CHAPTER 13

Monitoring Pressures during Mechanical Ventilation

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INTRODUCTION

Respiratory monitoring is a fundamental tool to evaluate lung mechanic and its pathological changes in critically ill patients, functioning as guide to personalize both invasive and noninvasive mechanical ventilation. In this chapter, we will focus on the main pressures that may be measured in a ventilated patient, including a synthetic explanation about the physiological principle and the clinical meaning of each parameter.

AIRWAY PRESSURE

Airway pressure (Paw), measured at airways opening, depends on the forces applied to the respiratory system by mechanical ventilation. Paw reflects the interaction between lung and ventilator, as expressed by respiratory system equation of motion:

$$Paw = (Vt / Crs) + (Flow \times Rrs) + (Pmus) + (PEEP)$$

where:

Vt = Tidal volume (mL)
Crs = Respiratory system compliance (mL/cmH_2O)
Rrs = Respiratory system resistance (cmH_2O × L/sec)
Pmus = Muscle pressure (cmH_2O)
PEEP = Positive end-expiratory pressure (cmH_2O)

Thus, at each moment of a respiratory cycle, Paw corresponds to the sum of resistive load (Flow × Rrs) + elastic load (Vt/Crs) + pressure generated by respiratory muscles (if spontaneous efforts are present) + PEEP (both externally applied PEEP and intrinsic PEEP, if present). The dynamic inspiratory Paw values (i.e. in presence of inspiratory flow) may reach very high values (50–60 cmH_2O), especially if Rrs is increased, without causing excessive lung injury; on the other hand, the static inspiratory Paw value (i.e. no-flow condition) considered as maximum limit to reach during mechanical ventilation is ≤30 cmH_2O.

PEAK AND PLATEAU PRESSURE

End-inspiratory airway occlusion consists in the simultaneous closure of inspiratory and expiratory valves of the ventilator circuit, at the end of inspiration; the maneuver is performed by pushing for 3–5 seconds the inspiratory hold ventilator button during controlled ventilation. When the occlusion is achieved during square flow volume controlled ventilation, a rapid flow-drop is observed, Paw falling from the highest airway-pressure level, named Ppeak, to a lower level named P1; the latter is measured when the flow reaches zero. The flow-drop is proportional to the resistive load imposed on inspiration. Starting from the P1 level, a further slow drop of airway pressure occurs; it is caused by pendelluft[1] (air redistribution between lung compartments with different filling-time constants) and by tissue-relaxation phenomena. The new, constant, and end-inspiratory level reached is the plateau pressure (Pplat), corresponds to end-inspiratory elastic load of the respiratory system (Fig. 1). Pplat is the estimate closest to the higher transalveolar pressure value, during the respiratory cycle. The limit of Pplat for the prevention of volutrauma is ≤30 cmH_2O. The current paradigm attributes ventilator-induced lung injury (VILI), amongst other factors, to the alveolar overstretching caused by very high-volume ventilation (volutrauma).[2,3] Furthermore, the measurement of Pplat allows calculation of Crs, corresponding to the ratio between the changes in lung volume for unitary change in airway pressure ($\Delta V/\Delta Paw$); respiratory system elastance is defined as Crs reciprocal (1/Crs). Physiologically, Ppeak is only slightly higher than Pplat and, for each level of Ppeak–Pplat difference, Ppeak and Pplat rise together in a proportional manner, if Vt is increased or if Crs is decreased. Conversely, if Ppeak rises with no changes in Pplat, increased Raw or elevated inspiratory flow values should be suspected.

