Alveolar Pressure/volume Curves Reflect Regional Lung Mechanics

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Introduction

The static pressure volume (P/V) curve has been regarded as the gold standard tool for assessment of the mechanical properties of the lung. On this curve, a lower inflection point (LIP) can be detected in some patients and in most patients an upper inflection point (UIP) can be seen. The most common interpretation of the LIP and the UIP is that LIP represents the point where alveoli collapse at the end of expiration and reopen at the start of inspiration and that the UIP represents the pressure above which alveoli become overdistended. It has been proposed that in order to avoid cyclic closing and opening and overdistension of alveoli, ventilation should be performed with pressures between the LIP and UIP, where the compliance of the lungs is highest.

The Lower Inflection Point

The background of LIP is complex and various hypotheses have been proposed. Gattinoni and co-workers have proposed that the weight of the edematous acute lung injury/acute respiratory distress syndrome (ALI/ARDS) lung results in a superimposed pressure, increasing vertically, causing a collapse of the most dorsal lung parts [1, 2]. The LIP should, according to this proposal, be the pressure that is high enough to counteract the threshold opening pressure and the superimposed pressure. This hypothesis has been further analyzed in a mathematical model by Hickling, who describes a continuous recruitment process during inflation [3]. Hubmayr has argued against this interpretation and favors a hypothesis where the LIP is caused by a gas/fluid interface in flooded lung parts [4].

The Volume below the Lower Inflection Point

In the literature on lung mechanics, the focus has been on the pressure level of the LIP, but very little is mentioned about the volume where the LIP is positioned. Clinical data are scarce, but from published P/V curves the volume can be estimated to lie between 50 and 150 ml [5–7]. Compliance below the LIP can be estimated to be 5–20 ml/cmH_2O based on these curves. It is important in this context to realize that compliance is closely related to the size of the lung. Thus, if you apply pressure control ventilation to a mouse or an elephant with a pressure that in a human results in normocapnia, you will have normocapnia in both these animals, as the compliance

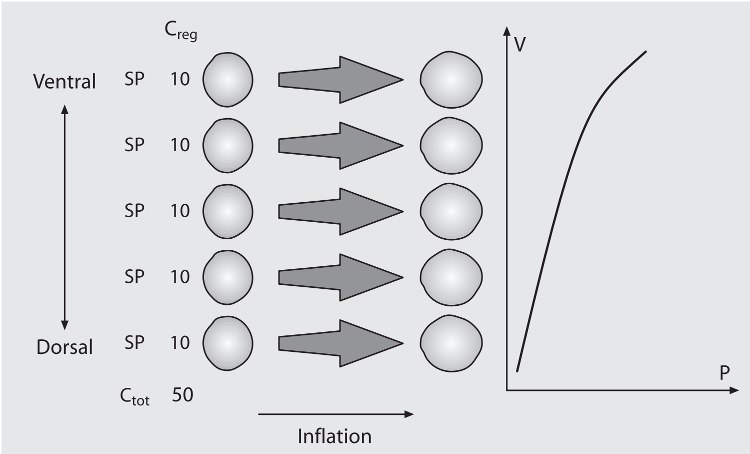

Fig. 1. Regional compliance (Creg), superimposed pressure (SP), and pressure/volume (P/V) curve in a healthy lung. No lower inflection point (LIP) is detected and a decrease in compliance is noted as inflation reaches total lung capacity.

