Respiratory mechanics during general anaesthesia

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Abstract: Intraoperative mechanical ventilation is mandatory during many surgical procedures. Knowledge in this field has been widely derived from the experience in the treatment of patients with acute respiratory distress syndrome in the intensive care unit. However, also in surgical patients without lung injury, mechanical ventilation settings affect the clinical outcome, and in particular the occurrence of postoperative pulmonary complications (PPCs). A deep understanding of respiratory physiology is mandatory for the clinician, in order to tailor ventilation settings based on the specific characteristics of each patient. In this paper we will discuss the basis of lung physiology applied to the mechanical ventilation in the operating room. The role of compliance, tidal volume, positive end-expiratory pressure (PEEP), plateau pressure, driving pressure, stress index, mechanical power and other ventilator-derived parameters will be discussed. The above-mentioned physiological parameters are easy to measure and can guide the clinician to assess and titrate mechanical ventilation parameters, but the clinical impact of guiding mechanical ventilation based on these parameters has yet to be determined.

Keywords: Surgery; mechanical ventilation; pulmonary physiology

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Introduction

The correct interpretation of physiology is a cornerstone of clinical reasoning. Each year millions of patients undergo surgical procedures, with a non-negligible mortality rate and incidence of postoperative pulmonary complications (PPCs) (1,2). In this context, even small improvements can translate to a relevant reduction of morbidity and improved outcome after surgery. The last decade has seen a great interest on the possibility to reduce the incidence of PPCs through the adoption of ventilatory strategies aimed at minimising the potential damage induced by mechanical ventilation, namely using protective ventilation (3), similarly to what was previously proposed in patients with the acute respiratory distress syndrome (4). However, the optimal setting of the ventilator during general anaesthesia is still under debate. There is consensus that tidal volume (V_T) reduction to 6–8 mL per kg of predicted body weight improves the respiratory function (5) and reduces the incidence of PPCs (6). The role of positive end-expiratory pressure (PEEP) is more debated, with several authors proposing the use of higher PEEP levels but trials reporting inconsistent results (7,8). Monitoring tools during general anaesthesia are increasingly at the cutting edge, providing to clinicians the opportunity to gather in real-time several respiratory parameters, allowing the clinician to assess the patient comprehensively (9). However, there are often conflicting results concerning the optimal intraoperative ventilation settings, and translating into clinical action the different parameters available on the ventilator might not be straightforward.

The aims of this review are: (I) to provide a basic introduction to the respiratory physiology applied to intraoperative mechanical ventilation; (II) to resume the most recent evidence in the field; and to help the clinician interpreting respiratory physiology in the operating room.

Basic physiology and mechanical ventilation

The knowledge of respiratory system and lungs mechanics is essential to understand as well as to better interpret correctly the interaction between ventilator and patient. Respiratory system mechanics is the result of a complex interaction between the chest wall and the lungs. In physiologic conditions, respiratory muscles, elastic properties of chest wall and lungs play a central role in the generation of the airflow, creating a pressure gradient from the airway opening to the pleural cavity. In the intraoperative settings, due to the use of neuromuscular blockade and drugs reducing the respiratory drive, the muscular component is markedly reduced or, as occurs in most cases, completely abolished. As a consequence, the ventilator must create the airflow, to generate a positive pressure and consequently a tidal volume, independently from the action of respiratory muscles. The interpretation of all ventilator-derived parameters in the operating room is fundamental because they provide an early and simple way to optimize mechanical ventilation setting, recognize and manage intraoperative issues (10,11). In the next paragraphs we provide a concise overview to measure and to interpret physiology monitoring inside the operating room.

Elastic and resistive components of the respiratory system

The ratio between volume variation during the respiratory cycle, namely V_T, and the pressure gradient generated to achieve such V_T, i.e., [ΔP = plateau pressure (P_{plat}) − PEEP] is called compliance ($C = \Delta V/\Delta P$), thus, the ability of the respiratory system to be distended. The inverse of compliance is called elastance ($E = \Delta P/\Delta V$). Respiratory system compliance (C_{RS}) is given by the addition in parallel of chest wall (C_{CW}) and lung compliance (C_L), resulting in a total compliance value inferior to the single ones. Flow (Q) encounters a resistance, generating a pressure increase proportional to Q. The resistance of the airways (R) is estimated dividing the pressure drop by the flow that generated it. Therefore, the peak airway pressure (P_{peak}) is both influenced by the elastic and resistive properties of the respiratory system. To eliminate the resistive component, the airflow must be interrupted by using an end-inspiratory pause. Indeed, the most accurate value of compliance is calculated in condition of zero-flow; in this way, the pressure component related to resistance is abolished, allowing to calculate a value of pressure in static conditions at end-inspiration reflecting the elastic properties of the respiratory system or the lung alone. In particular, airway pressure measured in condition of zero-flow is called P_{plat} that differs from P_{peak} that is measured in presence of flow, thus carrying the effect of airway resistances. P_{plat} is the closest estimation of pressure inside the alveoli that can be measured non-invasively.

