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Interpretation and use of intraoperative protective ventilation parameters: a scoping review

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Abstract

Thirty years ago, the traditional approach to mechanical ventilation consisted of the normalization of $PaCO_2$ and pH at the expense of using a tidal volume (V_T) of 10–15 mL kg^{-1}. But then, the use of 6–8 mL kg^{-1} became a dogma for ventilating patients either with acute respiratory distress syndrome (ARDS) or without lung disease in the operating theatre. It is currently recognized that even low tidal volumes may be excessive for some patients and insufficient for others, depending on its distribution in the aerated lung parenchyma. To carry out intraoperative protective mechanical ventilation, medical literature has focused on positive end expiratory pressure (PEEP), plateau pressure ($P_{aw\ plateau}$), and airway driving pressure (ΔP_{aw}). However, considering its limitations, other parameters have emerged that represent a better reflection of isolated lung stress, such as transpulmonary pressure (P_L) and transpulmonary driving pressure (ΔP_L). These parameters are less generalized in clinical practice due to the requirement of an oesophageal balloon for their measurement and therefore their cumbersome application in the operating theatre. However, its study helps in the interpretation of the rest of the ventilator pressures to optimize intraoperative mechanical ventilation. This article defines and develops protective ventilation parameters, breaks down their determinants, mentions their limitations, and offers recommendations for their use intraoperatively.

Key words: tidal volume, PEEP, protective ventilation, plateau pressure, driving pressure, transpulmonary pressure, transpulmonary driving pressure.

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Thirty years ago, the traditional approach to mechanical ventilation consisted of achieving normalization of $PaCO_2$ and pH, for which patients were ventilated with tidal volumes (V_T) of up to 10–15 mL kg^{-1} of predicted body weight (PBW) [1].

The large multicentre ARDSnet trial demonstrated a decrease in mortality close to 25% in more than 800 patients with acute respiratory distress syndrome (ARDS) when 6 mL kg^{-1} of V_T was used instead of 12 mL kg^{-1} PBW, confirming that V_T limitation is a fundamental strategy to improve survival in patients with ARDS [2]. Since that trial, use of 6 mL kg^{-1} PBW (based on height and gender) has become a dogma for ventilating patients, either with ARDS or in the operating theatre. However, it is increasingly established and recognized that 6 mL kg^{-1} of V_T may be excessive for some patients and insufficient for others [3].

The paradigm of protective ventilation aims to individualize ventilatory support. Traditionally, the mainstay of this approach is given by low V_T and avoiding high airway pressures [4]. Indeed, although alveolar pressure is easy to estimate clinically through plateau pressure ($P_{aw\ plateau}$), the latter represents the distending pressure of the entire respiratory system. Ventilator settings based only on airway pressure measurements are inappropriate for most critically ill patients [4]. Currently, protective ventilation can be better understood in terms of limiting global and regional mechanical stress (pressure applied to the lungs) and strain (deformation from its resting position). Lung injury can occur due to overdistention (volutrauma/barotrauma), and recruitment and repetitive tidal collapse (atelectrauma), both mechanisms resulting in heterogeneous insufflation of areas of occupied or collapsed alveoli [5]. To carry out intraoperative protective mechanical ventilation, medical literature has focused on positive end expiratory pressure (PEEP), $P_{aw\ plateau}$, and airway driving pressure (ΔP_{aw}). However, considering its limitations, other parameters have emerged that represent a better reflection of isolated lung stress, such as transpulmonary pressure (P_L) and transpulmonary driving pressure (ΔP_L). These parameters are less generalized in clinical practice due to the requirement

of an oesophageal balloon for their measurement and therefore their cumbersome application in the operating theatre. However, their study and comprehension help us to better interpret the traditional parameter alterations to be able to take subsequent behaviours.

This review aims to develop the traditional concepts of protective ventilation and clarify definitions of the most representative parameters and their determinants. In addition, limitations on their use are mentioned and practical points are summarized to transfer their interpretation to the monitoring and ventilation configuration of the patient under general anaesthesia.

PROTECTIVE VENTILATION PARAMETERS

Tidal volume

Because high V_T ventilation can prevent or minimize pulmonary atelectasis, in the past it was common practice to use a V_T of 800–1000 mL, which translated into a V_T of up to 10–15 mL kg^{-1} [6]. Volumes that have been used in patients without ARDS under mechanical ventilation have been progressively decreasing [7]. In a 39-year period from 1975 to 2014, V_T decreased significantly in ICUs (annual decrease of 0.16 mL kg^{-1}) and in the operating theatre (annual decrease of 0.09 mL kg^{-1}) [8].

However, there is usually a misconception that the benefits of ventilating critically ill patients with low V_T of 6–8 mL kg^{-1} are irrelevant in surgical patients, due to the relatively healthy lungs and shorter duration of ventilation in the latter [6]. Intraoperative ventilation at low V_T has been shown not only to decrease airway pressures and generation of proinflammatory cytokines, but also to improve patient-centred outcomes, such as need for reintubation, length of hospital and ICU stay, and postoperative pulmonary complications (PPCs) [9–12]. PPCs are increased by V_T in a "dose-dependent" manner and generate higher mortality in patients undergoing mechanical ventilation for general anaesthesia [13].

Volume selected in a protective way (6–8 mL kg^{-1}) can be distributed differently according to the aerated lung volume that a certain patient has to receive. This means that even the same set V_T can produce different lung stress (distending pressure applied to lung parenchyma) between patients with similar PBW [14]. The size of the aerated lung can vary considerably in patients with consolidation, fluid, pulmonary exudate, or atelectasis [15]. It is precisely these patients that are at risk of overdistention injury even when ventilating with low V_T, because they have reduced aerated lung volumes [15]. In patients with low lung compliance, such as ARDS patients, or in the operating theatre those with pulmonary atelectasis, even V_T below 6 mL kg^{-1} of PBW can result in high strain (lung deformation from its resting position) [16].

In this sense, 3 randomized clinical trials have demonstrated a decrease in postoperative pulmonary complications in protectively ventilated surgical patients with V_T of 6–8 mL kg^{-1} together with positive end-expiratory pressure (PEEP) levels between 6 and 12 cm H_2O, a ventilatory strategy that was related to lower airway distending pressure (airway driving pressure or ΔP_{aw}) and greater lung compliance [12, 17, 18]. On the other hand, the use of strategies with low V_T is associated with hypercapnia and acidosis, probably due to less efficient alveolar ventilation [7]. These patients could benefit from strategies such as reducing instrumental dead space, increasing respiratory rate, lung recruitment manoeuvres associated with selection of an optimal PEEP, and prone position [15].

Therefore, titration of V_T according to PBW could be a starting point, but it does not ensure the absence of damage. A possible solution is titrating V_T according to ΔP_{aw} [5, 14, 16] or to transpulmonary pressure (P_L) [15]. These parameters could be better surrogates for limiting ventilator-induced lung injury (VILI) due to overdistention [15].

Limitations

If we use V_T as a target, there are situations in which ventilatory strategies based on low V_T do not confer lung protection [19]. For example, when ventilating obese patients during laparoscopic surgeries in the Trendelenburg position, a V_T of 6–8 mL kg^{-1} PBW with low PEEP can be harmful. In this scenario, atelectasis with collapse and cyclic reopening of alveolar units in one zone of the lung coexist with pulmonary overdistention in another zone and may cause injury [20]. The open lung approach consists of opening up lung parenchyma where areas of atelectasis and overdistention coexist, using lung recruitment manoeuvres and optimal PEEP selection, achieving an increase in aerated lung volume with greater availability of alveolar units for the same V_T [21]. As a result, more homogeneous ventilation is obtained, with less overdistention and collapse, and less lung damage [22, 23]. On the other hand, in patients without pulmonary pathology subjected to general anaesthesia and ventilated with an open lung approach, pulmonary recruitment and titrated PEEP, a V_T of 6 mL kg^{-1} or more may not be harmful to the lung if ΔP_{aw} is less than 13–15 cm H_2O [15, 24].