of the elephant lung is enormous and that of the mouse is very low. Gattinoni and Pesenti have has promoted the baby lung concept, where the ALI/ARDS patient is supposed to have a part of the lung collapsed and the rest – a small but supposedly healthy lung – a 'baby lung' that is quite normal [8]. This dichotomic view of the ALI/ARDS lung may be questioned as, most likely, the open parts of the lung are also to some extent affected by a lowered compliance as a result. When a P/V curve of such a lung is obtained, the compliance below the LIP will be low, representing compliance of the baby lung. The compliance of this baby lung will be dependent on its size, the smaller the baby lung, the lower the compliance. As the inflation continues and more alveoli are recruited, compliance will increase until alveoli at the very bottom of the lung with very low compliance are recruited. The reason for elaborating on this point is that the relationship between the size of the lung and compliance is fundamental for understanding the P/V curve. If a healthy lung (Fig. 1) is divided into, for example, five horizontal planes with alveoli of the same end expiratory size and compliance is measured for each of these parts of the lung, it would be a fifth of the total compliance. If an ALI/ARDS lung (Fig. 2) with a lowered total compliance of 30 ml/cmH_2O is divided in the same way, the most ventral part would have the highest compliance and the most dependent part the lowest compliance because of the superimposed pressure from the edematous tissue. The compliance of these five parts would, when added, result in a total compliance of 30 ml/cmH_2O and could, if the superimposed pressure is increasing linearly, be 10, 8, 6, 4 and 2 ml/cmH_2O from top to bottom of the lung. If the three most dependent compartments of the lung are collapsed (Fig. 3), the total compliance would only be $10+8 = 18$ ml/cmH_2O.

Overdistension Versus Gas Compression

In ALI/ARDS, increased resistance is not a major factor, so instead of gas moving along the path of least resistance, we see the gas moving along the path of highest

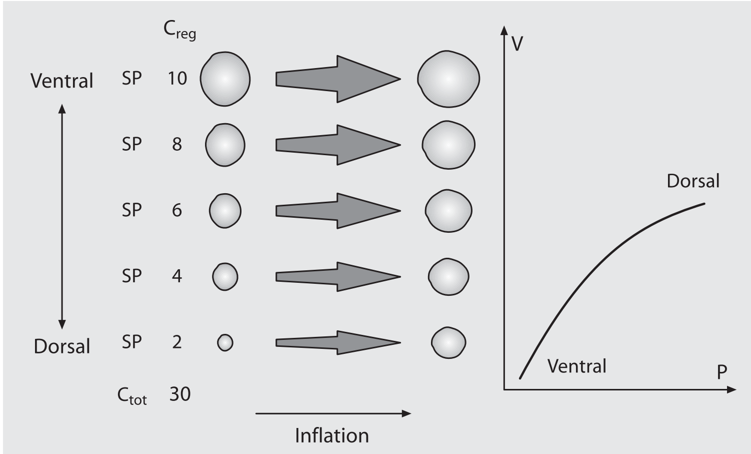

Fig. 2. Regional compliance (Creg), superimposed pressure (SP), and pressure/volume (P/V) curve in a lung with acute respiratory failure without collapsed alveoli. SP increases along the vertical axis. Functional residual capacity (FRC) is decreased and so is total lung capacity. The P/V curve shows no lower inflection point (LIP), but compliance is decreased and an upper inflection zone present, indicating that ventral lung regions are fully stretched (regional compliance ~zero) and recruitment of low compliant, dorsal alveoli at end of inspiration still on-going.

compliance. Following the path of highest compliance in an ALI lung without collapse, as in Figure 2, when inflation starts, the initial gas will naturally flow towards the non-dependent lung with highest compliance. Continuously during the inflation, when pressure increases, the alveoli of the most non-dependent lung will be expanded until not yielding any more (regional compliance = zero). Already before that, as pressure rises, gas will flow to more dorsal parts of the lung where compliance is low but, at this time point, higher than in the most ventral parts of the lung. The P/V curve of this lung will show a continuously decreasing compliance as inflation proceeds. When the pressure is high enough to inflate the most dorsal parts of the lung, the alveoli of the most ventral parts are already stretched to their structural limits and will not expand any further, i.e., compliance is decreasing towards zero. This will result in the final part of the P/V curve deflecting as a sign of low compliance in the dependent part of the lung rather than a sign of overdistension of the ventral part of the lung. The term overdistension is thus misleading as the deflection of the P/V curve indicates that pressure rises more than volume, i.e., gas is compressed.