MEAN AIRWAY PRESSURE

Mean airway pressure (Paw_{mean}) is the average pressure exerted on airway and lungs during the ventilatory cycle; Paw_{mean} is affected by many variables in mechanical ventilation:

- Inspiratory pressure
- PEEP and auto-PEEP
- Inspiration to expiration ratio
- Inspiratory pressure waveform

Paw_{mean} closely reflects mean alveolar pressure (Palv), in absence of significant airway obstruction.[4] The closer it approximates Palv, the more relevant it becomes, being mean alveolar pressure a major determinant of both respiratory and hemodynamic effects of ventilation. Typical Paw_{mean} values for passively ventilated patients ranges from 5 to 10 cmH_2O in normal subjects, from 20 to 30 cmH_2O if Crs is markedly reduced and from 10 to 20 cmH_2O in presence of airflow obstruction.

POSITIVE END-EXPIRATORY PRESSURE

An end-expiratory airway occlusion maneuver consists in the simultaneous closure of inspiratory and expiratory ventilator's valves at the end of expiration, during controlled ventilation. The maneuver is obtained by holding for 3–5 seconds the end-expiratory occlusion button. During this period, airway pressure re-equilibrates in all lung compartments, so that Paw will correspond to average PEEP level. In the presence of gas trapping, Paw will rise from set PEEP to total PEEP and this rise is named auto-PEEP (Fig. 1).

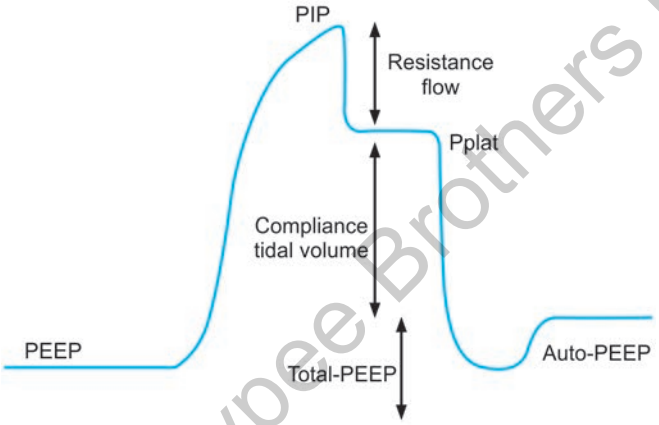

Fig. 1: Airway pressure trace of a volume-targeted breath, after performing an end-inspiratory airway occlusion maneuver. Flow is interrupted at the end of inspiration, allowing the measurement of the quasi-static pressures of respiratory system. PEEP: positive end-expiratory pressure; PIP: peak inspiratory pressure; Pplat: end-inspiratory plateau pressure; auto-PEEP: pressure exerted by the incompletely exhaled air, in presence of small-airways obstruction (difference between total PEEP and PEEP applied).

For mild to severe forms of acute hypoxemic respiratory failure, PEEP ≥5 cmH_2O is needed in order to improve oxygenation, but debates still happen about the so-called "optimal" PEEP[5] and its determinants.[6,7] PEEP should maximize gas exchanges by minimizing the end-expiratory atelectasis while limiting the end-inspiratory overdistension. Different methods of setting PEEP in hypoxemic respiratory failure have been proposed; in some cases, the primary goal is the improvement of oxygenation, whereas in others lung-protective ventilation strategies are privileged, even at the price of sub-optimal oxygenation. Each method has both advantages and shortcomings. Below, we report a brief description of the methods mainly used in clinical practice.

Strategies to Select PEEP

ARDSnet Protocol

This strategy is based on increasing the PEEP levels when high FiO_2 values are needed to obtain a viable SpO_2, as reported in Table 1. The clinical trial performed by the acute respiratory distress syndrome (ARDS) Network in 2004,[8] on patients affected by ARDS, aimed to compare the mortality between patients ventilated according to the Table 1 settings (lower FiO_2, higher PEEP) and patients ventilated with higher FiO_2 and lower PEEP levels. No significant difference in mortality was found.