At the end of inspiration, the expiratory valve is released to allow passive expiration, and a PEEP can be applied. Another important factor to keep in mind is the intrinsic PEEP ($PEEP_i$ or auto-PEEP). It could be defined as the pressure generated by the trapped volume in airway at the end of expiration, it's related to the compliance, a common finding in patients with obstructive disease. Usually, a clearly sign of $PEEP_i$ is when the flow starts from a negative value at end-expiration; in this case setting a prolonged I:E ratio and decreasing respiratory rate (with the help of a neuromuscular blockade and sedation) reduce the air-trapping, thus dropping the total airway pressure during expiration. Most anaesthesia machines do not allow setting an expiratory hold: therefore, it is important to recognize visually the signs of airflow limitation. The most immediate method relies on the visual inspection of the flow-time curve, if the flow does not reach zero before the next breath starts, $PEEP_i$ is likely. When flow limitation occurs, it could be either due to airway obstruction or airway collapse. Inspecting the flow-volume loop, a steep bending of the expiratory branch of the loop immediately after it has reached its peak suggests the presence of airway collapse (*Figure 1*) (9). Some authors have also proposed a tool to assess the presence of expiratory flow limitation based on a small reduction in PEEP and the inspection of the flow-volume loop. If decreasing PEEP do not increase the expiratory flow, the patient has expiratory flow limitation. This phenomenon has been linked to the occurrence of PPCs (12).

Modes of ventilation in the operating room

In the operating room, controlled modes are the most used due to the abolishment of the respiratory activity, namely volume-controlled ventilation (VCV), pressure-controlled ventilation (PCV), and dual-controlled modes (13). Despite several studies, it has not been established superiority of one mode on the other (14). VCV mode is a ventilatory mode

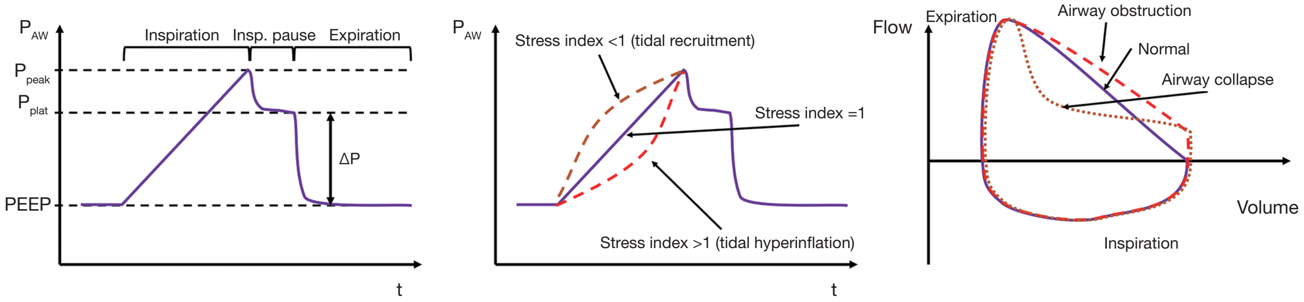

Figure 1 Visual inspection of ventilator curves. (A) Measurement of ΔP using an end-inspiratory pause during VCV; (B) visual assessment of the stress index (see text); (C) flow-volume loop in a patient with normal resistance (continuous line), airway obstruction (red dashed line) and airway collapse (maroon dotted line). Note that in both airway obstruction and collapse the flow does not reach zero at end expiration. VCV, volume-controlled ventilation.

that deliver a constant flow in a given time, thus the V_T is computed measuring the area under the square flow-time curve (Q×t). In VCV mode, after a rapid rising of pressure due to initial overcoming respiratory resistance, pressure rises linearly until the P_{peak} is reached, that correspond to the opening of expiratory valve. The clinician sets V_T, respiratory rate, inspiratory to expiratory (I:E) ratio and PEEP. In all modern ventilators, to reliably calculate P_{plat}, is possible to set an end-inspiratory flow pause as percentage of the inspiratory time (typically 10–20%): in this way, both inspiratory and expiratory valves are closed, flow is zero and airway pressure approximates P_{plat}. In patients in which a high respiratory rate or a very high airway resistance prevent the airway pressure to stabilise on the P_{plat} during the brief end-expiratory pause, another option is to reduce respiratory rate to the minimum value to increase the inspiratory time, and consequently the duration of the end-inspiratory pause. In PCV mode, the independent variable set by clinician is the airway inspiratory pressure (P_{insp}). In this mode, the pressure-time curve is approximately square while the flow-time curve has an initial vertical increment to rapidly reach the desired pressure and then a decremental trend that only in ideal condition reaches zero. The clinician sets the P_{insp}, respiratory rate, I:E ratio and PEEP. In this mode, the airway pressure obtained is a value in between the values of P_{peak} and P_{plat} that would have been measured in VCV, and in ideal condition of zero flow it will correspond to P_{plat}. More recently, dual-controlled modes became available. In these modes, that have different names according to the ventilator manufacturer, the clinician sets the target V_T, then the ventilator will deliver a PCV ventilation with decelerating inspiratory flow, automatically adjusting the P_{insp} in order to maintain the desired V_T target (15).