Let us consider the behavior of another example of a five-compartment lung, where the three most dependent compartments are collapsed during the start of an inflation (Fig. 3). In this case the initial compliance will be 18 ml/cmH_2O and when the airway pressure is high enough to overcome the superimposed pressure and the threshold opening pressure of the mid compartment alveoli (the most non-dependent compartment of the three collapsed compartments), compliance will increase by 8 ml/cmH_2O, which is the compliance of that very compartment. In contrast to the situation where all compartments are open already from the start of inspiration, this sudden increase in compliance will result in a LIP of the P/V curve. As the airway pressure increases enough to open or recruit the two most dependent compartments, compliance will further increase by 6 and 4 ml/cmH_2O. When inflation pro-

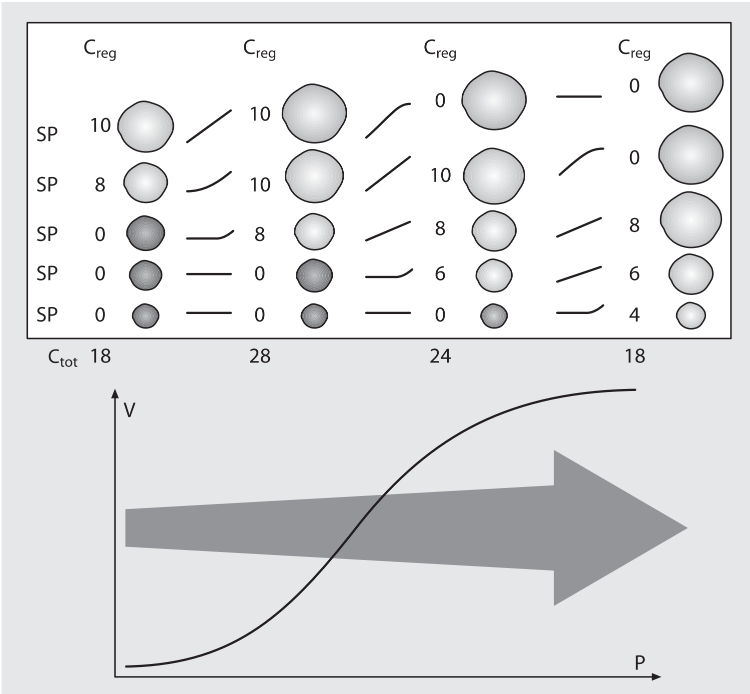

Fig. 3. Regional compliance (Creg), superimposed pressure (SP), and regional and global pressure/volume (P/V) curves in a lung with ALI/ARDS with collapsed alveoli. SP increases along the vertical axis. Functional residual capacity (FRC) is decreased and so is total lung capacity. The P/V curve shows a lower inflection point (LIP) as ventral, open parts represent a small lung volume and thus have low compliance, which increases when more dorsal parts of the lung are recruited. An upper inflection point (UIP) is present, indicating recruitment of low compliant, dorsal alveoli at end-inspiration when ventral lung regions are already stretched to their structural limits (compliance ~zero).

ceeds, the P/V curve will show a continuous decrease in compliance, as compliance in the most ventral parts of the lung decreases towards zero (as in the previous example, where all five compartments were open from the start of inflation). Compliance of the last part of the P/V curve will reflect the compliance of the dependent parts of the lung.

Volume Dependent Compliance

The changing of compliance along the P/V curve, i.e., volume-dependent compliance, reflects that different parts of the lung have different properties. Normally the regional differences are arranged along a vertical axis, so that the highest compliance of the P/V curve represents the most ventral parts of the lung and the lowest compliance the most dependent, dorsal part of the lung (Figs. 4, 5) [9]. However, in some cases the regional differences in mechanical properties of the lung occur more randomly. In any case, whether regional differences in compliance are arranged vertically or randomly, the volume-dependent compliance of the P/V curve is a measurement of these differences.