A possible explanation is that this over-simplistic approach cannot always guarantee success—the lack of correlation between PEEP levels and respiratory mechanic could result in a suboptimal lung recruitment (atelectasis) or in alveolar overdistension (increased lung stress).[9,10] Moreover, the elevated PEEP values recommended in the higher FiO_2 range may worsen ventilation to perfusion ratio (increase in dead space fraction), with a detrimental effect on right ventricular function (increase in afterload and pulmonary hypertension) possibly until acute Cor Pulmonale.[11] However, testing high PEEP levels in patients

Table 1: ARDSnet ventilation-guide panel to select higher PEEP/lower FiO_2 values.[8]

FiO_2	0.3	0.3	0.3	0.3	0.3	0.4	0.4	0.5	0.5	0.5–0.8	0.8	0.9	1.0	1.0
PEEP	5	8	10	12	14	14	16	16	18	20	22	22	22	24

(PEEP: positive end-expiratory pressure).

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requiring higher FiO_2 may be considered as a reasonable option, especially in the emergency setting.

Highest Compliance

Assuming Crs as an index of lung response to mechanical recruitment, PEEP is set to the value corresponding to maximal Crs. Both increasing and decreasing PEEP value beyond this point will worsen Crs by overdistension or derecruitment, respectively.

The clinical protocol, in brief, might be as follows:

- A recruitment maneuver is performed.
- Static compliance (that is Vt/Pplat-PEEPtot, at the end of a 4 seconds end-inspiratory hold) should be measured after each 2–3 cmH_2O PEEP decrease of 2–3 cmH_2O from a level usually corresponding to 20–25 cmH_2O.
- The PEEP level to which corresponds the highest static Crs will be set in the ventilator.

This approach has been recently questioned from both a physiological point of view (mismatch between the highest static compliance and the best gas exchanges) and from a clinical perspective (increased mortality in ARDS patients group treated with this approach vs. standard lower PEEP levels).[12]

Transpulmonary Pressure

Transpulmonary pressure (P_L) results from the difference applied across the lungs at any time-point during the respiratory cycle (Fig. 2). P_L is calculated as the difference between airway pressure (Paw, in dynamic conditions) or pressure inside the alveoli (approximated to Pplat plus total PEEP, in static conditions) and pleural pressure (which cannot be directly measured, being the esophageal pressure a reasonable surrogate). Thus, esophageal pressure catheter placement and esophageal pressure traces monitoring are needed in order to measure P_L.

Negative end-expiratory P_L (P_L <0 cmH_2O) increases the risk of alveolar derecruitment and atelectasis, whereas high end-inspiratory P_L (>25 cmH_2O) leads to alveolar overdistension, with additional VILI. Based on these observations, a bedside method to select optimal PEEP has been implemented:[13]

- PEEP is set to keep end-expiratory P_L around 0–10 cmH_2O;
- Or the highest PEEP yielding end-inspiratory $P_L \leq 25$ cmH_2O, which will also be associated with the least negative end-expiratory P_L.

Another approach to set PEEP, ever based on P_L, distinguishes the measure of respiratory system elastance from the measure of lung elastance (Ers and E_L, respectively), in order to calculate the percentage of airway pressure applied to lung parenchyma at the end of inspiration.[14] In details:

- End-inspiratory P_L is calculated as
$$P_L = Pplat \times E_L/Ers$$
- PEEP is set to obtain an end-inspiratory $P_L \leq 25$ cmH_2O.

The method of titrating PEEP according to the P_L values has a strong physiological rationale: P_L measures de facto the mechanical stress applied to the lung under mechanical ventilation, allowing personalized rather than average PEEP selection. However, technical limitations of esophageal pressure monitoring and assumptions about pleural pressure value at zero airway pressure might limit their validity.[15]