Driving pressures

The difference between P_{plat} and PEEP is called driving pressure (ΔP, *Figure 1*), namely the dynamic strain of lung fibres and, in other terms, the ratio of V_T to the compliance. High ΔP values have been recently related to the development of PPCs in patients undergoing mechanical ventilation for surgery (16,17). When a high ΔP (>13 cmH_2O) is detected, a further reduction of V_T or increasing lung recruitment with a higher PEEP level to minimize ΔP should be attempted. However, while no trial tested the effects of a V_T reduction to levels lower than those already considered protective (6–8 mL per kg of predicted body weight) in patients with a high baseline ΔP, the role of higher PEEP was tested in two trials with no beneficial effects (7,8). On the other hand, in an individual patient meta-analysis, patients in which increasing PEEP was associated with greater ΔP showed the highest incidence of PPCs (17). Under the assumption that C_{RS} reflects the amount of aerated lung volume, the ΔP is considered a surrogate of the dynamic strain, which is defined as the ratio of V_T to the end expiratory lung volume. However, in a recent study questions this assumption, observing that the approximation of the dynamic strain with ΔP is unreliable when the lung is aerated above its normal functional residual capacity, which often occurs with the use of PEEP (18). In conclusion, ΔP is a marker of risk for PPCs, but it is still to be clarified how the clinician should react when an increased ΔP is observed.

Plateau pressure

P_{plat} is the pressure at end inspiration in static condition and represents the inspiratory stress of the respiratory system or the lung. Higher plat has been shown to be associated with increased risk of developing PPCs (16). Interestingly, relatively low levels of P_{plat} (higher than 16 cmH_2O) have been found associated with worse postoperative outcome. This suggests that the healthy lungs, at least in patients undergoing surgery, may be injured even by low levels of respiratory stress.

Transpulmonary pressure

Another fundamental concept debated in clinical settings is the transpulmonary pressure (P_L), defined as the actual pressure distending the lung, defined as the difference between the airway pressure and the pleural pressure (19). This measurement is used to estimate P_L both at end-inspiration and end-expiration. In order to eliminate the resistance component, the inspiratory pressure is usually acquired in absence of flow. In addition, instead of the pleural pressure that is challenging to be acquired in clinical settings, oesophageal pressure (P_{es}) is measured through an oesophageal balloon catheter that gives an acceptable, even if questioned (20), approximation of pleural pressure. In summary, at end inspiration $P_{L,\text{ end-inspiration}} = P_{plat} - P_{es,\text{ end-inspiration}}$ while $_{\text{at end-expiration}}$ $P_{L,\text{ end-expiration}} = P_{EEP} - P_{es\text{ , end expiration}}$ (19). The $P_{L,\text{ end-inspiration}}$, may be used to estimate the maximal stress of the lung at inspiration (avoiding values higher than 20 cmH_2O). On the other hand, $P_{L,\text{ end-expiration.}}$ may help to optimize the level of PEEP to avoid opening and closing of the alveolar units and hopefully lung injury. For this aim, PEEP is set at a value in order to zeroed or reaching positive (+2 cmH_2O) values od $P_{L,\text{ end-expiration}}$ However, the need for an oesophageal balloon limits the application of this technique mainly for research purposes. Further, the correct, accurate and precise interpretation of oesophageal pressure is under discussion.

