The utility of esophageal pressure measurement in patients with acute respiratory failure

Utilitatea măsurării presiunii esofagiene la pacienții cu insuficiență respiratorie acută

Abstract

Esophageal pressure ($P_{es}$) measurement offers a good estimate of the respiratory variability of the pleural pressure. It is a minimally invasive method that can be used at bedside to quantify the respiratory effort and to determine the transpulmonary pressure. It can measure the intensity of spontaneous breathing and calculate the respiratory muscle effort known as the work of breathing (WOB). It has been used initially as a research tool to study the chest wall and lung mechanics in healthy subjects, but also in patients with acute lung injury. It has also been used in the clinical diagnostic recording of sleep. $P_{es}$ is usually measured by inserting a catheter with an air-filled latex balloon in the esophagus via the nose or the mouth. Recent studies have demonstrated that $P_{es}$ measurement can be useful in the management of patients with acute respiratory failure (ARF) who require invasive mechanical ventilation. Due to the fact that it can detect patient-ventilator asynchronies and assess respiratory muscle effort, $P_{es}$ measurement can improve patient-ventilator interaction and optimize the process of ventilator weaning. Furthermore, it allows positive end-expiratory pressure (PEEP) titration, which avoids the deleterious effects of intrinsic PEEP and improves oxygenation in mechanically ventilated patients. In patients with ARF requiring non-invasive ventilation, $P_{es}$ measurement has been used as a research tool only, but benefits similar to those seen in invasive mechanical ventilation are to be expected and thus further studies are required to acknowledge this fact.

Keywords: pleural pressure, pulmonary mechanics, mechanical ventilation, invasive ventilation

Rezumat

Măsurarea presiunii esofagiene ($P_{es}$) este o metodă minim invazivă care permite estimarea variației respiratorii a presiunii pleurale. Aceasta poate fi efectuată la patul pacientului și permite cuantificarea efortului muscular respirator și determinarea presiunii transpulmonare. Cu ajutorul acestei tehnică poate fi măsurată intensitatea activității musculare din cadrul respirației spontane și poate fi calculat efortul respirator (work of breathing – WOB). Metoda a fost utilizată inițial în scop de cercetare și a permis investigarea mecanicii pulmonare și a cutiei toracice la persoane sănătoase, dar și la pacienți cu patologie pulmonară acută. De asemenea, este utilizată și în investigația sindromelor de apnee în somn. Tehnica de măsurare presupune introducerea unui câtre cu balon la nivelul esofagului pe cale orală sau nazală. Studii recente au demonstrat utilitatea măsurării $P_{es}$ la pacienții cu insuficiență respiratorie acută care necesită ventilator și cu ventilator de suport. De asemenea, această tehnică permite titrarea PEEP (positive end expiratory pressure), fapt ce permite evitarea efectelor nocive ale PEEP-ului întrins și optimizarea oxigenării la pacienții ventilizați mecanic. Măsurarea $P_{es}$ a fost studiată și la pacienții cu insuficiență respiratorie acută în care a fost utilizată în ventilația noninvasivă doar în scop de cercetare. Este probabil că beneficiile măsurării $P_{es}$ în ventilația noninvasivă să fie similare cu cele observate în ventilația mecanică invazivă, dar acest fapt necesită confirmare prin studii suplimentare.

Cuvinte-cheie: presiune pleurală, mecanică pulmonară, ventilație mecanică, ventilație invazivă

Introduction

Based on the assumption that pressure in the adjacent pleura is transmitted to the esophagus, esophageal pressure ($P_{es}$) monitoring, a minimally invasive respiratory method that has been used for decades (for the first time in 1949), has proved to be an accurate estimate of pleural pressure and consequently of transpulmonary pressure\(^{(1)}\). It has enhanced the knowledge regarding mechanical properties of the chest wall and the lung. Furthermore, it has led to a better understanding of the pathophysiological mechanisms of acute respiratory failure in mechanically ventilated patients.

$P_{es}$ measurement can provide a measure of the intensity of spontaneous effort and thus measure the work of breathing. This is especially useful in patients with acute respiratory distress syndrome in which esophageal pressure measurement has been shown to optimize and guide ventilator management, improving patient ventilator interaction and ventilator weaning\(^{(2,4)}\). It is also used during polysomnography to quantitatively assess the respiratory effort, aiding in the diagnosis of sleep-related diseases\(^{(5)}\).

Despite its proven usefulness, monitoring of $P_{es}$ is still rarely used in clinical practice, being more frequently seen as a research tool only. This may be related to technical difficulties such as insertion and proper positioning of the esophageal catheter, obtaining accurate readings and interpretation of measurements.

