Pleural and transpulmonary pressures during invasive mechanical ventilation in children

ONLINE SUPPLEMENT

Methodology for research

To be included in this review, the articles needed to focus on the technical aspects and applications of esophageal (P_{ES}) and transpulmonary (P_L) pressures measurements in the (pediatric) intensive care unit (P)ICU, be written in English, and involve human participants. Both adult and pediatric studies were eligible. We deliberately chose to keep the most relevant studies performed in adult population, which are considered as *princeps* articles. Papers were excluded if they concerned patients treated with noninvasive ventilation (NIV). Neonatal studies were excluded because the technique has not been validated in neonates especially preterms, and this very specific population cannot be compared with older children in terms of physiology and management. We also excluded studies focused on esophageal manometry and transpulmonary pressure in another field than acute respiratory disorders, or on respiratory muscle function outside of ICU. We included all observational, interventional, retrospective and prospective studies, case-series and reviews.

The research strategy was performed on Pubmed/Medline and Embase bibliographic databases for studies published until September 2021, using the following key-words:

- For Pubmed/Medline

(("mechanical ventilation" OR ventilator OR ventilators OR "Respiration, Artificial"[Mesh] OR "Respiratory Distress Syndrome" OR "Artificial Respiration")) AND ("esophageal pressure" OR "oesophageal pressure") AND (English[lang])

- For Embase

('esophagus pressure'/exp) AND 'artificial ventilation'/exp AND ([english]/lim) AND [embase]/lim NOT ([embase]/lim AND [medline]/lim)

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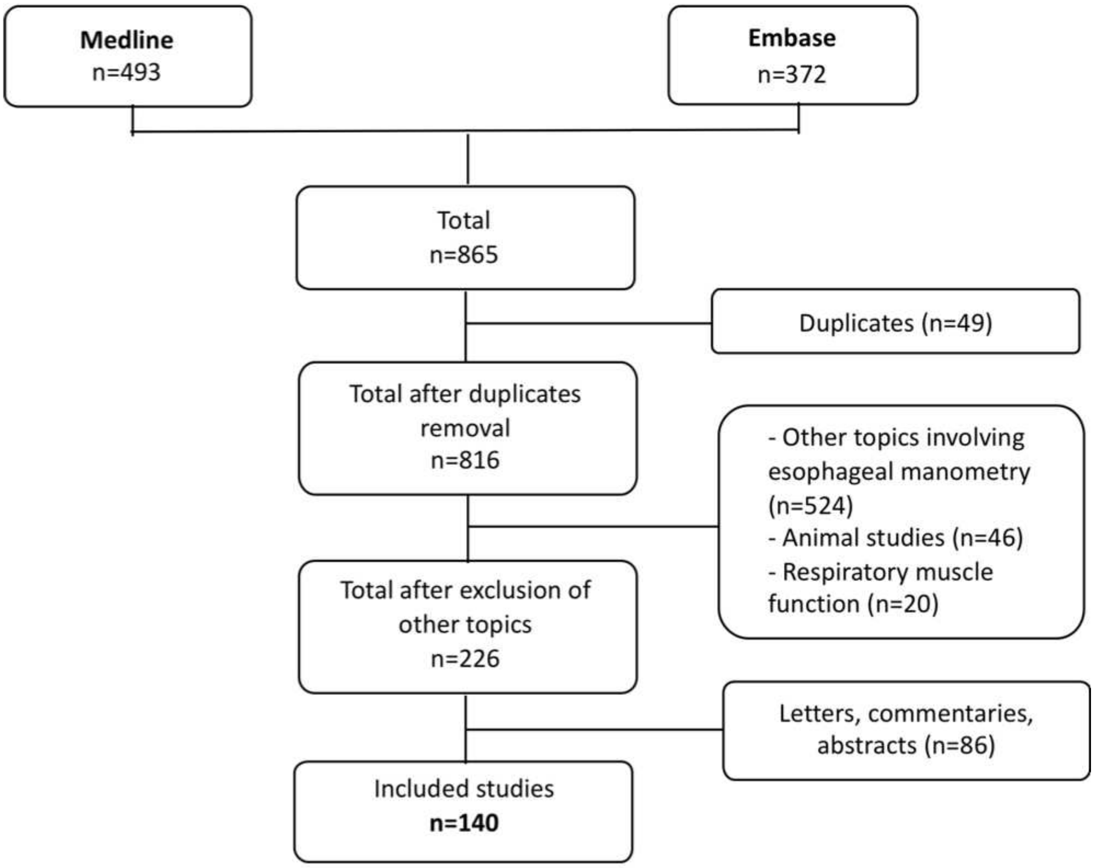
One author (MV) removed the duplicates, performed a first manual screening of the titles and abstracts, and secondarily excluded the editorial, comments, and non-published abstracts. We grouped the studies by topic, and summarized the type of settings and populations, study design, main objectives and outcomes, and results. Results were presented in all children without subdivision into age groups, due to the lack of evidence and reference values in pediatric literature.