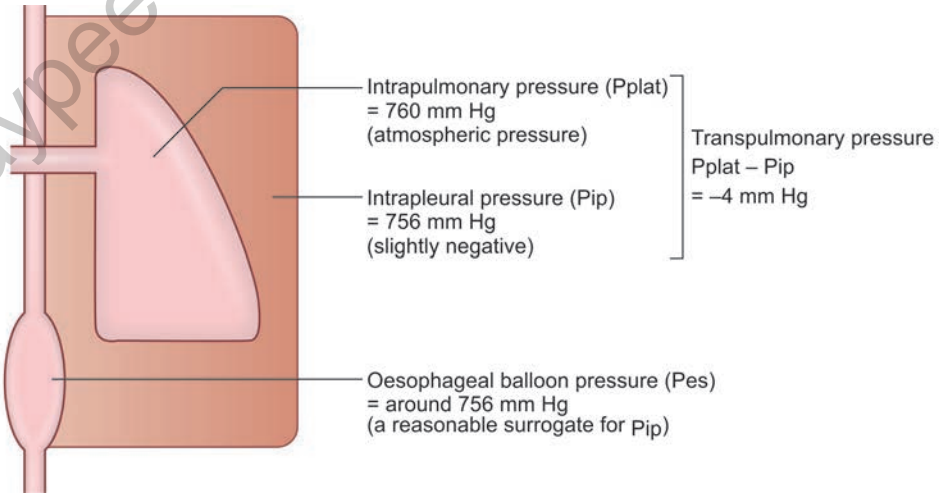

Fig. 2: Physiological pressures of respiratory system.

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Evaluation of Lung Recruitment by CT Scan

It is possible to determine the optimal PEEP through the evaluation of thoracic CT scans performed in ARDS patient, at different pressure levels. For example, a significant reduction of nonaerated lung area after a recruitment maneuvers at 45 cmH_2O, could indicate that high PEEP level is preferable[16] (Fig. 3). However, CT remains an undesirable option because of excessive exposure to radiations, as well as the logistics and the necessity of dynamic PEEP titration along the ventilation time-course.[17] Conversely, CT is useful to set PEEP in patients needing repeated scans for clinically unsolved issues.

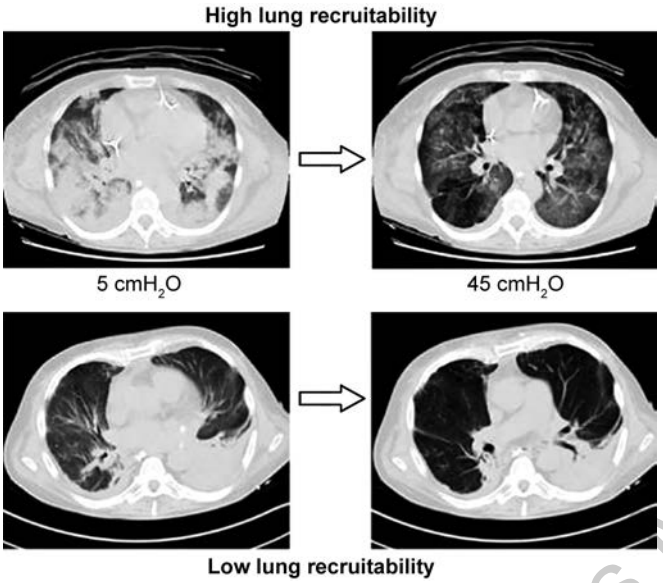

Fig. 3: Example of lung CT scan of patients with high or low potential of lung recruitment. Arrows depict the morphologic change from a condition of low airway pressure (i.e. 5 cmH_2O), to one of high airway pressure (i.e. 45 cmH_2O). Higher PEEP should be considered in the case of high recruitability. (modified with permission from: Umbrello M. et al. Int J Mol Sci 2017).

Electrical Impedance Tomography as Measure of Improved Regional Respiratory Mechanics

Electrical impedance tomography (EIT) is a new, noninvasive imaging method, based on changes in electrical properties of a section of chest tissues, induced by the respiratory cycle. The data are inferred from a series of superficial skin electrodes (belt) measurements and are used to create dynamic tomographic image of the examined lung portion (around half of the whole lungs in an adult) (Fig. 4). Assessing the dynamic changes in electrical impedance of different thoracic regions allows regional measure of ventilation. Indeed, EIT is useful primarily in the evaluation of air distribution across the lung (i.e. detection of ventilation dyshomogeneities), as well as changes in dependent and nondependent regional lung compliance. PEEP level associated with the more homogenous air distribution (reduced regional stress) + improvement of lung compliance in dependent regions (recruitment) + no changes of lung compliance in nondependent region (no overdistension), could be chosen as the optimal PEEP.[18] At last, through EIT use, it is possible to obtain radiation-free dynamic lung images during mechanical ventilation, allowing quicker real time adjustments in ventilation parameters.[19]