In this article we discuss the physiological background behind $P_{es}$ measurement and we focus on the description of the technique and the current clinical implementations of this method.
Physiological background

The respiratory system is comprised of lungs and chest wall, each of these components generating a certain load. Intrathoracic pressures must overcome this load to inflate the lungs. In spontaneous breathing, the contraction of respiratory muscles generates pressure (P_{mus} – muscular pressure), which results in lung inflation. The mechanical ventilation can completely substitute or assist the activity of respiratory muscles. In ventilated patients, the pressure generated by the ventilator (P_{aw} – airway pressure) and P_{mus} form the total pressure applied to the respiratory system (P_{total} = P_{aw} + P_{mus}). P_{total} must overcome the elastic and resistive opposing forces of the respiratory system to inflate the lung. This relation is expressed in the following equation (also called the equation of motion):

\[ P_{total} = P_0 + E_{rs} \times V + R_{rs} \times F(1) \]

where \( P_0 \) = P_{aw} at the beginning of the respiratory cycle (zero or positive value if intrinsic PEEP or PEEPi is present), \( E_{rs} \) = the respiratory system elastance, \( R_{rs} \) = the respiratory system resistance, \( V \) = the difference in volume between instantaneous volume and the relaxation volume of the respiratory system, and \( F \) is the airflow. (1) 

It has been shown that changes in P_{es} match the changes in pleural pressure (P_{pl}) applied to the lung surface (7). Transpulmonary pressure (P_{t}) is the difference between P_{aw} and P_{pl}, which is equivalent to \( P_{t} = P_{aw} - P_{es} \) (Figure 1). Given the fact that absolute P_{es} values can be influenced by many factors (lung volume, weight of the mediastinum, abdominal pressure, posture, etc.), they may not always reflect the exact absolute values of P_{pl}, but in the clinical setting variation of P_{es} (\( \Delta P_{es} \)) is considered to be equivalent to \( \Delta P_{pl} \) during stable conditions (8).

Elastance (also called elastic resistance) is a measure of the work needed to be generated by the respiratory muscles and/or ventilator to expand the lungs. It is equal to the change in pressure that is required to achieve one unit of volume change.

Elastance = \( \Delta P/\Delta V = 1/\text{Compliance} \)

\( E_{rs} = E_{cw} + E_{L} \), where \( E_{cw} \) is the elastance of the chest wall and \( E_{L} \) is the elastance of the lung. So, equation 1 can be expressed as:

\[ P_{total} = P_0 + (E_{cw} \times V) + (E_{L} \times V) + R_{rs} \times F \]

In conditions where there is no muscular activity (passive conditions), P_{mus} = 0 and consequently P_{total} = P_{aw}, where P_{aw} is generated and monitored by the ventilator. V and F are also measured by the ventilator. During end-expiratory occlusion maneuvers, F = 0 and in such a situation the equation will become:

\[ P_{aw} = P_0 + (E_{cw} \times V) + (E_{L} \times V) \]

As \( E_{cw} = \Delta P_{cw}/\Delta V \) and \( E_{L} = \Delta P_{L}/\Delta V \), P_{es} measurement (and consequently of P_{t}) is useful to estimate what fraction of P_{aw} is applied to overcome each of E_{cw} and E_{L}.

Figure 1. Representation of relevant pressures of the respiratory system.

\( P_{aw} \) – airway pressure or pressure generated by the ventilator; \( P_{es} \) – pressure at body surface; \( P_{pl} \) – pleural pressure; \( P_{alv} \) – alveolar pressure \( \approx \) = \( P_{aw} \) at 0 flow; \( P_{es} \) – esophageal pressure; \( P_{aw} \) – pressure difference across the chest wall; \( P_{t} \) transpulmonary pressure.
In conditions where there is respiratory muscle activity (i.e., spontaneous breathing effort) \( P_{\text{mus}} \) becomes an important component for the equation for motion (equation 1) and the estimation of \( P_{L} \) is only possible through \( P_{\text{es}} \) measurement.

The work of breathing (WOB) and the pressure-time product of the esophageal pressure (PTP es) allow for an estimation of the respiratory muscle effort which may provide useful information regarding ventilator efficiency in patients with invasive or non-invasive ventilation during spontaneous breathing. They can be calculated using \( P_{\text{es}} \) measurement.