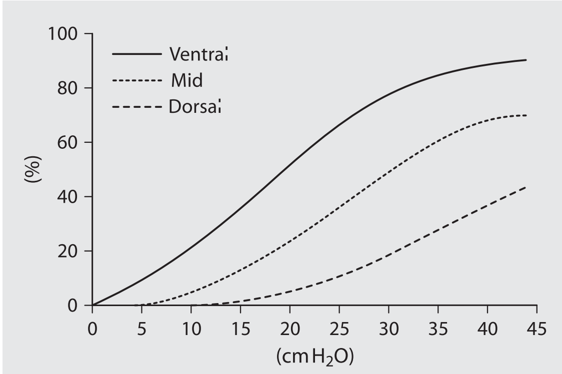

Fig. 4. Electric impedance tomography tracings from left lung of a patient with pneumonia. Relative regional tidal volume on the Y-axis and airway pressure on the X-axis. The pressure/volume (P/V) curves are obtained during a low flow inflation, which gives time for partial equilibration of visco-elastic forces. Note that the lower inflection point (LIP) is positioned at a much higher pressure in the dorsal parts of the lung. No gas enters the mid region until a pressure of ~6 cmH_2O is reached and aeration/ventilation of the most dependent region requires a pressure of about 15 cmH_2O. When compliance of the ventral lung regions are close to zero (P/V curve parallel to x-axis) compliance in the most dorsal lung regions still increases. Modified from [9] with permission

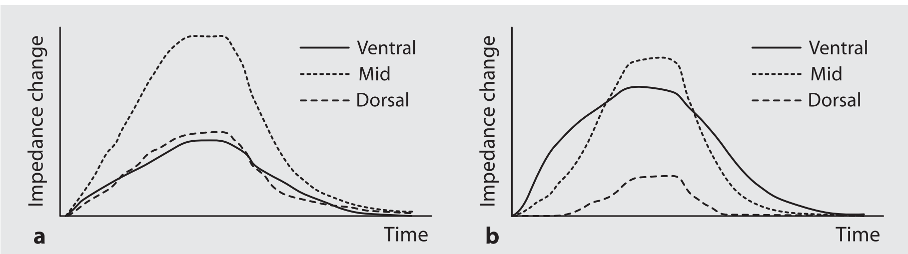

Fig. 5. Impedance changes (corresponding to lung volume changes) in the ventral, mid and dorsal region of the lung, in a pig during one tidal breath, before (**a**) and after saline lavage (**b**). In the healthy lung (**a**), gas enters all three regions from the start of inspiration. Compliance is equal in the ventral and dorsal regions, and higher in the mid region. Saline lavage (**b**) changes regional compliance and, thereby, the relative tidal volume distribution. At the start of the breath, gas will enter the ventral region with the highest compliance, now representing a proportionally larger part of the open lung. The mid region initially fills slowly due to lower compliance and the start of the inflation of the dorsal region is markedly delayed.

So far, all references to P/V curves are static P/V curves that are rarely used in clinical practice. The most common lung mechanics monitoring modality is the pressure volume loop based on pressure and flow measured in the ventilator or at the Y-piece. These dynamic loops are to a high degree influenced by the endotracheal tube resistance, which distorts the loop, resulting in a right shift of the inspiratory limb and a left shift of the expiratory limb of the loop. A loop that represents the lung mechanics more closely can be obtained by plotting the tracheal pressure versus volume instead. The tracheal pressure can either be calculated from the y-piece airway pressure and an algorithm for the endotracheal tube resistance [10] or measured directly by insertion of a narrow pressure line through the tube [11]. From the tracheal pressure loop an alveolar P/V curve can be obtained by multiple linear regression analysis of the loop, which is divided into six slices, where compliance is assumed to be constant within each slice, for volume dependent compliance calculations [12]. We have used another approach for obtaining an alveolar P/V curve from direct tracheal pressure measurements: The Dynostatic algorithm. This algorithm is based on the assumption that inspiratory and expiratory resistance of the airway is reasonably similar at the same lung volume during inspiration and expiration [13, 14].