Application in clinical practice

Pulmonary ventilation with low V_T constitutes a fundamental parameter of protective ventilation; therefore, a set V_T of 6–8 mL kg^{-1} PBW serves as an initial setting parameter [20]. However, it has been pos-

tulated that an even more beneficial strategy would be to titrate it individually. V_T could be chosen integrating other parameters such as optimal peep levels with or without recruitment maneuvers and the use of driving pressure. The target would be to select a V_T value based on reducing driving pressure and increasing respiratory system compliance [15, 19, 25].

PEEP

PEEP is the positive pressure at the end of expiration. Low PEEP levels (5 cm H_2O) are routinely used in patients undergoing mechanical ventilation. This practice aims to keep the lung open at the end of expiration, prevent small airway and alveoli closure, minimize the damaging effects of cyclic opening and collapsing of the alveoli, and increase the lymphatic flow, facilitating drainage of pulmonary oedema [16, 26]. Furthermore, PEEP would facilitate lung homogenization by recruiting previously non-ventilated alveolar units, thus avoiding excessive tension in the margins between aerated and non-aerated regions of the lung parenchyma (stress raisers) [1, 4, 27]. Both mean airway pressure (MAP) and the plateau pressure ($P_{aw\ plateau}$) will increase with increasing PEEP, but this increase may be accentuated to a greater or lesser extent depending on the compliance of the respiratory system (if the latter is low, the increase in pressures will be higher, and vice versa). In contrast, airway driving pressure is not affected by changes in PEEP levels unless they result in changes in lung compliance. Increases in PEEP will only be protective when they result in an increase in lung compliance, which will be reflected in a decrease in ΔP_{aw} [7, 28]. PEEP, therefore, should be selected individually according to the patient's requirements [29].

$$PEEP = PEEP_{volume} \times E_{rs},$$

where *PEEP* is the positive pressure at the end of expiration, $PEEP_{volume}$ is the volume generated by PEEP, which is calculated as the difference between EELV (end expiratory lung volume) and FRC (functional residual capacity), and E_{rs} is the respiratory system elastance (Figure 1 and Table 1).

Limitations

PEEP is only beneficial when it is associated with an increase in functional lung volume, i.e. aerated lung volume (in a patient with high recruitability), reducing lung inhomogeneities. An inappropriately high level could be associated with potential deleterious effects such as pulmonary overdistention and impaired cardiac output [16]. Conversely, an inappropriately low PEEP level could be associated with atelectasis, leading to reduced lung compliance (low functional lung volume) with higher ΔP_{aw}, and to haemodynamic alterations due to the effects of hypoxic pulmonary vasoconstriction on the right heart [27, 30].

Application in clinical practice

If using PEEP as an objective, there will be situations in which it could be beneficial or harmful depending on the value we have chosen and the mechanical characteristics of the thoraco-pulmonary system (lung-chest wall). Thus, a high PEEP level could be beneficial in an obese patient in laparoscopic surgery after a recruitment manoeuvre, while the same PEEP level in a patient with normal BMI (body mass index) and healthy lungs would cause overdistention [19].

Therefore, probably an adequate way to select PEEP levels would be through a recruitment mano-

<table>
<tr><td rowspan="5">Peak pressure
$P_{aw\ peak}$</td><td colspan="4">Delta peak-plateau
$P_{aw\ peak} - P_{aw\ plateau} = Flow \times Resistance$</td></tr>
<tr><td rowspan="4">Plateau pressure
$P_{aw\ plateau} = (V_T + PEEP_{volume}) \times E_{rs}$</td><td rowspan="2">PEEP
$P_{aw\ PEEP} = PEEP_{volume} \times E_{rs}$</td><td>Esophageal pressure at end expiration
$P_{es\ PEEP} = PEEP_{volume} \times E_{cw}$</td><td></td></tr>
<tr><td>Transpulmonary pressure at end expiration
$P_{L\ PEEP} = PEEP_{volume} \times E_L$</td><td rowspan="3">Transpulmonary pressure at end inspiration
$P_{L\ plateau} = (V_T + PEEP_{volume}) \times E_L$</td></tr>
<tr><td rowspan="2">Airway driving pressure
$\Delta P_{aw} = V_T \times E_{rs}$</td><td>Transpulmonary driving pressure
$\Delta P_L = V_T \times E_L$</td></tr>
<tr><td>Esophageal driving pressure
$\Delta P_{es} = V_T \times E_{cw}$</td></tr>
</table>

FIGURE 1. Determinants of protective ventilation parameters. Where $P_{aw\ peak}$ is airway peak pressure, delta peak plateau is the difference between the peak and the plateau pressure, $P_{aw\ plateau}$ is airway plateau pressure, V_T is tidal volume, $PEEP_{volume}$ is volume generated by PEEP, E_{rs} is respiratory system elastance, E_L is lung elastance, E_{cw} is chest wall elastance, $P_{aw\ PEEP}$ is positive end expiratory pressure or PEEP, ΔP_{aw} is airway driving pressure or respiratory system driving pressure (ΔPrs), $P_{L\ PEEP}$ is transpulmonary pressure at end of expiration, ΔP_L is transpulmonary driving pressure or lung driving pressure, ΔP_{es} is oesophageal driving pressure or driving pressure across the chest wall (ΔP_{cw}) or the change in pleural pressure between the end of inspiration and the end of expiration (ΔP_{pl}), $P_{L\ plateau}$ is transpulmonary pressure at the end of inspiration, $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration, and $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration

TABLE 1. Protective ventilation parameters

Variable	Definition	Formula and determinants	Importance/Benefits	Target/Limits	Limitations /Clarifications
PEEP ($P_{aw\ PEEP}$)	Positive end expiratory pressure	Relationship between PEEP volume ($PEEP_{volume} = EELV - FRC$) and respiratory system elastance: $P_{aw\ PEEP} = PEEP_{volume} \times E_{rs}$	Keeps the lung open	> 5 cm H_2O	– Difficult to find optimal PEEP – Individualized according to requirements. – Insufficient PEEP: atelectrauma, stress raiser – Excessive PEEP: hemodynamic alterations and lung overdistension
Peak pressure ($P_{aw\ peak}$)	Paw measured under inspiratory flow conditions	2 components: – Delta peak-plateau = generated by inspiratory flow and airway resistance – $P_{aw\ plateau}$	Easy to calculate in mechanical ventilation	< 30 cm H_2O	– Influenced by elastic and resistive properties of the respiratory system (lung and chest wall) – Peak pressure may increase due to: ↑respiratory system resistance and/or ↑inspiratory flow (V_T/Inspiratory time) and/or ↑Plateau pressure – Its value > 5 above the plateau pressure points towards ↑resistance and/or the inspiratory flow
Plateau pressure ($P_{aw\ plateau}$)	Paw measured during inspiratory pause (no flow conditions) Respiratory system distending pressure due to tidal volume delivery (involves PEEP in its measurement)	$P_{aw\ plateau} = (V_T + PEEP_{volume}) \times E_{rs}$ (lung + chest wall)	Alveolar pressure surrogate. Represents the elastic recoil pressure of the respiratory system (lung + chest wall) Involves the stress caused by PEEP	< 25–30 cm H_2O	– Increased if high PEEP – It does not reflect the load to which the lung is exposed in isolation (high chest wall elastance can generate high plateau pressure without risk of lung injury)
Airway driving pressure (ΔP_{aw})	Pressure above PEEP that distends the respiratory system due to tidal volume delivery	$P_{aw\ plateau} - P_{aw\ PEEP} = V_T \times E_{rs}$ (lung + chest wall)	Represents the cyclic strain to which the respiratory system is exposed in each ventilation Useful in PEEP and/or V_T selection Removes the stress caused by PEEP	< 13–15 cm H_2O	– It does not reflect the load to which the lung is exposed in isolation (high chest wall elastance can generate high ΔP_{aw} pressure without risk of lung injury) – PEEP effects are not considered (in the context of very high PEEP, there may be normal ΔP_{aw} and an overdistended lung at risk of damage)
Transpulmonary pressure at end inspiration ($P_{L\ plateau}$)	Lung distending pressure in isolation due to tidal volume delivery (involves PEEP in its measurement)	$P_{aw\ plateau} - P_{es\ plateau} = (V_T + PEEP_{volume}) \times E_L$	Represents the elastic recoil pressure of the lung Reflects the total stress to which the lung is exposed in each ventilation (cyclic stress due to ΔP_L + static stress caused by PEEP) Removes the chest wall distending pressure	< 15–20 cm H_2O	– It considers the total pressure load imposed on the lung. It does not consider interface zones (stress raisers) – It does not consider other determinants variables of VILI such as respiratory rate and inspiratory flow – Limitations associated to oesophageal catheter
Transpulmonary driving pressure (ΔP_L)	Pressure above PEEP that distends the lung in isolation due to tidal volume delivery	$P_{L\ plateau} - P_{L\ PEEP} = V_T \times E_L$	Represents the cyclic stress to which the lung is exposed in each ventilation Removes the stress caused by PEEP Removes the chest wall distending pressure	< 10–12 cm H_2O	– It reflects the change in lung stress due to tidal volume delivery. – PEEP effects are not considered – It does not consider other determinants variables of VILI such as respiratory rate and inspiratory flow – Limitations associated to oesophageal catheter

