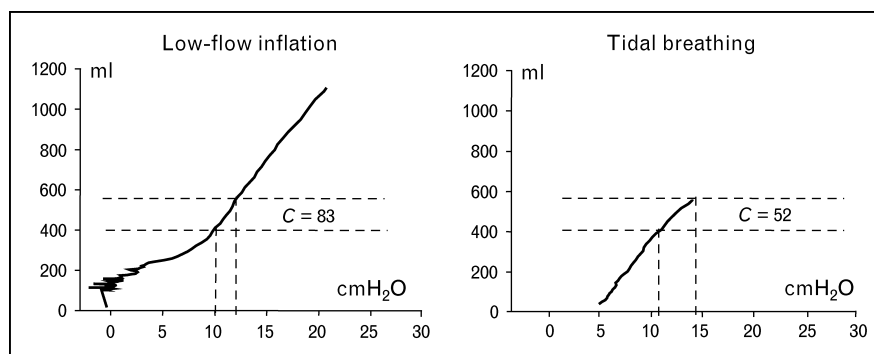


In this patient the lower inflection point (LIP) is around 8 cmH₂O, which can be seen as the inflection in the pressure trace (indicated by arrows) during inspiration and expiration. During the slow inflation the pressure is below the LIP for more than 6 s. During therapeutic tidal ventilation at a rate of 20 breaths/min the corresponding time is only 1.5 s and this is a too short time for collapse to occur. bpm, breaths/min; I : E, inspiration : expiration. From [30] with permission.

much lower compliance than the static *P/V* curve, which the authors speculate to be explained by an additional pressure needed to distribute the tidal volume, to displace secretions into the alveoli and to overcome viscoelastic forces. Another important finding is that the end-expiratory lung volume is higher during dynamic conditions than during static measurements, starting the inflation from the same pressure level. This indicates that the alveolar pressure may not fall as much during tidal breathing as during a static *P/V* curve procedure. The authors concluded, somewhat surprisingly,

that the dynamic *P/V* curve cannot be used for setting the ventilator as it does not reliably reflect the static *P/V* curve contour, but the differences in position of the LIP are partly explained by the fact that no attempt was made to correct for the endotracheal tube resistance impact on the pressure measurements. It should be emphasized that both functional methods, i.e. the Slice method and the DSA, eliminate the effect of all airway resistance during both inspiration and expiration, giving an alveolar *P/V* curve that should be more adequate to compare to the static *P/V* curve [30].

Figure 2 Total respiratory system alveolar *P/V* curves obtained by the Dynostatic Algorithm in a patient with acute lung injury

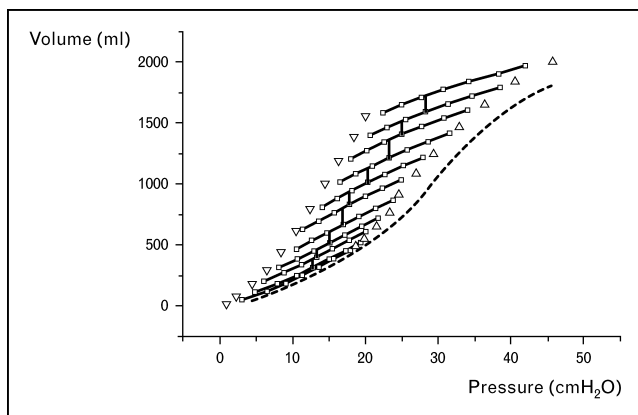


During a low-flow inflation (left) a prominent lower inflection point (LIP) is seen at around 8 cmH₂O followed by a high constant compliance without an apparent upper inflection point even though the total volume inflated reaches 1100 ml. During tidal breathing (right), inspiration starting from a pressure level of 4 cmH₂O, no LIP is seen but a tendency to an upper inflation zone in spite of the inflated volume being only half of the slow inflation volume. The calculated compliance of the tidal breath at the end of inspiration, between 400 and 555 ml is 52 ml/cmH₂O, but at the same volume ranged during low-flow inflation is as high as 83 ml/cmH₂O. Modified from [20] with permission.