Extracted studies flow-chart

Supplemental figure 1: Studies flow-chart



Detailed method for the insertion of the catheter, the measurement of P_{ES}, and the calculation of P_L

Insertion and measurement

First, the catheter balloon has to be totally emptied before insertion. After local anesthesia, the catheter is inserted nasally or orally, with the patient placed in a semi-recumbent position (supine position 30°), until the catheter balloon reaches the stomach. Appropriate placement of intragastric balloon may be estimated with the « Nose-Earlobe-Xiphoid process-Midline of the Umbilicus (NEMU) » method (1). The balloon is then inflated with the maximum volume of air to avoid folds of the balloon, and then deflated until 0.5 mL of air remains, and the catheter is connected to a pressure transducer, which is in turn connected to a dedicated acquisition system, or to the ventilator. Intragastric position of the balloon is confirmed by the visualization of a positive pressure deflection during SB (active condition) or during gentle external compression of the abdomen (passive condition). The catheter is then gradually withdrawn up to the intrathoracic lower-mid esophagus: cardiac artifacts appear or increase, which may attenuate the esophageal waveform. The accurate position is obtained when the catheter balloon reaches the intrathoracic position, either because the positive P_{ES} deflection becomes negative (active condition), and/or because the baseline of the waveform may suddenly change (passive condition). Another way that may help to confirm the correct position of the catheter balloon is to look at the P_{ES}/Volume curve, which should be linear, and the P_{ES}/Airway pressure (P_{AW}) loop, which should be nonlinear and show hysteresis due to the resistive properties of the airways (2).

At this step only, the balloon can be accurately filled with a calibrated amount of air (calibration procedure or filling test) (Figure 2.A). After having completely emptied the balloon, the balloon is progressively inflated with steps of 0.1 to 0.2 mL of air, with a simultaneous observation of the ΔP_{ES} tracing after a few seconds for pressure stabilization.

These low volume levels are particularly important in children because pediatric catheters have a small length and diameter (3). Inflation is performed until the visualization of a sudden and important increase of the baseline tracing, which corresponds to the amount of injected air close to the one leading to overdistension of the balloon. The “optimal filling volume” is the lowest one associated with the maximal ΔP_{ES}, reflecting the volume where the esophageal elastance (E_{ES}) is minimal (3, 4). The procedure is then finished by inflating the balloon with the maximum volume of air, followed by a progressive deflation until the “optimal filling volume”.

The validation of the balloon’s position is performed through a dynamic occlusion test consisting in three to five airway expiratory occlusion maneuvers (Figure 2.B). During an active condition, the ratio between ΔP_{ES} and ΔP_{AW} ($\Delta P_{ES}/\Delta P_{AW}$) is measured during SB against a closed airway, whereas during a passive condition, it is measured during gentle manual compression on the chest while performing an airway occlusion (5). As lung volume does not change during a no-flow condition, if the balloon is well positioned, the variations of ΔP_{AW} are only reflected by ΔP_{ES}, and the ratio approaches unity (0.8-1.2), indicating that P_{ES} provides a valid measure of pleural pressure (P_{PL}) (6).

Calculation of P_L

P_L, the transmural pressure of the lung (P_{AW} minus P_{PL}), is estimated by substracting P_{ES} from P_{AW} (*direct-method*). However, as P_{ES} does not equal P_{PL} over the entire lung, the calculation of P_L with the direct-method may lead to misinterpretations of lung mechanics. Other methods have thus been proposed. The *released-method* has been developed to measure P_{ES} at the atmospheric pressure (P_{ATM}) rather than at PEEP, assuming that P_{PL} equals zero at P_{ATM} (7). However, this technique requires a disconnection from the ventilator, which might be challenging. The *elastance-derived method* is based on the principle that during inflation, P_L depends on the changes of P_{ES} and P_{AW} rather than on their absolute value. As these variations are linear, P_L might be calculated as $P_L = P_{AW} * E_L/E_{RS}$ and represents the proportion of P_{AW} required to inflate only the lungs (8).

Recently, Yoshida *et al.* measured P_{ES} and P_{PL} in the dependent and non-dependent lungs of pigs and human cadavers. Inspiratory P_L calculated from the elastance-derived method reflected the values measured in the non-dependent regions, and inspiratory and expiratory P_L calculated from the direct-method reflected values in the dependent regions (9). Even if these results have not been reproduced in patients yet, this study provided new insight on the use of P_L-targeted ventilatory strategies in the heterogeneous lung, in particular for (Figure 2C):

i) PEEP titration: in order to maintain positive end-expiratory P_L, avoid collapse, and atelectrauma of the mid-posterior lung, the direct-method is recommended;

ii) Protective ventilation: in order to limit end-inspiratory P_L, avoid excessive lung stress, and volutrauma of the anterior lung, the elastance-derived method is recommended. In adults, end-inspiratory P_L should be limited to 20-25 cmH_2O and ΔP_L to 10-12 cmH_2O (10).

References

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