$P_{aw\ PEEP}$ – airway PEEP pressure, $PEEP_{volume}$ – volume generated by PEEP, EELV – end expiratory lung volume, FRC – functional residual capacity, E_{rs} – respiratory system elastance, $P_{aw\ peak}$ – airway peak pressure, $P_{aw\ plateau}$ – airway plateau pressure, V_T – tidal volume, E_{rs} – respiratory system elastance, ΔP_{aw} – airway driving pressure or respiratory system driving pressure (ΔP_{rs}), $P_{L\ plateau}$ – transpulmonary pressure at the end of inspiration, E_L – lung elastance, ΔP_L – transpulmonary driving pressure or lung driving pressure

euvre, in patients with risk factors for atelectasis, and a PEEP titration according to the respiratory system compliance or to the airway driving pressure (ΔP_{aw}), parameters that better relate pressure to volume delivered [21,23,30]. However, to prevent overdistention, it is possible to differentiate responders to recruitment manoeuvres from non-responders. In responders, airway driving pressure is reduced due to an increase in functional residual capacity (FRC). In non-responders, FRC does not increase and therefore PEEP should not be increased any further [21].

In practice, it is recommended that PEEP = 0 cm H_2O (ZEEP) should be avoided, a lower PEEP limit greater than 5 cm H_2O be used, and then it should be individualized [20]. In this sense, one way to titrate PEEP is to seek an improvement in respiratory system compliance by a decrease in airway driving pressure [2, 7].

Airway peak pressure

Peak airway pressure ($P_{aw\ peak}$) is the maximum pressure measured in the airway at the end of inspiration. Unlike $P_{aw\ plateau}$, $P_{aw\ peak}$ is influenced by both the elastic and resistive properties of the respiratory system. At the bedside, the difference between peak and plateau pressures can be easily individualized during an inspiratory pause during volume-controlled ventilation. Immediately after the inspiratory pause, a rapid pressure drop is observed, which represents the pressure dissipated to overcome airway resistance. To calculate the airway resistance, this pressure difference is divided by the inspiratory flow. In normal subjects, airway resistance values do not exceed 15 cm $H_2O\ L^{-1}\ s^{-1}$ under controlled mechanical ventilation [16].

During mechanical ventilation, $P_{aw\ peak}$ depends on $P_{aw\ plateau}$, and on the pressure difference between these 2 pressures ($P_{aw\ peak} - P_{aw\ plateau}$), which is determined by both the inspiratory flow and airway resistance.

$$P_{aw\ peak} = (P_{aw\ peak} - P_{aw\ plateau}) + P_{aw\ plateau}$$

$$P_{aw\ peak} = \Delta V \times R_{aw} + (V_T + PEEP_{volume}) \times E_{rs},$$

where $P_{aw\ peak}$ is airway peak pressure, $P_{aw\ plateau}$ is airway plateau pressure, ΔV represents inspiratory flow, R_{aw} is airway resistance, $PEEP_{volume}$ is volume generated by PEEP, and E_{rs} is respiratory system elastance (Figure 1 and Table 1).

In patients without increases in airway resistance and/or obstructions in the ventilatory circuit, the maximum inspiratory pressure (MIP) or peak inspiratory pressure (PIP) is approximately equal to the plateau pressure [7]. During pressure-controlled ventilation, the set ventilator pressure (MIP) is comparable to the $P_{aw\ plateau}$ during volume-controlled ventilation if inspiratory flow seen on the flow-time curve reaches zero, a situation in which MIP will constitute a surrogate of alveolar pressure.

Limitations

It is influenced by the elastic and resistive properties of the respiratory system as a whole. Therefore, it is difficult to use it as a parameter that represents the load to which the lung is subjected in isolation.

Application in clinical practice

Because plateau pressure constitutes a determinant of peak pressure, when $P_{aw\ peak}$ is elevated, a high plateau pressure should be ruled out so as to consider the causes of a high delta $P_{aw\ peak} - P_{aw\ plateau}$.

Once inspiratory flow (ΔV) is established, the delta pressure generated depends on an airway resistance value.

For example, during volume-controlled ventilation, once V_T and inspiratory time were established, $P_{aw\ peak} - P_{aw\ plateau}$ generated will depend on the airway resistance value. That is to say, in the face of an increase in resistance such as endotracheal tube kinking, secretions, bronchospasm, etc., the pressure difference between the $P_{aw\ peak}$ and $P_{aw\ plateau}$ will increase by increasing the $P_{aw\ peak}$ [31].

$$\uparrow \Delta P = \uparrow P_{aw\ peak} - P_{aw\ plateau} = \Delta V \times \uparrow R_{aw}$$

In the same way, at a constant resistance value, changes in inspiratory flow (ΔV) modify pressure differences.

For example, during volume-controlled ventilation, once V_T is established, the decrease in inspiratory time (by decreasing the I : E ratio from 1 : 2 to 1 : 4, increasing the respiratory rate or increasing the inspiratory pause time in anaesthesia ventilators) will generate an increase in inspiratory flow (ΔV) and this will determine an increase in $P_{aw\ peak}$, thus increasing the pressure difference between $P_{aw\ peak}$ and $P_{aw\ plateau}$ [31].

$$\uparrow \Delta P = \uparrow P_{aw\ peak} - P_{aw\ plateau} = \uparrow \Delta V \times R_{aw}$$

It is suggested that a peak pressure < 30 cm H_2O be used in mechanically ventilated patients without ARDS both during volume-controlled ventilation and pressure-controlled ventilation [7].

Airway plateau pressure

Plateau pressure, or airway plateau pressure ($P_{aw\ plateau}$), is the pressure measured in static conditions during an inspiratory pause in volume-controlled ventilation, and that results from the sum of pressures associated with tidal volume and volume generated by PEEP, if it is present. Because it is estimated during zero flow conditions, it avoids taking into account the pressures required to exceed airway resistance [3]. In other words, the $P_{aw\ plateau}$ is not affected by changes in inspiratory flow or airway

resistance [16] and only reflects the elastic properties of the respiratory system [32].

The $P_{aw\ plateau}$ is thus determined by changes in V_T, E_{rs}, and PEEP levels [31].

The importance of plateau pressure lies in the fact that it is considered a surrogate, a reflection of alveolar pressure (P_{alv}), which is the real pressure that distends the entire respiratory system (lung plus chest wall) [33]. In this sense, it also involves the pressure required to surpass the chest wall elastance, and therefore this "alveolar pressure" does not reliably reflect the pressure load to which only the lung is exposed. Pulmonary distending pressure in isolation is evaluated with transpulmonary pressure, which represents the elastic recoil pressure of the lungs [29].

