Novel method of transpulmonary pressure measurement with an air-filled esophageal catheter

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Methodologies

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Abstract

Background

There is a strong rationale for proposing transpulmonary pressure-guided protective ventilation in acute respiratory distress syndrome (ARDS). The reference esophageal balloon catheter method requires complex in vivo calibration and dedicated ventilator with auxiliary pressure port. A simple, inexpensive, accurate and reproducible method of measuring esophageal pressure would greatly facilitate the measure of transpulmonary pressure to individualize protective ventilation in the intensive care unit.

Results

We propose an air-filled esophageal catheter method without balloon, using disposable catheter and transducer that allows reproducible esophageal pressure measurements, and that does not require any specific ventilator equipment. We use a 49 cm-long thin low compliance polyvinyl 10 Fr suction catheter, positioned in the lower third of the esophagus and connected to an air-filled disposable blood pressure transducer bound to the monitor. To guarantee air transmission, the transducer is pressurized by an air-filled infusion bag allowing its integrated flush device to deliver continuous air flow and to obtain a stable esophageal waveform. Calibration requires simple zeroing the transducer open to atmospheric pressure. Esophageal pressures recorded on the monitoring are expressed in mmHg and need to be converted in cmH$_2$O. We tested our novel method in 10 consecutive intubated patients with severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) infection. We calculated the target transpulmonary pressures for protective lung and diaphragm ventilation, both in passive and spontaneously breathing conditions. Esophageal to airway pressure change ratio was close to one in both conditions (median [P25;P75] = 0.94 [0.92;1.00] and 0.98 [0.96;1.01]). We adjusted ventilator settings towards recommended pressure targets to limit atelectrauma, barotrauma, inspiratory effort and lung stress, by modifying positive end-expiratory pressure, tidal volume, or inspiratory pressure accordingly.

Conclusions

We propose a simple, inexpensive and reproducible method for esophageal pressure monitoring with an air-filled esophageal catheter without balloon. It holds the promise of widespread bedside use of transpulmonary pressure-guided protective ventilation in patients with ARDS.

Background

There is a strong rationale for proposing transpulmonary pressure (P$_L$)-guided protective ventilation in acute respiratory distress syndrome (ARDS) [1–4]. The ARDS lung is modeled in two regions, one consolidated and collapsed, responsible for the impairment of oxygenation, and one functional region called “baby lung”. This latter region is also inflamed, responsible for the ARDS mechanical
characteristics, and at risk for evolving ventilator-induced lung injury [5, 6] and patient self-inflicted lung injury [7]. To limit global lung stress, lung and diaphragm-protective ventilation starts by limiting tidal volume (Vt) and thereby airway driving pressure (ΔP) [8], with greater mortality benefit recently demonstrated in ARDS patients with higher driving pressures and respiratory system elastance values [9]. However, this airway pressure (Paw) approach does not take into account altered chest wall elastance (Ecw) [10], often increased in critically ill patients with extrapulmonary ARDS [11], nor end-inspiratory, end-expiratory and driving transpulmonary pressures all triggering the VILI. Driving P_{L} (ΔP_{L}) is the real global distending force stressing the lung [12]. End-expiratory P_{L} (P_{L}\text{ee}) , elastance-derived end-inspiratory P_{L} (P_{L}\text{ei,ER}) , pleural pressure swing and transpulmonary pressure swing (ΔP_{L}\text{dyn}) are demonstrated as key determinants of atelectrauma in mid-to-dependent zones, barotrauma/volutrauma in non-dependent zones, inspiratory effort and dynamic lung stress, respectively [13]. Also, to optimize protective ventilation and to quantitatively confirm its protective settings, taking lung stress, respiratory effort, potential dyssynchrony, Ecw and lung elastance (El) into account [1, 14], we need to monitor both airway and pleural pressures. Esophageal pressure (Pes) is a well-known surrogate of the pleural pressure [3]. The difference between airway and Pes, the esophageal pressure swing (ΔPes) divided by Vt and the ΔP_{L} divided by Vt are valid estimates of P_{L} , Ecw and El, respectively [3]. Therefore, a simple, inexpensive, accurate, and reproducible method of measuring esophageal pressure reflecting pleural pressure would greatly facilitate protective ventilation in the intensive care unit. While the esophageal balloon catheter method requires a thick 10cm-long balloon catheter, complex in vivo calibration [15], dedicated ventilator equipment and delivers discontinuous esophageal monitoring, our new methodology simplifies greatly the approach.