Stress index

During VCV, the analysis of the pressure-time curve can add precious information that can help setting ventilation parameters. In condition of constant airflow, as occurs during inspiration in VCV, airway pressure rises linearly, assuming that C_{RS} remains constant. Non-linearity of the pressure-time curve during the inflation phase denotes a non-constant compliance during V_T insufflation. When the compliance increases during inspiration, as during a phenomenon of intra-tidal lung recruitment, the slope of the pressure-time curve decreases over time, resulting in a downward concavity. Therefore, a patient in which intra-tidal recruitment occurs might benefit from a PEEP increase to stabilise the alveoli and avoid cyclic opening and closing of respiratory units, a mechanism potentially leading to lung injury. On the other hand, if C_{RS} decreases during inspiration, as suggested by an upward concavity of the pressure-time curve, this suggests that the lung is cyclically over-distended during inspiration. In this case a reduction of PEEP and/or V_T might be warranted. A mathematical explanation of this phenomenon is described by a power equation of motion applied to the pressure of the airways: $P_{aw} = a \times t^b + c$. Where *a* represent the slope of P-t curve in a given time of measurement *t*, and *c* the pressure at the beginning of inspiration. The constant *b* is a non-dimensional number that describe the shape of P-t curve named "stress index". For values of b=1 the P-t curve obtained is linear, if b<1 curve is downward, if b>1 curve is upward. Stress index values are related to important features of ventilator-induced lung injury (VILI). A value of stress index not equal to 1, so a non-linear P-t curve, were related to pulmonary damage (21). Grasso *et al.* showed with computed tomography imaging that stress index values below 1 are related to atelectrauma, due to the cycling reopening of alveoli during mechanical ventilation (22). Stress index values above 1 are related to dynamic hyperinflation and cause an overdistention of the alveoli. Clinician could adapt ventilatory settings to respiratory system characteristics of the patient, modifying V_T and PEEP. In the context of a protective ventilation, the use of stress index could help clinicians to set the correct V_T and to titrate carefully the PEEP level. Measuring the stress index requires complex calculations, but its estimation can be done by eyeballing the pressure-time curve, as illustrated in *Figure 1* (23).

Assisted ventilation modes in the operating room

The above-mentioned physiological parameters could also help the operator to set not only controlled ventilation modes, but also different type of assisted ventilation modes, nowadays also available in anaesthesia ventilators and potentially useful in selected patients (24). Usually, general anaesthesia is associated with controlled ventilation and endotracheal intubation, but, when a neuromuscular blockade is not necessary for the type of surgery, the patients can be maintained in spontaneous breathing or in different assisted ventilation modes with laryngeal mask.

PSV could be used during general anaesthesia or in deeply sedated patients under minor surgery or at the emergence of anaesthesia (13).

Pressure support ventilation (PSV) is an assisted mode in which each breath is patient triggered and supported by a positive pressure provide from the ventilator, when it detects patient inspiratory effort as a drop in pressure or a difference in the flow signal between inspiration and expiration (7). Compared to spontaneous breathing without respiratory support, PSV reduces the work of breathing and increases tidal volume and so minute ventilation (25). Furthermore, compared to controlled ventilation modes, PSV allows diaphragmatic motion and ventilation/perfusion matching (25), since during assisted modes, lower neuromuscular blockade and sedation levels are needed (26). In a 2014 study, Capdevila and colleagues showed that, in patients under general aesthesia for knee arthroscopic surgery and ventilated through a laryngeal mask, PSV reduces propofol consumption compared to both spontaneous breathing and VCV, supraglottic airway leaks and airway removal time compared to VCV (27).

Synchronized intermitted mandatory ventilation (SIMV) is a hybrid ventilation mode in which the patient could trigger spontaneous breathing assisted with a pressure support by the ventilator. If the patient doesn't trigger any breath and the respiratory rate drops under the set value, the machine provides mandatory breaths (7). Therefore, SIMV could be a useful tool in the operating room for those patients that still have a residual respiratory drive, but with the safety that, if the patient trigger doesn't come, the set respiratory rate will be maintained by mandatory breaths (13). So clearly, SIMV can also use at the emergence of the anaesthesia, gradually reducing the set respiratory rate and the set pressure support. Compared to PSV, SIMV is available on older ventilators. In all assisted modes, airway pressure underestimates the actual distending pressure of the lungs, because the ventilator does not measure the muscular effort of the patient. This must be kept in mind, as ΔP should be ideally kept at lower values compared to controlled modes. The magnitude of the inspiratory effort could be estimated with an inspiratory hold during muscle relaxation (28), however most anaesthesia ventilators do not allow to perform such manoeuvre.

Conclusions

The above-mentioned physiological parameters are easy to measure and can guide the clinician to assess, titrate and optimize mechanical ventilation parameters. In non-obese patients during anaesthesia, we suggest using volume control ventilation or pressure regulated volume control, keeping a VT 6–8 mL/Kg PBW, P_{plat} lower than 16 cmH_2O, ΔP lower that 13 cmH_2O, PEEP equal or below 5 cmH_2O, and stress index equal or lower than 1. The clinical impact of guiding mechanical ventilation based on these parameters has yet to be determined.

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Footnote

Conflicts of Interest: The authors have no conflicts of interest to declare.

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