The $P_{aw\ plateau}$ thus represents the best clinical way to assess airway pressure under static conditions, and therefore it can be used to estimate transpulmonary pressure [3].

$$P_{aw\ plateau} = PEEP + \Delta P_{aw}$$

$$(V_T + PEEP_{volume}) \times E_{rs} = (PEEP_{volume} \times E_{rs}) + (V_T \times E_{rs})$$

Where $P_{aw\ plateau}$ is airway plateau pressure, *PEEP* is positive pressure measured at the end of expiration, ΔP_{aw} is the airway driving pressure, and E_{rs} is the respiratory system elastance (Figure 1 and Table 1).

The recommendation of the ARDS network protocol to limit the $P_{aw\ plateau}$ below 30 cm H_2O to improve survival derives from the evidence obtained during spontaneous ventilation, in which total lung capacity is achieved with a transpulmonary pressure of 25 cm H_2O. If a patient has normal chest wall elastance, it corresponds to a $P_{aw\ plateau}$ of 30 cm H_2O, a pressure level below which was shown to generate minimal inflation and therefore the absence of VILI in an animal study [34] (Figure 1).

Limitations

During a patient's mechanical ventilation, a high $P_{aw\ plateau}$ may not be injurious per se, when instead of being applied to inflate the alveoli, it is mostly used to inflate a high elastance chest wall [29].

In 1988 Dreyfus *et al*. [35] demonstrated that injurious pulmonary oedema occurred in healthy paralyzed animals during pressure-controlled ventilation with high V_T and high airway pressures, but it did not occur in those ventilated with similar airway pressures and low V_T due to straps applied around their abdomen and chest. These straps were a simple way to increase chest wall elastance, and therefore, for the same airway pressure or plateau pressure, pulmonary distending pressure or transpulmonary pressure was lower and did not cause injury [29]. These experiments demonstrated that the volume that caused lung stretching, and not the airway pressure, was the most important factor in determining injury, a finding that led them to employ the term 'volutrauma'. We currently interpret these findings as an indirect demonstration of the importance of transpulmonary pressure in determining 'lung trauma' and injury, which in fact does not occur if this pressure is kept within certain limits, no matter how high the plateau pressure is [29].

In this way, ventilating patients with high chest wall elastance and limiting the plateau pressure to 30 cm H_2O, far from inducing damage by baro- or volutrauma, this can lead to atelectasis with shunt and hypoxaemia, in addition to lung damage due to increased stress raisers (e.g. in obese patients, pregnant women, patients with pleural effusion, neuromuscular diseases, or capnoperitoneum) [3]. On the one hand, high chest wall elastance is effectively protective for the lungs, but it entails an increase

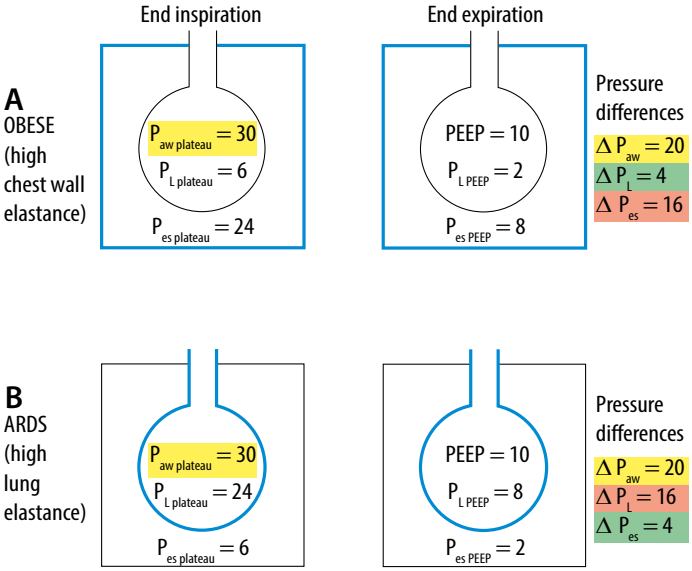

FIGURE 2. Representation of airway and pleural (oesophageal) pressures in 2 patients with different chest wall and lung elastance during end inspiration and end expiration. Two patients with different mechanical properties of the lung and chest wall are presented; both ventilated with the same high plateau pressure ($P_{aw\ plateau}$) and high airway driving pressure (ΔP_{aw}) (represented in yellow). In A, the patient has high chest wall elastance, and therefore presents a low transpulmonary pressure ($P_{L\ plateau}$) and a low transpulmonary driving pressure (ΔP_L) (represented in green), thus with a low risk of lung damage. At the same time, it presents high pleural pressures (e.g. ΔP_{es}) (represented in red), which probably implies some haemodynamic repercussion. Patient B with high pulmonary elastance has high transpulmonary pressure ($P_{L\ plateau}$) and high transpulmonary driving pressure (ΔP_L) with the consequent risk of lung damage (represented in red) but with low pleural pressures therefore (e.g. ΔP_{es}) (represented in green), without haemodynamic repercussions. Actually, the risks of mechanical ventilation in patients ventilated with similarly high airway pressures range from the risk of lung damage if the lung elastance is high and the chest wall elastance is low, and haemodynamic instability in the opposite situation [3, 31]. Where $P_{aw\ plateau}$ is airway plateau pressure, PEEP is positive end expiratory pressure, ΔP_{aw} is airway driving pressure, $P_{L\ PEEP}$ is transpulmonary pressure at end of expiration, ΔP_L is transpulmonary driving pressure o lung driving pressure, ΔP_{es} is oesophageal driving pressure or driving pressure across the chest wall (ΔP_{cw}) or the change in pleural pressure between the end of inspiration and the end of expiration (ΔP_{pl}), PL plateau is transpulmonary pressure at the end of inspiration, $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration, and P_{es} PEEP is oesophageal pressure at the end of expiration. All pressures are expressed in cm H_2O

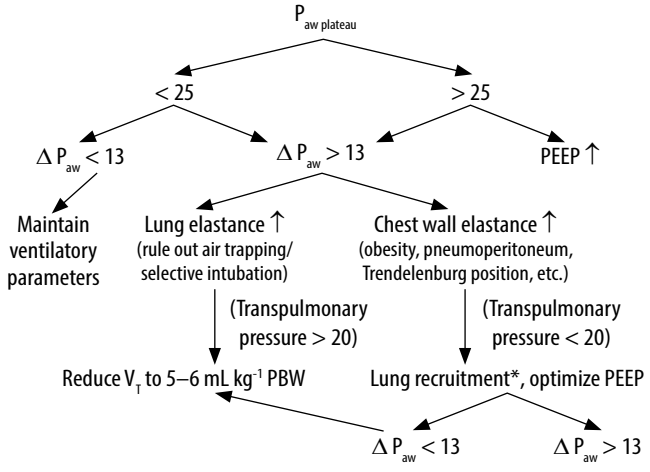

FIGURE 3. Algorithm for programming protective ventilation parameters: V_T = 6–8 mL kg^{-1} PBW, RR targeting an $EtCO_2$ of 35 to 45 mmHg, PEEP ≥ 5 cm H_2O, I : E ratio (the one that allows expiratory flow to reach zero, and the longest inspiratory time e.g. 1 : 1.5), if high peak airway pressure, check high Delta peak plateau and rule out kinked orotracheal tube, secretions, mucus, etc.). Where VCV is volume control ventilation, V_T is tidal volume, RR is respiratory rate, PEEP is positive end expiratory pressure, I : E ratio is the ratio between inspiratory time : expiratory time, $P_{aw\ plateau}$ is airway plateau pressure, and ΔP_{aw} is airway driving pressure.

*The decision to recruit the lung should also be based on other parameters such as the air test, the increased capnographic gap ($PaCO_2$ – End tidal CO_2) and/or decreased PAFI. All pressures are expressed in cm H_2O

in pleural pressure, which will have haemodynamic repercussions through an increase in pressure in the right atrium, which will then decrease venous return and cardiac output [3]. On the other hand, ventilating patients with the same $P_{aw\ plateau}$ of 30 cm H_2O but with a low chest wall elastance, will generate a high transpulmonary pressure, which is the true pulmonary distending pressure and the one that generates lung damage at high values [3] (Figure 2).