Methods

An adapted air-filled esophageal catheter method without balloon, using disposable catheter and transducer allows reproducible esophageal pressure measurements, without specific ventilator requirements.

1. Materials:

Here we use a disposable low compliance polyvinyl esophageal suction catheter, originally intended for oral, nasopharyngeal or tracheobronchial suctioning, of 49 cm long, 10Fr and 3.3-2.0 mm outer-inner diameters. As shown in Figure 1a, the catheter is connected via a Luer-lock transfer connector to an air-filled disposable blood pressure transducer bound to the monitor. The transducer is identical to the one intended for blood pressure monitoring and contains a flush device delivering a continuous flow of 3 mL/h with a differential pressure of 200 mmHg between infusion bag pressure and physiological pressure monitored. A one-liter saline infusion bag is emptied, backfilled with air and pressurized over 250 mmHg by a pressure bag and connected to the air-filled IV set with drip chamber and roll clamp. Air-labeled flags are disposed along the air-filled pressure line for safety.

2. Placement of the esophageal catheter:
To facilitate the nasal or oral placement of the esophageal catheter and its visualization on chest X-ray, a siliconized guide wire of nasogastric enteral feeding tube is temporarily inserted in the catheter and bended to match desired length. The catheter follows the naso- or orogastric feeding tube if present, until its extremity is positioned first in the stomach. The pressure transducer line is connected to the catheter with the appropriate connector, and the roll clamp on the infusion set is opened to allow continuous flush and signal. A stable pressure waveform is then visualized. Proper gastric position is confirmed by auscultation of a 10 mL of air flush and by observation of positive deflections on waveform during inspiration or when gentle stomach compressions are imposed. The catheter is withdrawn to the lower third of the esophagus, taking a nasal-tragus-xyphoid distance – 5 cm for nasal placement, and mobilized until esophageal waveform is confirmed by small cardiac artifacts and spontaneous inspiratory negative deflections.

3. Esophageal pressure measurements:

The open-ended catheter is flushed with air before starting to remove any distal secretion. The remaining air is then aspirated to prevent artifacts. The line is left open to air to equilibrate for a few seconds. One ml of air is injected to allow optimal pressure transduction. We record the zero with the transducer open to atmospheric pressure. Appropriate position of the catheter is confirmed in three ways, by chest X-ray with the guide wire, by visualization of cardiac artefacts on esophageal waveform, and by equivalent changes in esophageal and airway pressures during dynamic end-expiratory occlusion maneuver. In passive breathing condition, gentle external chest compressions are performed during expiratory occlusion. In active breathing condition, spontaneous efforts occur against occlusion. Esophageal to airway pressure change ratio (DPes/(DPaw)) should be close to one (± 10-20%). Values are recorded in mmHg and converted in cmH$_2$O. Cost of our novel method is 17.6€ for one complete disposable circuit.

4. Diaphragm and lung-protective ventilation:

In passive breathing condition, supine patients are sedated and ventilated in volume control mode. End-inspiratory and end-expiratory occlusions are performed to obtain plateau airway pressure (Pplat), plateau esophageal pressure (Pes,plat), total positive end-expiratory pressure (PEEPtot), end-expiratory esophageal pressure (Pes,ee), DP (DP = (Pplat – PEEPtot)) and DPe (DPe = (Pes,plat – Pes,ee)). Ecw (Ecw = DPe/Vt) is calculated as the ratio of DPe to Vt, El (El = Ers – Ecw) is obtained by subtracting Ecw from respiratory system elastance (Ers; Ers = DP/Vt). Elastance ratio (ER; ER = El/Ers) is the lung to the respiratory system elastance ratio. Three transpulmonary pressures are calculated, with potential therapeutic targets [1, 14]: i) elastance-derived end-inspiratory $P_\text{L}$ ($P_{\text{LEi}_{ER}}$, $P_{\text{LEi}_{ER}} = P_{\text{plat}} \times E_{\text{rs}}/E_{\text{rs}}$) < 20 cmH$_2$O; ii) end-expiratory $P_\text{L}$ ($P_{\text{L}}; P_{\text{L}} = (\text{PEEPtot} – \text{Pes,ee})$ > 0 cmH$_2$O; iii) driving $P_\text{L}$ ($D_{\text{P_L}}; D_{\text{P_L}} = (\text{DP} - \text{DPe}) = (P_{\text{plat}} – P_{\text{L}}) < 10-12$ cmH$_2$O.