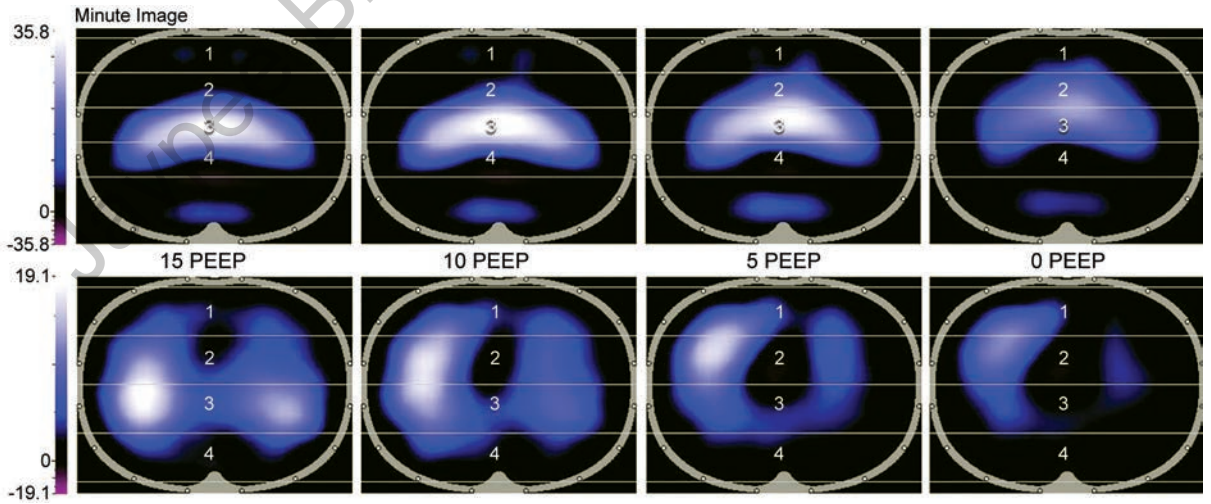

Fig. 4: Electrical impedance tomography images, showing the distribution of ventilation at different PEEP levels. Different PEEP are tested to detect the one associated with the lowest heterogeneity in air distribution across the lung.
Source: Bikker IG, et al. Crit Care 2011;15(4):R193.

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DRIVING PRESSURE

Mechanical ventilation is a well-recognized cause of lung damage; it is better known as VILI.[20,21] The first mechanism of VILI is the alveolar wall rupture because of excessive distension during ventilation (volutrauma). Volutrauma depends on the interaction between the size of tidal volume and the size of residual ventilated lung.[21] Pneumothorax, subcutaneous emphysema, pneumomediastinum, and gas embolism are further complications. Given that Crs is strongly correlated to the end-expiratory aerated volume during acute lung injury, airway driving pressure expresses Vt normalized to functional lung, representing a simple bedside assessment of lung strain. Driving pressure (ΔP) may be routinely calculated during controlled ventilation (no-inspiratory efforts) as follows: Pplat minus total PEEP. Then, ΔP reflects the sum of cyclic deformations of lung parenchyma imposed on ventilated, preserved alveolar units. Cyclic strain predicts pulmonary injury better than Vt per kilogram of ideal body weight, likely because the size of functional lung during a disease state, is better expressed by Crs than by ideal body weight. Cyclic strain, VILI, and survival index should all be correlated with ΔP rather than with Vt.[22] Driving pressure <15 cmH_2O minimizes lung strain and, in ARDS patients, this threshold is strongly associated with improved long-term survival.[23]