Therefore, we consider that using a single $P_{aw\ plateau}$ level to define potential harm could be overly simplistic, and it could lead to the administration of insufficient pressure to some patients and excessive pressure to others [36]. Given that what generates VILI is not the pressure applied to the airway but rather the pressure applied to the lungs (transpulmonary pressure), it follows that a better limit or safe pressure threshold could be a transpulmonary pressure level rather than a certain $P_{aw\ plateau}$ level [36].

For this reason, there are authors who propose monitoring oesophageal pressure in patients with risk factors for chest wall stiffness. In these cases of high chest wall elastance, a safe threshold of 30 cm H_2O for plateau pressure may actually be higher and still be safe [1].

Application in clinical practice

It is suggested that a $P_{aw\ plateau}$ below 25–28 cm H_2O should be used in mechanically ventilated patients without ARDS during both volume-controlled and pressure-controlled ventilation [7].

Its use as the only safety parameter without taking into account other features of patient mechanics could lead to an insufficient ventilation (in patients with high chest wall elastance such as in obesity) or an excessive one (in patients with high lung elastance such as in ARDS). Therefore, it should be used considering other patient factors, such as the ones that increase or decrease chest wall elastance. We can mention 3 scenarios:

- If the $P_{aw\ plateau}$ is less than 25 cm H_2O and airway driving pressure is less than 13 cm H_2O, then ventilatory parameters could be maintained because we would be ventilating within limits that are considered safe.
- If the $P_{aw\ plateau}$ is greater than 25 cm H_2O, considering its determinants, it should be ruled out that this is not generated by high PEEP levels.
- If the $P_{aw\ plateau}$ is greater than 25 cm H_2O and the airway driving pressure is greater than 13 cm H_2O, considering PEEP levels within certain limits, causes of increased respiratory system elastance should be assessed (Figure 3).

Airway driving pressure

The airway driving pressure (ΔP_{aw}) or (ΔP_{rs}) (respiratory system driving pressure) is the pressure required during lung expansion to overcome the elastic forces generated by the lung parenchyma, pleura, and chest wall [28]. Unlike the plateau pressure it represents the pressure above PEEP required to overcome the elastic recoil of the respiratory system as a whole generated by the delivery of tidal volume [27].

Another way of interpreting the ΔP_{aw} is the oscillation between the end of inspiration and the end of expiration of the respiratory system elastic pressure [37]. Thus, assuming that there is no auto-PEEP, ΔP_{aw} estimates the increase in alveolar pressure during inspiration and its decrease during expiration representing the pressure change during tidal volume ventilation [15, 29].

It is important to recognize that ΔP_{aw} involves 2 components, one related to the expansion of the lung and the other related to the expansion of the chest wall [38].

$\Delta P_{aw} = \Delta P_L + \Delta P_{pl}$,

where ΔP_L is the transpulmonary driving pressure and ΔP_{pl} is the change in pleural pressure or driving pressure across the chest wall (ΔPCW) or oesophageal driving pressure (ΔP_{es}) (Figure 1 and Table 1).

This implies that ΔP_{aw} can be elevated by both elastic components or at the expense of one of them. Therefore, increases in chest wall elastance in isolation can affect this parameter without increasing pulmonary stress, globally represented by transpulmonary driving pressure [5].

Chest wall elastance may be increased in conditions such as obesity, abdominal compartment syndrome, kyphoscoliosis, chest wall burns, or increased muscle tone due to dyssynchrony with the ventilator. Conversely, it could be decreased by muscle paralysis [39].

ΔP_{aw} is easily calculated at the bedside as the difference between the plateau pressure and PEEP.

$\Delta P_{aw} = P_{aw\ plateau} - PEEP$

It is equivalent to the relationship between V_T and respiratory system compliance (C_{rs}) [14]. So, assuming C_{rs} reflects the amount of aerated lung volume, ΔP_{aw} is considered a surrogate of dynamic or cyclic lung strain (or stretch). The latter is defined as the ratio between V_T and FRC [32]. Therefore, the higher the FRC, the higher the C_{rs} (due to greater aerated lung volume) and the lower the ΔP_{aw}. In this way ΔP_{aw}, unlike $P_{aw\ plateau}$ and PEEP (which are static estimates of stress in the respiratory system), constitutes a dynamic indicator because it represents the cyclic strain that lung parenchyma (and the chest wall) are exposed to during each ventilatory cycle [2, 15].

$\Delta P_{aw} = V_T/C_{rs}$

$\Delta P_{aw} = V_T \times E_{rs}$,

where V_T is the tidal volume, C_{rs} is the respiratory system compliance, and E_{rs} is the respiratory system elastance. ΔP_{aw} conveys the relationship between the V_T applied above a certain PEEP and the respiratory system compliance.

Using a statistical model known as multilevel mediation analysis, information from 3562 patients with ARDS was analysed from 9 randomized controlled trials, which demonstrated that ΔP_{aw} is the ventilatory parameter that best predicts survival at 60 days in ARDS [37, 40] and not V_T or PEEP [2].

Amato *et al*. [40] suggested that the ventilatory impact of V_T on lung injury could be better predicted if it was normalized to C_{rs} rather than PBW. ΔP_{aw} was shown to be the final mediator on the effects of lowering V_T and $P_{aw\ plateau}$ on mortality in patients with ARDS [29].

A recent meta-analysis involving 17 studies and more than 2250 patients showed that changes in PEEP levels that resulted in an increase in ΔP_{aw} (i.e. without modifying or even decreasing C_{rs}) were associated with greater postoperative pulmonary complications [2, 32].

In patients with low lung compliance (e.g. with atelectasis, consolidation, oedema), even setting low V_T (< 6 mL kg^{-1} PBW) could result in high ΔP_{aw}, i.e. in high strain (V_T/CRF) [16].

For this reason, it is suggested that V_T should be adjusted considering ΔP_{aw} (or V_T/C_{rs}). Because C_{rs} is directly related to the aerated lung volume, ΔP_{aw} reflects the level of V_T related to the aerated lung volume [1]. Using ΔP_{aw} as a safety limit, it could be a better way to adjust V_T to decrease dynamic or cyclic strain during mechanical ventilation [2, 5].

Most surgical patients (without ARDS) will have ΔP_{aw} < 10 cm H_2O, reflecting a normal or close to normal C_{rs}. In contrast, in patients with moderate to severe ARDS or other restrictive diseases (e.g. major pulmonary effusions, interstitial diseases, etc.), it will be more common to find an ΔP_{aw} > 10 cm H_2O, reflecting either a decreased C_{rs} or an inappropriate selection of V_T or PEEP [2].

Even more, V_T could be higher than 6 mL kg^{-1} and ΔP_{aw} could remain below 14 cm H_2O [15]. Limiting ΔP_{aw}, possibly keeping it below 14 cm H_2O, can be achieved either by decreasing V_T or by increasing C_{rs} [37]. If the former remains constant and the latter increases, ΔP_{aw} will decrease proportionally. Furthermore, under steady conditions in C_{rs}, ΔP_{aw} will increase if V_T increases [7].

One way to increase compliance is through lung recruitment with recruitment manoeuvres and a higher PEEP level or through prone positioning [1, 21, 23].

In this context, ΔP_{aw} could also be a valuable tool for setting PEEP. Regardless of the strategy used to titrate PEEP, changes on its levels should be considered in the impact on ΔP_{aw}, in addition to other variables such as gas exchange and haemodynamics [2]. A decrease in ΔP_{aw} after increasing PEEP necessarily reflects lung recruitment and a decrease to their cyclic strain. Conversely, an increase in ΔP_{aw} suggests a non-recruitable lung in which overdistention prevails over recruitment [7].

If, after optimizing PEEP, ΔP_{aw} remains > 15 cm H_2O, it is suggested that V_T should be lowered and causes of increased chest wall elastance be considered. In these cases, the placement of an oesophageal catheter to measure transpulmonary driving pressure (ΔP_L) could be a useful strategy [2], although this strategy is probably not a practical recommendation and is not applicable in the field of anaesthesiology.