In active condition, semi-recumbent patients are ventilated in pressure support mode with spontaneous inspiratory efforts. Peak airway pressure (Ppeak), inspiratory esophageal pressure (Pes,i), PEEP, end-expiratory esophageal pressure (Pes,ee), DPe (DPe = (Pes,i – Pes,ee)) and dynamic airway driving
pressure (DPdyn; DPdyn = (Ppeak – PEEP)) values are measured. Three transpulmonary pressures are also calculated, with potential therapeutic targets [1, 14]: peak PL (PLpeak; PLpeak = (Ppeak – Pes,i)) < 20 cmH₂O, DPes < -10 to -15 cmH₂O and dynamic PL swing (DPLdyn; DPLdyn = (DPdyn – DPes)) < 15 cmH₂O.

**Results**

After approval of our protocol by the local internal review board, a surrogate consent was obtained for 10 consecutive severe acute respiratory syndrome-coronavirus-2 (SARS-CoV-2) infected patients, intubated and mechanically ventilated for ARDS. Under passive breathing conditions, we calculated ΔP, ΔPes and partitioned elastances parameters, as well as PLeiER, PLee and ΔPL, to evaluate the risk of barotrauma in non-dependent zones, of atelectrauma in mid-to-dependent zones and the global lung stress, respectively (Fig. 1b; Table 1a). In active breathing conditions, we measured PLpeak, ΔPes and ΔPLdyn, to evaluate inspiratory stress, inspiratory effort and dynamic lung stress (Fig. 1c; Table 1b). Esophageal to airway pressure change ratio was close to one in both conditions (Table 1, Fig. 1b and 1c).
Table 1
Relevant pressures obtained in 10 SARS-CoV-2 ARDS patients in passive (1a) and active (1b) breathing conditions.

| Breathing condition | Ventilatory parameter          | Median (P25;P75)         |
|---------------------|--------------------------------|--------------------------|
| A. Passive (n = 10) | ΔPes/ΔPaw (ratio)              | 0.94 (0.92;1.00)         |
|                     | ΔP (cmH2O)                     | 12.7 (10.1;18.5)         |
|                     | ΔPes (cmH2O)                   | 2.7 (1.8;2.7)            |
|                     | Ers (cmH₂O/(ml/kg))            | 2.6 (1.6;3.5)            |
|                     | Ecw (cmH₂O/(ml/kg))            | 0.4 (0.3;0.5)            |
|                     | El (cmH₂O/(ml/kg))             | 2.1 (1.3;3.1)            |
|                     | ER (ratio)                     | 0.84 (0.77;0.90)         |
|                     | PLei,ER (cmH₂O)                | 22.2 (18.8;23.7)         |
|                     | PLee (cmH₂O)                   | -0.2 (-1.2;1.5)          |
|                     | ΔPL (cmH₂O)                    | 10.5 (8.4;16.6)          |
| B. Active (n = 7)  | ΔPes/ΔPaw (ratio)              | 0.98 (0.96;1.01)         |
|                     | PLpeak (cmH₂O)                 | 22.3 (20.2;23.2)         |
|                     | ΔPes (cmH₂O)                   | -19.5 (-23.6;-11.5)      |
|                     | ΔPL dyn (cmH₂O)                | 25.2 (22.7;27.3)         |

ΔP driving pressure, ΔPes esophageal pressure swing, ΔPes/ΔPaw esophageal to airway pressure change ratio, ΔPL driving transpulmonary pressure, ΔP_L dyn dynamic transpulmonary pressure swing, Ecw chest wall elastance, El lung elastance, ER lung to respiratory system elastance ratio, Ers respiratory system elastance, P_Lee end-expiratory transpulmonary pressure, P_Lei,ER elastance-derived end-inspiratory transpulmonary pressure, P_Lpeak peak transpulmonary pressure.