WOB done in each respiratory cycle is considered as the area enclosed in the pressure volume loop and is graphically referred to as the Campbell diagram (Figure 2). Mathematically it is expressed as:

\[
\text{WOB} = \int \text{Pressure} \times \text{Volume}
\]

Elastic and resistive forces of the respiratory system must be overcome by the \( P_{\text{es}} \) swings during inspiration to allow air movement through the airways. These forces can be estimated by comparing the difference between \( P_{\text{es}} \) during active inspiration and \( P_{\text{es}} \) during passive conditions. \( P_{\text{es}} \) during passive conditions is measured on the pressure-volume curve when the respiratory muscles are completely relaxed and the airways are closed, and reflects the static recoil pressure of the relaxed chest wall (\( P_{cw} \)). \( P_{cw} \) can only be obtained during passive inflation (i.e., muscle paralysis). This measurement can be used later as a reference value when the patient recovers spontaneous breathing. In circumstances where passive inflation is not possible, \( P_{cw} \) is calculated using the equation that describes the elastic forces of the chest wall:

\[
P_{cw} = \frac{V_{t}}{2C_{cw}},
\]

where \( C_{cw} \) is the compliance of the chest wall, and it can be given a theoretical value (i.e., 4% of the predicted vital capacity per cmH\(_{2}\)O).

Consequently, \( P_{\text{mus}} \) can be expressed as:

\[
P_{\text{mus}} = P_{cw} - P_{\text{es}}
\]

and given the fact that \( W_{\text{mus}} \) (work performed by respiratory muscles) is expressed as:

\[
W_{\text{mus}} = \int (P_{cw} - P_{\text{es}}) \times \Delta V
\]

PTP es refers to the integral of pressure over time and can be expressed as:

\[
\text{PTP} = \int P \times \Delta t.
\]

Therefore, PTP es = \( P_{\text{mus}} \times T_{\text{mus}} \) (cm H\(_{2}\)O x seconds) with \( T_{\text{mus}} \) being the time of muscle contraction.

WOB is expressed in joules (J). One J represents the energy required to move 1L of air through a 10 cm H\(_{2}\)O pressure gradient. WOB can be either expressed as work per liter of ventilation (WOB per 1 breathing cycle divided...
by the tidal volume: 0.35J/L in healthy individual), or as work per unit of time (joules are multiplied per cycle by the respiratory rate to obtain the power of breathing: 2.4 J/minute in healthy individual)(13).

**Technique**

To measure $P_{es}$, a catheter or a small transducer must be inserted and correctly positioned in the esophagus(129). The most common technique is to use a catheter with an air-filled latex balloon at its sealed distal end and a pressure transducer at its proximal open end. The patient must be positioned in a semi-recumbent position. Small quantity of local anesthetic must be delivered to the nose and oropharynx to improve tolerance. The catheter is inserted through one of the nostrils. The catheter is then advanced into the stomach. The balloon must be inflated with a specific amount of air (ranging from 0.5 to 4 ml, depending on the catheter design) and the pressure transducer connected to a dedicated acquisition system (which may be part of the ventilator) or a patient monitoring system(126). A positive pressure deflection during spontaneous inspiration indicates that the balloon is in the stomach. The catheter has to be slowly withdrawn until a negative pressure deflection during inspiration is recorded, meaning that the balloon is in the esophagus(130). The estimation of $P_{pl}$ is most accurate when the balloon is in the lower third of esophagus. Another method of estimating the length required to reach the lower third of the esophagus is by using the Stanford formula for esophageal manometry: $0.228 \times \text{height (cm)}^{16}$.

After the recording has started, the validation of the measurement is required. The classic method of validating $P_{es}$ measurement is the dynamic occlusion test which measures the ratio of change in airway opening pressure during three spontaneous respiration cycles against a closed airway, regardless of patient cooperation. If $\Delta P_{es}/\Delta P_{aw}$ ratio is close to 1 (acceptable range: 0.8-1.2), than the measurement is valid(17). It can also be performed by applying manual chest compression during airway occlusion (for example, in paralyzed or sedated patients)(18).

It is important to underline that the amplitude of $P_{es}$ signal can be influenced by a series of factors such as patient position, lung volume, esophageal peristaltic and balloon position(19). Moreover, cardiac activity can distort the $P_{es}$ signal. Swallowing is not affected by the catheter and thus its position can be maintained for several days.

**Clinical use of $P_{es}$ – invasive ventilation**

In patients with severe acute respiratory failure who require invasive mechanical ventilation, monitoring and understanding patient-ventilator interaction are a key component of a successful treatment in the intensive care unit (ICU). The adjustment of ventilator settings is usually based on $P_{aw}$-flow waveforms, arterial blood gas analysis, and peripheral oxygen saturation. These parameters alone cannot properly determine the presence of patient-ventilator asynchrony(20), nor can they quantify respiratory muscle activity (the amount of WOB). Thus, excessive respiratory muscle work is difficult to detect(21,22).