It is suggested that a target of ΔP_{aw} < 13–15 cm H_2O be used [41].

Limitations

A problem with this parameter to help in the guidance of V_T selection is that one of its components is the plateau pressure, which, as we mentioned above, is influenced by the chest wall elastance. Thus, 2 patients with the same ΔP_{aw} may have different risk of VILI. A high ΔP_{aw} in the context of high chest wall elastance probably implies that this is due to the chest wall component and that the lung is not being subjected to high and injurious pressures [2, 15]. In this scenario, ΔP_{aw} may be high at the expense of ΔP_{pl}, with transpulmonary driving pressure being at normal or low values.

<table>
<tr><td rowspan="4">Plateau pressure
$P_{aw\ plateau} = (V_T + PEEP_{volume}) \times E_{rs}$</td><td rowspan="2">Transpulmonary pressure
at end inspiration
$P_{L\ plateau} = (V_T + PEEP_{volume}) \times E_L$</td><td>Transpulmonary pressure at end expiration
$P_{L\ PEEP} = PEEP_{volume} \times E_L$</td><td></td></tr>
<tr><td>Transpulmonary driving pressure
$\Delta P_L = V_T \times E_L$</td><td rowspan="2">Airway driving pressure
$\Delta P_{aw} = V_T \times E_{rs}$</td></tr>
<tr><td rowspan="2">Esophageal pressure
at end inspiration
$P_{es\ plateau} = (V_T + PEEP_{volume}) \times E_{cw}$</td><td>Esophageal driving pressure
$\Delta P_{es} = V_T \times E_{cw}$</td></tr>
<tr><td>Esophageal pressure at end expiration
$P_{es\ PEEP} = PEEP_{volume} \times E_{cw}$</td><td></td></tr>
</table>

FIGURE 4. Determinants of protective ventilation parameters. Where $P_{aw\ plateau}$ is airway plateau pressure, V_T is tidal volume, $PEEP_{volume}$ is volume generated by PEEP, E_{rs} is respiratory system elastance, E_L is lung elastance, E_{cw} is chest wall elastance, $P_{L\ plateau}$ is transpulmonary pressure at the end of inspiration, $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration, $P_{L\ PEEP}$ is transpulmonary pressure at end of expiration, ΔP_L is transpulmonary driving pressure or lung driving pressure, ΔP_{es} is oesophageal driving pressure or driving pressure across the chest wall (ΔP_{cw}) or the change in pleural pressure between the end of inspiration and the end of expiration (ΔP_{pl}), $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration, and ΔP_{aw} is airway driving pressure or respiratory system driving pressure (ΔP_{rs}) [31]

$$\uparrow \Delta P_{aw} = \Delta P_L + \uparrow \Delta P_{pl}$$
$$\uparrow \Delta P_{aw} = V_T \times E_L + V_T \times \uparrow E_{CW},$$

where ΔP_{aw} is airway driving pressure, ΔP_L is transpulmonary driving pressure, ΔP_{pl} is oesophageal driving pressure, V_T is tidal volume, E_L is lung elastance, and E_{CW} is chest wall elastance. Oesophageal driving pressure is elevated due to increased chest wall elastance (Figures 1 and 4).

Thus, a high value of airway driving pressure may overestimate the risk of lung injury [42].

Therefore, in these cases of increased chest wall elastance, a better indicator of the dynamic stress lungs are being subjected to in isolation is transpulmonary pressure or transpulmonary driving pressure. These could be measured, limiting V_T to keep it within a safe range [14–16]. However, as we mentioned, it is a difficult measurement to implement in anaesthesiology due to the cumbersome and impractical nature of placing an oesophageal catheter and measuring pleural pressures intraoperatively.

Finally, the effects of PEEP and its continuous strain are not considered in the ΔP_{aw} approach. For example, a theoretically safe level of 12 cm H_2O of ΔP_{aw} could become harmful if PEEP is 20 instead of 0 cm H_2O [36]. This implies that an ΔP_{aw} still in the safe range could be injurious if PEEP levels are high, generating overdistention per se.

This is because VILI related to excessive strain can be linked to its static and dynamic components. Static strain results from application of PEEP and its resultant deformation in the lungs above their functional residual capacity. Dynamic strain results from cyclic insufflation of the aerated lung with each ventilation and is therefore linked to ΔP_{aw} [15] (Table 1).

Application in clinical practice

In situations of high chest wall elastance (e.g. capnoperitoneum, obesity, increased intra-abdominal pressure, etc.), airway driving pressure may be high at the expense of an increase in pleural pressures (oesophageal driving pressure or ΔP_{es}), without the lung being at risk of damage, because the true pulmonary distending pressure (transpulmonary driving pressure or ΔP_L) will be at a lower level. If this is not considered, ventilatory parameters could be unnecessarily reduced to lower the value of airway driving pressure, which runs the risk of increasing atelectasis. In these cases of suspected high chest wall elastance, it would make more sense to assess the option of recruitment and optimization of PEEP levels to improve lung compliance and therefore decrease ΔP_{aw} [23].

Conversely, in cases where it is estimated that chest wall elastance is not elevated, airway driving pressure represents a good surrogate of transpulmonary driving pressure. In addition, there may be scenarios in which there is low ΔP_{aw} but excessively high PEEP (e.g. 20 cm H_2O), causing a static strain high enough to induce lung damage.

Finally, if ΔP_{aw} is high at the expense of high lung elastance (e.g. ARDS), the most appropriate behaviour would be to lower V_T to decrease airway driving pressure (Figure 3).

Transpulmonary pressure

Transpulmonary pressure (P_L) is the pressure that distends the lungs in isolation. It constitutes the pressure generated in the lungs regardless of the effects on the chest wall and abdomen [29]. It is represented by the pressure difference between the inside of the lung (airway pressure) and the pressure on the surface of the lung (pleural pressure or its surrogate oesophageal pressure) [3]. P_L is the relevant pressure when we consider the stress applied to lung tissue in each insufflation, and because a certain stress is associated with a certain strain, P_L is strictly related to VILI generation [3, 33, 38].

Measurement of P_L can be done at the end of inspiration or at the end of expiration [32].

When measured at the end of inspiration or at plateau pressure ($P_{L\ plateau}$), it is relevant when it comes to preventing damage from lung hyperinflation [3, 38]:

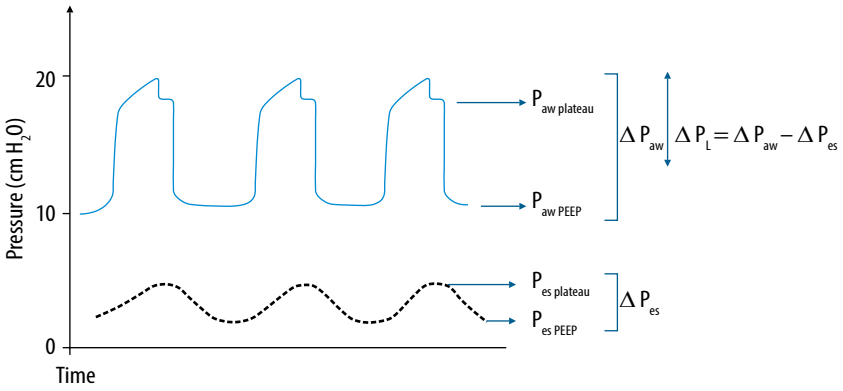

FIGURE 5. Representation of transpulmonary pressures. Airway pressure waveforms and oesophageal pressure waveforms. The double arrow represents the difference between the airway driving pressure (ΔP_{aw}) and the oesophageal driving pressure (ΔP_{es}), which is the transpulmonary driving pressure (ΔP_L). Paw plateau is airway plateau pressure, $P_{aw\ PEEP}$ is positive end expiratory pressure or PEEP, ΔP_{aw} is airway driving pressure, ΔP_L is transpulmonary driving pressure or lung driving pressure, ΔP_{es} is oesophageal driving pressure or driving pressure across the chest wall (ΔP_{cw}) or the change in pleural pressure between the end of inspiration and the end of expiration (ΔP_{pl}), P_{es} plateau is oesophageal pressure at the end of inspiration, and $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration

$P_{L\ plateau} = P_{aw\ plateau} - P_{es\ plateau}$,

where $P_{L\ plateau}$ is transpulmonary pressure at the end of inspiration, $P_{aw\ plateau}$ is airway plateau pressure, and $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration (Figures 4 and 5).