In a study on acute lung injury (ALI) patients using the DSA [20], it was shown that in two of the patients a clear LIP was seen during low-flow inflation, which was totally absent during tidal ventilation [31] (Fig. 2). The first systematic study comparing static and dynamic/functional measurements of lung mechanics in patients with ALI and ARDS was presented in 2006 [8**]. Functional lung mechanics were measured during ongoing mechanical ventilation with an incremental PEEP procedure using the Slice method and quasistatic P/V curves were obtained during low-flow inflation. The compliance at an alveolar pressure of 25 cmH₂O was 30 ml/cmH₂O when measured during dynamic conditions and 60 ml/cmH₂O measured by the quasistatic technique (Fig. 3). This is a clinical confirmation of the results of Hickling's computations [25]. Also, they found that the functional P/V curve showed a decrease of compliance at pressure levels where the static curve showed increased compliance. Static measurements may therefore be misleading, giving an impression of a need for a higher PEEP level than necessary and still showing no sign of overdistension at high pressure levels. The different results of static and dynamic/functional measurements of lung mechanics are clearly shown, but there are few reasonable explanations for the phenomenon.

A recent study may provide a possible explanation for the differences between lung mechanics obtained during static and dynamic conditions [32*]. Using optoelectronic plethysmography for chest wall volume change and a super syringe for controlling inflated volume, the blood volume shift in and out of the thorax during the measure-

Figure 3 Quasistatic P/V curve (dashed line) obtained by low-flow inflation method and alveolar P/V curves (black lines) obtained during an incremental positive end-expiratory pressure (PEEP) trial



Note that the slopes of the dynamic P/V curves at higher PEEP levels are less steep compared to that of the quasistatic P/V curve. This indicates a lower compliance when measured during dynamic vs. quasistatic conditions. In addition, end-expiratory lung volume at each PEEP level is higher during dynamic vs. quasistatic conditions. From [8**] with permission.

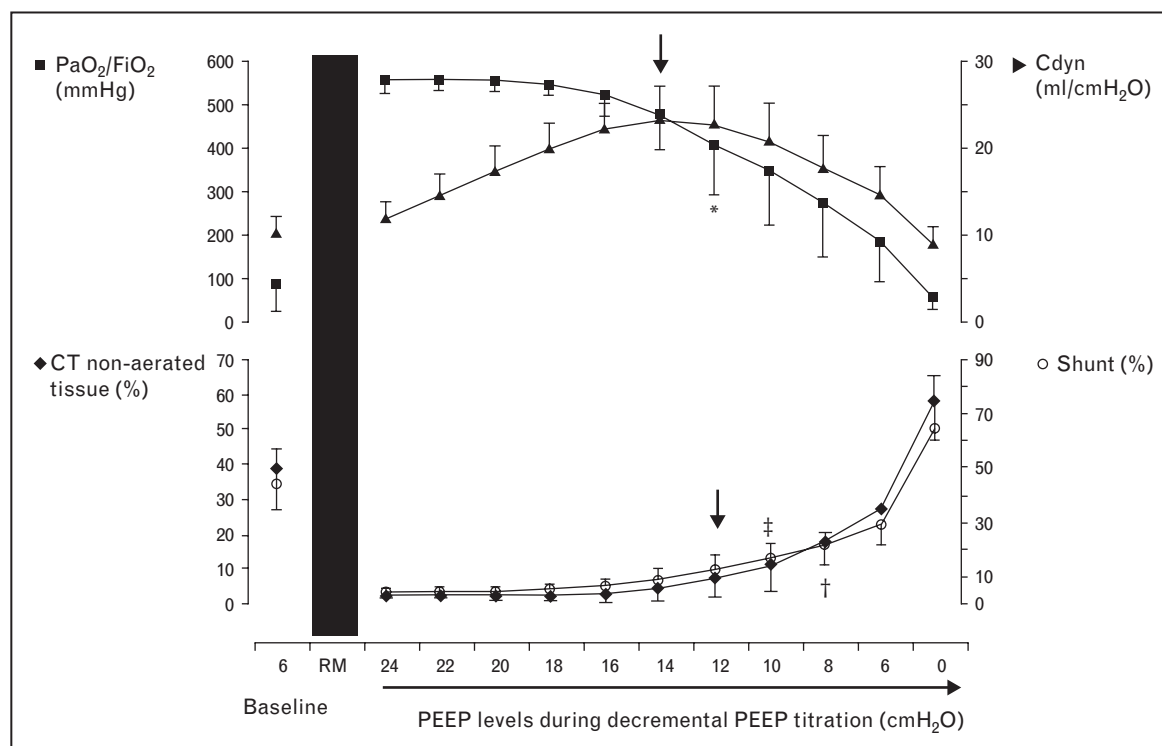
ment of a static P/V curve could be calculated. The volume shift did not seem to affect the position of the LIP, but the hysteresis of the inflation–deflation curves was significantly decreased. The unrecovered volume at the end of the deflation was almost twice as high using the conventional, corrected gas volume as compared to the volume obtained by optoelectronic plethysmography. One can speculate that during tidal volume the blood volume shift will be much less, as it takes time both to squeeze blood volume out of the thorax during inspiration and to let it return during deflation. The effect of the inertia of the blood volume in the thorax will be more obvious the faster the respiratory rate or the inspiration, which may be one of the explanations for the differences between static and dynamic/functional P/V curves. Chiumello *et al.* [32*], however, did not compare gas volume and optoelectronic plethysmography volume during static and dynamic conditions, which would be needed to clarify these effects.