ESOPHAGEAL AND TRANSPULMONARY PRESSURE

Esophageal pressure (Pes) is a surrogate of pleural pressure (Ppl) and is measured using a dedicated catheter equipped at the tip with an esophageal balloon. Paw minus Pes is an accurate estimation of transpulmonary pressure (P_L) in surrounding balloon catheter region. Respiratory mechanic, lung volume, lung and chest elastance, abdominal pressure, posture, esophageal smooth muscle wall contractions, and intrinsic balloon properties can influence Pes absolute values. Moreover, pleural pressure, and thus esophageal pressure, changes within the pleural space due to both gravitational gradients and lung regional inhomogeneity. However, data from literature suggest that Pes remains an effective, acceptable surrogate of mean Ppl. To this end, the correct placement and the adequate inflation of the esophageal balloon cover a primary role. The esophageal balloon must be placed in the lower third of esophagus. To be sure about the correct catheter positioning, two tests may be performed—(1) Positive pressure occlusion test by compressing the thorax of a passively-ventilated patients, during an end-expiratory pause and (2) Baydur test is performed in pressure support ventilation through airway occlusion during an inspiratory effort. Specifically, in the first case, sedated and paralyzed patients are subjected to an external manual pressure on the rib cage and esophageal and airway pressure changes are recorded during the expiratory pause (positive pressure occlusion test). In the second case, during spontaneous breathing, an inspiratory pause is performed and the subsequent esophageal pressure swings are recorded. In both cases, a ratio between the changes in esophageal and airway pressure (ΔPes/ΔPaw) close to unity, validates the correct catheter positioning.

The difference between Paw and Ppl defines the transpulmonary pressure (P_L). P_L allows to separate the pressure delivered to the lungs from the one acting on chest wall and abdomen.[24,13] P_L is the measure of the stress applied by mechanical ventilation onto parenchymal lung structures, thus representing one of the main determinants of VILI. Measuring P_L at patient's bedside is a useful guide in ventilation settings, ranging from the choice of the optimal PEEP (see above) to the reduction of Pplat and the selection of a personalized driving transpulmonary pressure, with a potential impact on ARDS survival.[25]

LUNG STRESS AND STRAIN

Lung stress and strain are the main determinants of VILI, resulting both from an excessive transpulmonary pressure (stress) and from a dearranged ratio between lung volume variations and functional residual capacity (strain). In physic, stress reflects the internal distribution of the counterforces per unit area, as reaction and balance to an external load; translated to the lung, stress corresponds to the lung distending pressure. Strain is defined as the system deformation divided by the initial condition and reflects the relationship between tidal volume and the mechanical characteristics of lung ventilated-area. Stress and strain are reciprocally linked, as showed by the formula:

$$\text{Stress} = k \times \text{strain}$$

This equation, referred to the respiratory system, becomes:

$$\text{Transpulmonary pressure } (P_L) = k \times VT/FRC$$

Then, higher transpulmonary pressures correspond to larger deformation of the lung. The best clinical surrogates of stress and strain are: (1) P_L calculated as Paw – Pes and (2) ΔP calculated as Pplat – PEEPtot. Again, transpulmonary and driving pressure might be key to decrease the risk of VILI in patients suffering from acute hypoxemic respiratory failure.

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INSPIRATORY PRESSURE DURING SPONTANEOUS BREATHING

In spontaneously breathing patients, lung stress and strain largely depends from patient's inspiratory efforts rather than from mechanical ventilation settings.[26] Thus, the measurement of pressures closely reflecting the patient's effort, is fundamental to set protective assisted mechanical ventilation.