P_L measured at the end of expiration, or transpulmonary pressure associated with PEEP ($P_{L\ PEEP}$) is relevant to preventing lung collapse [3, 38]:

$P_{L\ PEEP} = PEEP - P_{es\ PEEP}$,

where $P_{L\ PEEP}$ is transpulmonary pressure at the end of expiration, *PEEP* is positive pressure at the end of expiration, and $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration (Figure 4).

The P_L measured at the end of inspiration ($P_{L\ plateau}$), represents the total stress given by the cyclic stress to which lungs are exposed during each ventilation (transpulmonary driving pressure or ΔP_L) and the addition of the static stress measured by P_L at the end of expiration ($P_{L\ PEEP}$) [43]:

$P_{L\ plateau} = \Delta P_L + P_{L\ PEEP}$

$(V_T + PEEP_{volume}) \times E_L = (V_T \times E_L) + (PEEP_{volume} \times E_L)$,

where $P_{L\ plateau}$ is transpulmonary pressure at end inspiration, ΔP_L is transpulmonary driving pressure, $P_{L\ PEEP}$ is transpulmonary pressure at end expiration, V_T is tidal volume, E_L is lung elastance, and $PEEP_{volume}$ is the volume generated by PEEP (Figure 4).

For a given $P_{aw\ plateau}$, the $P_{L\ plateau}$ depends on the relationship between lung elastance (E_L) and that of the respiratory system (E_{rs}), the latter being the sum of E_L plus E_{CW} [3, 44].

$P_L = P_{aw\ plateau} \times (E_L/E_{rs})$,

where, P_L is transpulmonary pressure at the end of inspiration, $P_{aw\ plateau}$ is airway plateau pressure, E_L is lung elastance, and E_{rs} is respiratory system elastance.

If we consider, for example, a patient with an elastance ratio of 0.8 ($E_L/E_{rs} = 0.8$) (e.g. ARDS) and an $P_{aw\ plateau}$ of 30 cm H_2O, their P_L will be 24 cm H_2O. This is considered a pulmonary distending pressure level that corresponds to a dangerous lung volume close to total lung capacity. In contrast, for another patient with an elastance ratio as low as 0.2 (e.g. obesity or pregnancy), the same $P_{aw\ plateau}$ of 30 cm H_2O will correspond to a P_L of only 6 cm H_2O, which may be associated with lung collapse and hypoxaemia [3, 36].

In this way, it follows that for the same V_T and $P_{aw\ plateau}$, depending on the relationship between E_L and E_{rs}, it could result in completely different P_L and, consequently, different risks of VILI [4, 45].

Measurement of pressure that distends lungs alone may be a better approach to guiding ventilatory management, especially in patients with increased chest wall elastance in whom the $P_{aw\ plateau}$ and airway driving pressure are elevated, but without this necessarily implying a risk of lung damage [4]. For a given V_T, a stiffer chest wall will lead to the development of higher pleural pressures because more of the airway driving pressure will be displacing the chest wall. In these cases, for a given $P_{aw\ plateau}$, transpulmonary pressure will become lower as chest wall elastance increases (e.g. abdominal hypertension or severe obesity) and vice versa [46] (Figure 2).

Although direct measurement of pleural pressure through pleural catheters is theoretically and practically possible, the most practical way to estimate pleural pressure in clinical practice is oesophageal manometry [3].

To better characterize ventilatory mechanics, P_L must be estimated under static conditions, i.e. when flow in the system is zero. This is mandatory to prevent having to take into account the pressure necessary to exceed airway resistance. The pressure measured under static conditions, during an inspiratory pause, is the plateau pressure, already referred to in this article [3].

Assessment of P_L could be useful for several reasons. On the one hand, for differentiating patients

who could benefit from higher airway pressures due to their increased chest wall elastance from those who, despite having low airway pressure levels, are still under risk of overdistention [4]. Another benefit of its use would be for determining the pressure required to keep lungs open. Because oesophageal pressure is a surrogate of pleural pressure, a negative transpulmonary pressure at the end of expiration would correspond to collapsed lungs [3]. It has therefore been proposed for choosing PEEP levels, aiming to obtain a positive value of transpulmonary pressure at the end of expiration, and thus avoiding atelectasis [29].

Limiting P_L to less than 15–20 cm H_2O appears to be a physiologically reasonable approach for mitigating VILI [30, 32, 38].

Limitations

Transpulmonary pressure is the total load imposed to the elastic fibres of the lung parenchyma. However, if lungs are heterogeneous, it may have an additional load in lung interface areas with a multiplication factor that can reach "2" according to the stress raiser model (calculation of Cressoni *et al.*) [47]. This means that a transpulmonary pressure of 30 cm H_2O can reach a local value of up to 60 cm H_2O in interface areas between open and closed regions of the lungs [27]. Therefore, global indices (such as P_L) do not reflect regional stress or strain [5]. This is important for 2 reasons. One is that in patients with pathologies that cause pulmonary heterogeneities, target values for P_L should be lower. And the second is that a pulmonary homogenization strategy in lungs with atelectasis, such as prone positioning or selecting adequate PEEP levels, would be beneficial by reducing stress raisers [26, 44, 48, 49].

Another limitation of using only an isolated P_L value to guide mechanical ventilation in a protective way is that it also does not take into account the ventilatory rate and inspiratory flow as variables that also contribute to VILI development [3]. In this line of thought, mechanical power is an integrative and comprehensive parameter that involves all the components related to lung injury due to mechanical ventilation. It is easy to understand that, for the same transpulmonary pressure, we can have different associated mechanical power values depending on all the other variables that contribute to it (such as PEEP levels, respiratory rate, V_T, inspiratory flow, and ΔP_{aw}) [3, 49].

Application in clinical practice

Despite its cumbersome measurement that reduces its applicability, it helps us as a concept to understand possible causes of high airway pressures and to differentiate between the pressure to which lungs are exposed and the pressure that acts on the chest wall and the abdomen.

P_L plateau is included, together with oesophageal pressure at the end of inspiration ($P_{es\ plateau}$), within the parameters that determine $P_{aw\ plateau}$. So, if we assume that chest wall elastance is normal, then $P_{aw\ plateau}$ could be a good surrogate of P_L (Figure 4).

$$P_{aw\ plateau} = P_{L\ plateau} + P_{es\ plateau}$$

On the other hand, if the chest wall elastance is high, the $P_{aw\ plateau}$ will be mainly determined by pleural pressure (or its surrogate, oesophageal pressure). In this way, we can infer whether the ventilation is damaging the lungs (i.e. elevated P_L) or the patient's haemodynamics (i.e. elevated P_{es}) by decreasing the venous return [50, 51]. Differences between $P_{aw\ plateau}$ and P_L will be more pronounced in obese patients or others with restrictive chest wall disorders (i.e. high chest wall elastance). In these cases, low transpulmonary pressure (less than 20 cm H_2O) is considered a protective ventilatory strategy regardless of the $P_{aw\ plateau}$ [21] (Figure 2).