By using $P_{es}$ real time measurement, the patient’s respiratory muscle activity and patient-ventilator synchrony during assisted ventilation can be accurately monitored. This can be useful in several potential deleterious situations. It can detect: ineffective or missed (wasted) respiratory efforts during assisted ventilation(23), excessive $P_{aw}$ and $V_{t}$ values during synchronized pressure-targeted ventilation modes especially when lung protective ventilation is desired(24), excessive flow or excessively short inspiratory time(25), respiratory muscle contraction triggered by the ventilator in sedated patients (respiratory entrainment)(26). Improving patient-ventilator interaction by adjusting ventilatory parameters such as inspiratory pressure, $V_{t}$, inspiration time, mandatory respiratory rate, etc. can lead to shortening of the duration of mechanical ventilation.

Another important issue in mechanical ventilation is the failure to detect or correctly estimate intrinsic PEEP (PEEPi), an event that is common in severe COPD or asthma exacerbation. It can lead to increased WOB, barotrauma, inappropriate ventilator triggering, hemodynamic instability and shock in mechanically ventilated patients(27). Before any volume of air can be displaced within the lung, an amount of pressure equal to PEEPi has to be generated. $P_{es}$ measurement is the most accurate method of quantifying PEEPi. The value of PEEPi is the drop in $P_{es}$ at end of the expiration, when the inspiratory muscles contract right before inspiratory flow starts(28).

Weaning, the process of removing the patient from mechanical ventilation and endotracheal intubation, must be considered as early as possible, as prolonged mechanical ventilation is associated with increased morbidity and mortality(29). During the weaning trial, estimation of WOB through $P_{es}$ measurement can be extremely useful. Studies have shown that progressive increase in PTP$_{es}$ is associated with weaning failure, while lack of change in PTP$_{es}$ is seen in weaning success patients(30). Moreover, during spontaneous breathing, change in PTP$_{es}$ during weaning is associated with acute left heart failure(31). Thus, $P_{es}$ measurement could be a simple tool in monitoring patients during weaning and may provide early signs for failure, giving time for therapeutic intervention and avoid reintubation.

Lastly, $P_{es}$ measurement has proved to be a useful tool in improving ventilator parameters in patients with ARDS in the Esophageal Pressure-Directed Ventilation study (EPVent) (27). $P_{es}$ strategy led to a higher PEEP at 72 hours (18 ± 5 cm H$_2$O vs. 12 ± 5 cm H$_2$O in the control arm). Despite failing to show any significant change in ventilator-free days, length of stay or duration of ventilation, $P_{es}$ strategy markedly improved arterial oxygenation and respiratory system compliance when compared to the control arm which used a standard protocol for adjusting ventilator parameters. Consequently, $P_{es}$-based adjustment of ventilatory parameters has been integrated in some ICU ventilators.

**Clinical use of $P_{es}$ – non-invasive ventilation**

There are only a few studies regarding $P_{es}$ measurement in patients with acute respiratory failure requiring non-invasive ventilation. All have used $P_{es}$ measurement as a research tool to estimate WOB in order to compare
different ventilation modes: CPAP with bi-level ventilation in acute pulmonary edema or different types of non-invasive ventilation to spontaneous breathing in patients with severe COPD exacerbation.

As opposed to invasive mechanical ventilation, \( P_{es} \) monitoring has not been studied as a tool that could improve patient-ventilator interaction in non-invasive ventilation in patients with acute respiratory failure, although we believe it might prove to be of similar usefulness. The ability to quantify PEEPi, to detect patient-ventilator asynchrony, to adjust inspiratory/expiratory pressure and backup respiratory rate by estimating WOB could reduce NIV failure rate and thus improve morbidity and mortality. Furthermore, given the fact that the correct amount of NIV has not been studied in published trials and is based solely on blood gas measurement and the experience of the medical staff, \( P_{es} \) measurement could provide useful information in the process of weaning from NIV.

Conclusion

\( P_{es} \) monitoring is a simple method that allows a better understanding of respiratory mechanics. It can provide valuable information regarding the respiratory muscle effort in an acute setting. It can be safely performed at the bedside inside and even outside of ICU. Besides its value as a research tool, it has proven its usefulness in the clinical setting in mechanically ventilated patients, being able to quantify the level of muscle unloading during ventilation or during weaning trial. It is also useful in titrating PEEP and provides better ventilation strategy in ARDS patients.

Despite this, \( P_{es} \) measurement in patients with ARF requiring ventilatory assistance (either invasive or non-invasive) is surprisingly low, with little data being published regarding the use of \( P_{es} \) in acute non-invasive ventilation.

While \( P_{es} \) measurement has been demonstrated to improve ventilator management in intubated patients with ARF, further research is required to ascertain the benefits in non-invasive ventilation.