Airway Occlusion Pressure (P0.1)

The airway occlusion pressure (P0.1) is the pressure developed in an occluded airway within 100 msec after the beginning of inspiration.[27] P0.1 is a good measure of respiratory center output, (i.e. patient's respiratory drive), even in the presence of respiratory muscles fatigue. High P0.1 values (>5 cmH_2O) indicate insufficient levels of support and the risk of acute exhaustion, while lower values (<2 cmH_2O) reflect an excessive respiratory assistance by the ventilator, both during assist-controlled and spontaneous modes of ventilation.[28]

Inspiratory Muscle Pressure Index (PMI)

During assisted mechanical ventilation, the difference between airway pressure right before the beginning of an inspiratory occlusion (Ppeak) and the end-inspiratory elastic recoil plateau pressure (Pplat) reflects the end-inspiratory muscle pressure (Pmus), which is correlated with the intensity of inspiratory effort. This difference is named Pmus index (PMI).[29] A PMI threshold of 6 cmH_2O is the level of inspiratory effort currently considered as reasonable clinical target.

Esophageal Pressure Swing (ΔPes)

ΔPes is the difference between Pes measured at the end of expiration and Pes measured at the end of inspiration. ΔPes defines the dynamic pressure change across the lungs, applied by the active patient's inspiratory activity. Measuring ΔPes allows accurate estimation of dynamic driving transpulmonary pressure (by adding the dynamic airway driving pressure) (Fig. 5) and of the inspiratory patient's effort, with 15–20 cmH_2O and 5–8 cmH_2O as acceptable thresholds, respectively.[30]

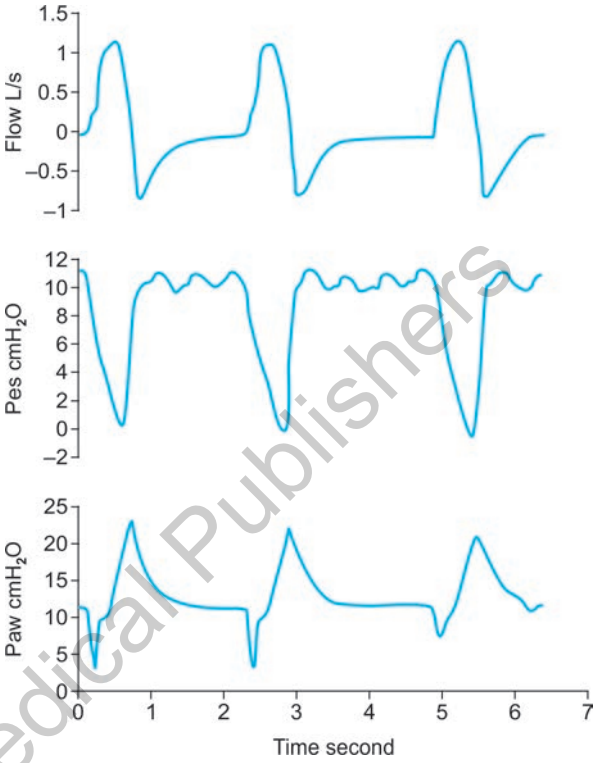

Fig. 5: Example of Flow, Paw and Pes swings during pressure support ventilation.

SALIENT POINTS

- Measuring bedside ventilation pressures of a patient in mechanical ventilation gives to clinician an array of powerful tools to understand the severity of the disease and select the most appropriate settings to decrease the risk of additional injury and ventilation failure.
- In ARDS patients, a PEEP level balancing alveolar recruitment and overdistention should be sought. Recruitment maneuvers and higher PEEP levels are useful in order to obtain a lung protection and not just to improve oxygenation.
- Driving pressure represents the Vt corrected for the Crs. In ARDS, using driving pressure may be a more accurate way to select Vt and minimize lung strain during mechanical ventilation.
- Transpulmonary pressure is computed as the difference between airway pressure and pleural pressure and allows to differentiate the pressure loads onto the lung and chestwall. High transpulmonary pressure indicate high lung stress and increased risk of VILI.
- In patients on spontaneous breathing, effort is the main determinant of transpulmonary pressure and long-term endurance, thus close monitoring should be applied to fully exploit the benefits associated with active inspiration.

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