Transpulmonary driving pressure

Transpulmonary driving pressure (ΔP_L) or lung driving pressure, represents the change or oscillation in transpulmonary pressure generated by V_T between the end of inspiration and the end of expiration [29]. It is calculated from the transpulmonary pressure difference between the P_L plateau and $P_{L\ PEEP}$,

$$\Delta P_L = P_{L\ plateau} - P_{L\ PEEP}$$

$$(V_T \times E_L) = (V_T + PEEP_{volume}) \times E_L - (PEEP_{volume} \times E_L),$$

where ΔP_L is transpulmonary driving pressure, $P_{L\ plateau}$ is transpulmonary pressure at the end of inspiration, $P_{L\ PEEP}$ is transpulmonary pressure at the end of expiration, V_T is tidal volume, E_L is lung elastance, and $PEEP_{volume}$ is volume generated by PEEP (Figure 4).

In other words, the transpulmonary driving pressure (ΔP_L) would be equivalent to the transpulmonary pressure at end inspiration ($P_{L\ plateau}$) without the distending pressure generated by PEEP ($P_{L\ PEEP}$).

Another method of analysing and interpreting transpulmonary driving pressure is through ΔP_{aw}. The airway driving pressure is composed of 2 pressures: the one applied in the lung (ΔP_L) and the one to the chest wall (ΔP_{pl}) [38]:

$$\Delta P_{aw} = \Delta P_L + \Delta P_{pl},$$

where ΔP_{aw} is airway driving pressure, ΔP_L is transpulmonary driving pressure, and ΔP_{pl} is change in pleural pressure or driving pressure across the chest wall (ΔP_{CW}) [5] or oesophageal driving pressure (ΔP_{es}) [2] (Figures 4 and 5).

The oesophageal driving pressure (ΔP_{es}) is the change in oesophageal pressure between inspiration and expiration and represents the pressure applied to the chest wall above PEEP due to V_T delivery.

$\Delta P_{es} = P_{es\ plateau} - P_{es\ PEEP}$ [3],

where ΔP_{es} is oesophageal driving pressure, $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration, and $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration (Figure 4).

Terminology clarification: it is possible to find in the literature the change in pleural pressure expressed as ΔP_{pl} or ΔP_{es} or ΔP_{CW} called oesophageal driving pressure [2], which represents the distending pressure of the chest wall in isolation, which is elevated in situations of high chest wall elastance.

Therefore, if we solve for the transpulmonary driving pressure from the previous equation:

The transpulmonary driving pressure (ΔP_L) is the same as the airway driving pressure (ΔP_{aw}) without the distending pressure generated by the chest wall or oesophageal driving pressure (ΔP_{es}) [52].

$\Delta P_L = \Delta P_{aw} - \Delta P_{es}$

$\Delta P_L = (P_{aw\ plateau} - PEEP) - (P_{es\ plateau} - P_{es\ PEEP})$

$V_T \times E_L = (V_T \times E_{rs}) - (V_T \times E_{cw})$,

where, ΔP_L is transpulmonary driving pressure, ΔP_{aw} is airway driving pressure, ΔP_{es} is oesophageal driving pressure, $P_{aw\ plateau}$ is airway plateau pressure, *PEEP* is positive pressure at end of expiration, $P_{es\ plateau}$ is oesophageal pressure at the end of inspiration, $P_{es\ PEEP}$ is oesophageal pressure at the end of expiration, V_T is tidal volume, E_L is lung elastance, E_{rs} is respiratory system elastance, and E_{cw} is chest wall elastance (Figures 4 and 5).

Therefore, ΔP_L only represents the pulmonary distending pressure generated by delivery of tidal volume without taking into account the pressure component required to mobilize the chest wall (ΔP_{es}) [29]. Both the properties of the chest wall and the abdomen influence ΔP_{aw} measurement. This influence can be misleading because an increase in chest wall elastance does not reflect an increase in the risk of lung injury and will still lead to an increase in ΔP_{aw} [38].

Because differences between ΔP_L and ΔP_{aw} are mainly due to increases in chest wall elastance, the latter can vary with respect to the former between minimal (e.g. lean patients, pneumonia) and wider (e.g. morbid obesity, abdominal hypertension) differences [2, 14]. For this reason, in these cases of high chest wall elastance, it is advisable to assess ΔP_L through an oesophageal catheter to appropriately quantify stress applied to the lungs. However, in conditions where chest wall elastance is normal and stable, changes in ΔP_{aw} will provide an appropriate surrogate for changes in ΔP_L and lung strain [38] (Figure 4).

The 14 cm H_2O limit of ΔP_{aw} suggested as a safety parameter for ventilation will depend on the elastance ratio (E_L/E_{rs}). ΔP_L depends, for a given ΔP_{aw}, on the relationship between lung elastance and respiratory system elastance:

$\Delta P_L = \Delta P_{aw} \times (E_L/E_{rs})$,

where ΔP_L is the transpulmonary driving pressure and ΔP_{aw} is the airway driving pressure.

Taking as an example a ΔP_{aw} value of 14 cm H_2O, this value can range from a ΔP_L of 2.8 cm H_2O (with an elastance ratio of 0.2) to 11.2 cm H_2O (with an elastance ratio of 0.8) [3]. Therefore, the same ΔP_{aw} with a limit value of 14 cm H_2O but with a ΔP_L of 2.8 cm H_2O would have a lower risk of lung damage than another patient with the same ΔP_{aw} and a ΔP_L of 11.2 cm H_2O (value close to the limit of 10–12 cm H_2O).

ΔP_L has several benefits. First, unlike P_L but like ΔP_{aw}, it removes the stress caused by PEEP levels, which does not necessarily contribute to lung injury and can sometimes even mitigate it [16, 29]. Second, like P_L but unlike ΔP_{aw}, it removes distending pressure from the chest wall [29]. Third, it is conceived that ΔP_L would better reflect the presence of regional inhomogeneities in mechanical properties of the lungs (i.e. overdistention and atelectasis). An increase in ΔP_L would be a better parameter to estimate tissue tension than other measurements of the respiratory system. Therefore, this parameter would represent a better surrogate of pulmonary stress and even a better predictor of clinical results than P_L [16].

In the clinical setting, upper limits of transpulmonary driving pressure would be 10–12 cm H_2O [37] (Table 1).

Limitations

The use of an oesophageal catheter and the difficulties in its measurements and interpretation limit its applicability.

According to Gatinoni *et al*. [3], measurement of oesophageal pressure and the data derived from it (P_L and ΔP_L) have very limited use in clinical practice despite being key variables to guide mechanical ventilation in a safe way. The author considers that this occurs mainly due to 2 reasons: first of all, the "the fatigue of studying", which involves the wise use of data derived from the measurement of oesophageal pressure that requires an adequate cultural background. Second, due to the "fatigue of acting", which points to the work that is added to usual clinical practice.

Application in clinical practice

ΔP_L then represents the distending force that acts only in the lung [1]. Therefore, if we use P_L and/or ΔP_L as a target for protective ventilation, we will be approaching the true values that generate lung damage during mechanical ventilation. However, the use

of an oesophageal catheter is time consuming and is difficult to apply in everyday anaesthetic practice.

In patients under mechanical ventilation, ΔP_L will always be lower than ΔP_{aw} because it does not consider chest wall elastance [2, 14]. Because the ΔP_L is contemplated within ΔP_{aw}, considering that the chest wall component of elastance is not elevated, then ΔP_{aw} will be a good surrogate for the ΔP_L [38] (Table 1).

CONCLUSIONS

Protective ventilation strategies for the patient under general anaesthesia involve the interpretation of a number of parameters. A thorough knowledge of their determinants and limitations is essential to individualize their use in clinical practice according to the best available evidence. Some of these parameters are part of the information that most mechanical ventilators and anaesthesia machines routinely display (e.g. V_T, PEEP, $P_{aw\ peak}$, $P_{aw\ plateau}$, and ΔP_{aw}). Others are less accessible in an operating theatre situation (e.g. P_L and ΔP_L), but their understanding contributes to monitoring and configuration of the traditional protective ventilation parameters. In patients in whom chest wall elastance is not elevated, airway plateau pressure may be a good surrogate of transpulmonary pressure, and airway driving pressure of transpulmonary driving pressure. Conversely, in the presence of increased chest wall elastance, airway plateau pressures or airway driving pressure at their superior limit values could be considered non-injurious to the lungs.

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