Setting the ventilator using lung mechanics measured during ongoing ventilation

In a study on isolated, perfused and ventilated rabbit lungs using the Slice method, it was found that setting the PEEP according to the intratidal compliance–volume curve improved the ventilation:perfusion ratio as assessed by the multiple inert gas elimination technique compared to setting PEEP above the LIP of the static P/V curve [33]. In an excellent study of static vs. dynamic/functional lung mechanics the static P/V curve was obtained with a modified multiple occlusion technique, and LIP and UIP determined by tracing a straight line on the linear part as the best fit by eye and functional lung mechanics by the Slice method [34]. When adjusting the PEEP level by the Slice method, compliance was plotted vs. tidal volume in six slices, and PEEP was set to avoid increasing compliance at low parts of the tidal volume and keeping the value as horizontal as possible through the six slices. PEEP was 20 cmH₂O (i.e. 17–22 cmH₂O) with the static method and 15 cmH₂O (i.e. 13–18 cmH₂O) with the functional method. During the 40 min of the trial period, compliance decreased when setting the ventilator according to the static LIP, whereas compliance remained unchanged when the functional LIP was used. This was attributed to the fact that the lung was exposed to a higher degree of mechanical stress, due to a plateau pressure that was 8 cmH₂O higher than during the PEEP set by the Slice method, 35 vs. 27 cmH₂O. Conventional two-point compliance was 33% higher in the functional group than in the static group.

Recently, a study using the two-point, static (no-flow) compliance was used for determining optimal PEEP in surfactant-deficient pigs [35**]. A lung recruitment

Figure 4 Changes in oxygenation, breath-by-breath (no-flow) static (as defined above) compliance, nonaerated lung tissue and shunt after a recruitment maneuver (RM) followed by decremental positive end-expiratory pressure (PEEP) steps in surfactant-deficient pigs



A PEEP below the maximal compliance (upper arrow) is associated with appearance of atelectasis seen on computed tomography (CT) (lower arrow). Cdyn, pulmonary compliance; FiO₂, fraction of inspired oxygen; PaO₂, arterial oxygen partial pressure. From [35**] with permission.

maneuver was followed by a decremental PEEP trial. Optimal PEEP was defined as the PEEP level above the pressure level where the first decrease of compliance was detected. The PEEP level where collapse started occurred at 14 cmH₂O and coincided with the point where oxygenation started to decrease (Fig. 4). PEEP was set 2 cmH₂O higher where a CT scan confirmed fully open lungs. This is an interesting approach to setting PEEP and can easily be adopted in clinical practice. The limitation of the study is that it was done in a very recruitable and fairly uniform lung injury model. Thus, there is a need for a study in ALI patients to confirm the findings and the clinical feasibility of the technique.

Conclusion

Classic static methods and dynamic/functional measurements of lung mechanics show different results. Dynamic/functional compliance is much lower and the PEEP needed to keep the lung open also seems to be lower in experimental studies comparing static and dynamic/functional methods. There is still no clear explanation of the differences. Going from static lung mechanics to lung mechanics obtained during ongoing ventilation seems to be an obvious goal; however, there are very few clinical

studies of how to set the ventilator by functional methods during ongoing ventilation. There is reason to believe that static and functional methods are complementary. The knowledge of static *P/V* curves is broad, whereas fairly little is known about the interpretation of functional *P/V* curves. Hopefully, this knowledge gap will be filled soon, as the dynamic/functional methods are much easier to use in clinical practice.

References and recommended reading

Papers of particular interest, published within the annual period of review, have been highlighted as:

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Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 110).

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