Discussion
The use of an air-filled esophageal catheter without balloon to measure esophageal pressure was only reported twice, to detect accidental esophageal intubation [16], and to measure esophageal pressure in pigs adapting a balloon catheter [17]. We describe here for the first time a method allowing stable and accurate P_L measurements, using a pressurized air-filled circuit made of disposable materials, and requiring only a simple calibration and flushing procedure, independently of any specific ventilator ports. The esophageal balloon method is the historical reference method but requires quite thick and expensive
material, time-consuming and sophisticated in vivo calibration [15], dedicated ventilator with auxiliary pressure port and delivers discontinuous esophageal monitoring. Our method provides stable continuous esophageal waveforms in both passive and active breathing conditions. In passive breathing conditions, elastance-derived end-inspiratory, end-expiratory and driving PL were recently validated as key pressures responsible for barotrauma/volutrauma in non-dependent zones [13], atelectrauma in mid-to-dependent zones [13] and the global lung stress [14], respectively. In active breathing conditions, peak end-inspiratory PL, esophageal pressure swing and transpulmonary pressure swing provide valid estimate of inspiratory stress, inspiratory effort and dynamic lung stress [1, 14]. Our method could help to adapt ventilator settings towards potential therapeutic targets from recent recommendations [2, 4, 14, 18], by modifying PEEP, Vt or inspiratory pressure accordingly.

Limitations of our method are its monocentric and small size pilot design. Next step will require multicentric validation on a larger cohort of patients and direct comparison with air-filled esophageal balloon catheter as the reference method. Even if esophageal pressure changes are valid estimate of pleural pressure changes, absolute esophageal pressure values should also be interpreted with caution. Using a high-resolution manometry catheter, a recent Swedish study [19] demonstrated a high variability of esophageal pressures along the esophagus, depending on complex interactions between patient’s position, lung and chest wall mechanics, part of the esophagus included as well as mediastinal weight and cardiac compression.

Conclusions

In summary, we propose a simple, inexpensive and reproducible tool for esophageal pressure monitoring using an air-filled esophageal catheter without balloon. It holds the promise of widespread bedside use of transpulmonary pressure-guided protective ventilation in patients with ARDS.

Abbreviations

ARDS Acute Respiratory Distress Syndrome

ΔP Airway driving pressure

ΔPaw change in airway pressure

ΔPdyn dynamic airway driving pressure

ΔPes change in esophageal pressure, esophageal pressure swing

ΔPes/ ΔPaw Esophageal to airway pressure change ratio

ΔPL Driving transpulmonary pressure, change in transpulmonary pressure

ΔPLdyn Dynamic change in transpulmonary pressure, transpulmonary pressure swing
Ecw Chest wall elastance

El Lung elastance

ER Elastance ratio of lung to respiratory system

Ers Respiratory system elastance

Paw Airway pressure

PEEP Positive End-Expiratory Pressure

PEEPtot Total PEEP

Pes Esophageal pressure

Pes,ee End-expiratory esophageal pressure

Pes,i Inspiratory esophageal pressure

Pes,plat Plateau esophageal pressure

\( P_L \) Transpulmonary pressure

\( P_{Le} \) End-expiratory transpulmonary pressure

\( P_{Lei_{ER}} \) Elastance-derived end-inspiratory transpulmonary pressure

\( P_{Lpeak} \) Peak end-inspiratory transpulmonary pressure

Ppeak Peak airway pressure

Pplat Plateau airway pressure

SARS-CoV-2 Severe Acute Respiratory Syndrome CoronaVirus 2

**Declarations**

Our study was performed in accordance with the Declaration of Helsinki and approved by the Belgian university hospital of Liege ethics committee (committee 707; reference 2012139). We obtained written informed consent of patients or next of kin before inclusion. The datasets used and analyzed during the current study are available from the corresponding author on reasonable request. There is no competing interests nor funding to declare. Each author made substantial contributions to the conception (PBM, NS, DL, PPM), acquisition, analysis and interpretation of data (PBM, JB, GP, DL) or draft and revision of the work (PBM, BL, DL, PPM). All authors read and approved the final manuscript. We warmly thank Mr Martin Cravatte for its precious drawing collaboration.
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