Fast and Slow Lung Mechanics

The most prominent feature of the dynamic alveolar P/V curve, which represents the mechanic properties of the lung during on-going therapeutic ventilation, is that compliance is lower than compliance of the static P/V curve of the same patient. Also, if any LIP is present in the dynamic P/V curve it is usually not very prominent and the UIP is not an inflection point but rather a zone of decreasing compliance.

The reason for this difference in behavior of the lung during static and dynamic conditions can probably be explained by the time factor playing a more important role than expected. As seen in Figure 6, during a low flow inflation in an ALI patient a prominent LIP at 8 cmH_2O is seen followed by a high and constant compliance throughout the inflation up to 1100 ml. In contrast, during tidal breathing in the same patient where inspiration starts from a pressure level of 4 cmH_2O no LIP can be detected and there is a tendency for an upper inflection zone in the P/V curve in spite of the volume being only half of that during the low flow inflation [15]. This is explained by the fact that during tidal breathing there is not sufficient time for equilibration of visco-elastic forces of the lung.

There are several studies indicating that low tidal volume ventilation causes less damage to the alveoli than a high tidal volume [16, 17]. The level of positive end-expiratory pressure (PEEP) seems to have less impact on ventilator-induced lung injury (VILI) as long as it is not set at very low levels or at 0 cmH_2O. However, the UIP of the static or the dynamic P/V curve does not represent overdistension, but rather recruitment of the most dorsal lung compartments with the lowest compli-

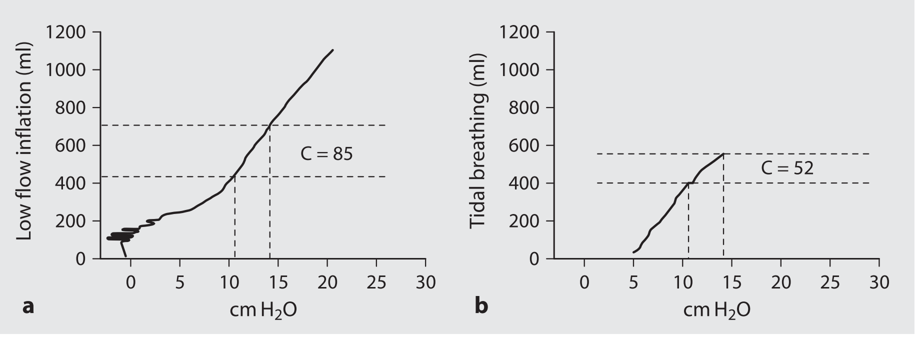

Fig. 6. Total respiratory system alveolar pressure/volume (P/V) curves obtained by the Dynostatic algorithm, in a patient with acute lung injury (ALI). During a low flow inflation (left panel) a prominent lower inflection point (LIP) is seen at ~8 cmH_2O followed by a high constant compliance without an apparent upper inflection point (UIP) even though the total volume inflated reaches 1100 ml. During tidal breathing (right panel) with inspiration starting from a pressure level of 4 cmH_2O, no LIP is seen but there is a tendency to an upper inflection zone in spite of the inflated volume being only half of the low flow inflation volume. The calculated compliance of the tidal breath at the end of inspiration, between 11 and 14 cmH_2O is 52 ml/cmH_2O but at the same pressure range during low flow inflation, it is as high as 85 ml/cm H_2O. Modified from [15] with permission

ance, during the last part of the inspiration. These alveoli are the same alveoli that collapse early at the beginning of the expiration. During static measurements this occurs at a higher lung volume than during dynamic conditions. This indicates that in patients it is important to monitor the lung mechanics during prevailing conditions to be able to set the ventilator optimally.

Conclusion

The compliance below the LIP, when present, is usually very low indicating that only a small lung volume is open when inspiration starts. The LIP of a dynamic P/V curve is usually not very prominent when compared to the LIP of a static P/V curve. There is probably no LIP without partial lung collapse. The UIP is not a sign of overdistension but rather a sign of low compliant, dorsal lung parts being recruited at the end of the inspiration, when the most compliant, ventral parts of the lung do not expand any further.

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