WHAT'S NEW IN INTENSIVE CARE

What's new in electrical impedance tomography

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Introduction

Electrical impedance tomography (EIT) is a dynamic, non-invasive, radiation-free, bedside lung imaging technique. Based on the application of alternate microcurrents spinning at 20–50 Hz along a set of electrodes (16 or 32, depending on the system) positioned around the patient's thorax, EIT allows continuous tomographic mapping of the changes in regional gas content inside the chest. This technique provides several relevant physiologic measures, including regional tidal volume, heterogeneity of ventilation distribution, gravitational distribution of respiratory system compliance, as well as pulmonary perfusion, cardiac output, and central intravascular volume status. We present here the most recent advances at the crossroad between physiologic understanding and clinical applications.

EIT to guide PEEP setting

In patients with the acute respiratory distress syndrome (ARDS), positive end-expiratory pressure (PEEP) is a critical component of protective mechanical ventilation. However, the effects of PEEP on aeration vary widely between patients and between different lung regions. Therefore, personalized PEEP setting, balancing regional alveolar recruitment and minimal overdistension, could fully exploit the clinical benefits of PEEP in each patient. To this end, EIT provides specific measures estimating regional recruitment and overdistension in a dynamic fashion (Fig. 1). In our opinion, the following recent findings have great potential for clinical relevance:

1. The PEEP level associated with the ratio between gravitationally non-dependent/dependent regional tidal volume closest to 1 (best homogeneity) could be selected to decrease regional lung stress raisers [1].

2. After an increase in PEEP, improvement of the regional respiratory system compliance in the most dependent lung regions is a sign of recruitment, especially in diffuse ARDS pattern; conversely, reduced compliance of the non-dependent lung regions indicates increased risk for overdistension [2]. A similar but more complex approach, which requires dedicated software for analysis, is based on assessment of changes in respiratory system compliance at the pixel level during a decremental PEEP trial: worsening compliance indicates alveolar collapse and prompts selection of the previous higher PEEP level, while improving compliance indicates reduction of overdistension and suggests lower PEEP as a safer choice [3]. This method has been applied in a population of severe ARDS patients supported with extracorporeal membrane oxygenation (ECMO) to select "personalized" PEEP level during ventilation with very low tidal volumes [4].

3. EIT measures the change in end-expiratory lung volume ($\Delta EELV_{EIT}$) between two PEEP levels, and absolute values of alveolar recruitment induced by PEEP increase can be calculated as the difference between $\Delta EELV_{EIT}$ and the increase in EELV predicted by respiratory system compliance at the lower PEEP (i.e., $Crs_{PEEPlow}$ times the PEEP change) [5]:

$$Recruitment_{EIT} = \Delta EELV_{EIT} - (Crs_{PEEPlow} \times \Delta PEEP)$$

4. The reduction in number of "silent spaces" (i.e., extremely hypoventilated lung units) measured by EIT at higher PEEP linearly correlates with recruitment measured by the reference pressure–volume

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curves method [6]; however, this remains a very preliminary approach limited to the research setting.

EIT provides dynamic bedside regional measures of recruitment and overdistension that may support clinical selection of PEEP. Hence, EIT might be a promising approach to improve selection of patients actually benefiting from an "open lung" ventilator strategy but this hypothesis should be tested in large, dedicated studied. To this end, the definition of validated thresholds for each parameter is crucial to design a clinical protocol for EIT-based personalized PEEP.

EIT to monitor spontaneous breathing

Spontaneous breathing is associated with multiple clinical benefits, including reduced respiratory muscles disuse, improved hemodynamics, and lower sedation needs, but it carries the risk of patient self-inflicted lung injury (P-SILI) [7]. Therefore, careful monitoring of spontaneously breathing ARDS patients is mandatory. EIT provides several useful measures for early detection of potentially injurious respiratory patterns, both in intubated and non-intubated patients.

It has been shown that early switch of intubated ARDS patients from controlled to assisted mechanical ventilation can be associated with strong inspiratory effort and occult pendelluft of air from non-dependent to dependent lung region causing excessive lung stretch [8]. EIT allows one to visualize occult pendelluft and guide clinical decisions to mitigate this phenomenon (e.g., increase PEEP or switch back to controlled mode).

EIT might also be useful to select personalized pressure support level [1] or to verify the individual response to alternative ventilation modes such as neurally adjusted ventilation assist (NAVA) [9] or pressure support plus sigh [10]. In these contexts, EIT-based measurements of improved ventilation homogeneity and optimized lung inflation provide a guide to avoid overassistance and reduce regional lung stress and strain [1, 9, 10].

In the later weaning phase, inhomogeneous shift of ventilation to the dependent lung assessed by EIT during a spontaneous breathing trial indicates strenuous inspiratory efforts and predicts weaning failure [11].

Finally, high flow nasal cannula (HFNC) is increasingly used in hypoxemic patients, but respiratory monitoring during HFNC application is usually limited. EIT could be initially used to select the personalized HFNC flow rate associated with significant PEEP effect, and then to monitor potentially injurious (i.e., too large) tidal volumes [12].

EIT to monitor hemodynamics

A novel application of EIT is the non-invasive assessment of central and pulmonary hemodynamics. Indeed, by application of a heart rate-based filtering to exclude impedance changes due to ventilation, EIT can directly and dynamically quantify regional changes of blood content, from which regional blood flow can be derived.

Focusing on the heart region, cardiac output and its variations can be estimated. Moreover, EIT might be used to predict fluid responsiveness by providing accurate evaluation of stroke volume variations inside the aorta (with higher level indicating higher chance of positive response to volume loading) [13].

When lungs are monitored with appropriate filtering, changes in regional blood content can be combined with regional ventilation to measure the inhomogeneity of ventilation–perfusion matching [4]. The accuracy of pulmonary perfusion monitoring may be greatly enhanced by the administration of a bolus of hypertonic saline solution [14]. By this technique (which should be performed under close monitoring of plasma sodium levels), lung perfusion defects (e.g., pulmonary embolism) and regional ventilation–perfusion matching (e.g., at different PEEP levels) can be quantified and monitored over time.

Finally, EIT can also provide a measure of extravascular lung water [15], allowing an objective assessment of the amount of lung edema during ARDS and potentially increasing our ability to stratify clinical severity and to verify the efficacy of treatment.

Although fascinating, most of the EIT-derived indexes of central and pulmonary hemodynamics have been validated only in animal models and will require more extensive tests in the clinical setting.

Limitations

Some significant limitations of the technique need to be discussed. First, EIT explores a limited cross-sectional slice of the thorax (about 10 cm), assuming that the remaining lung regions share the same characteristics. Second, EIT images reflect only relative (not absolute) impedance changes, thus requiring a baseline reference for each patient. Third, spatial resolution is limited and, since EIT displays only ventilated lung regions, the anatomical border between lung and non-pulmonary tissue cannot be clearly identified. Finally, EIT measurements may be affected by body movements and by the position of the belt.
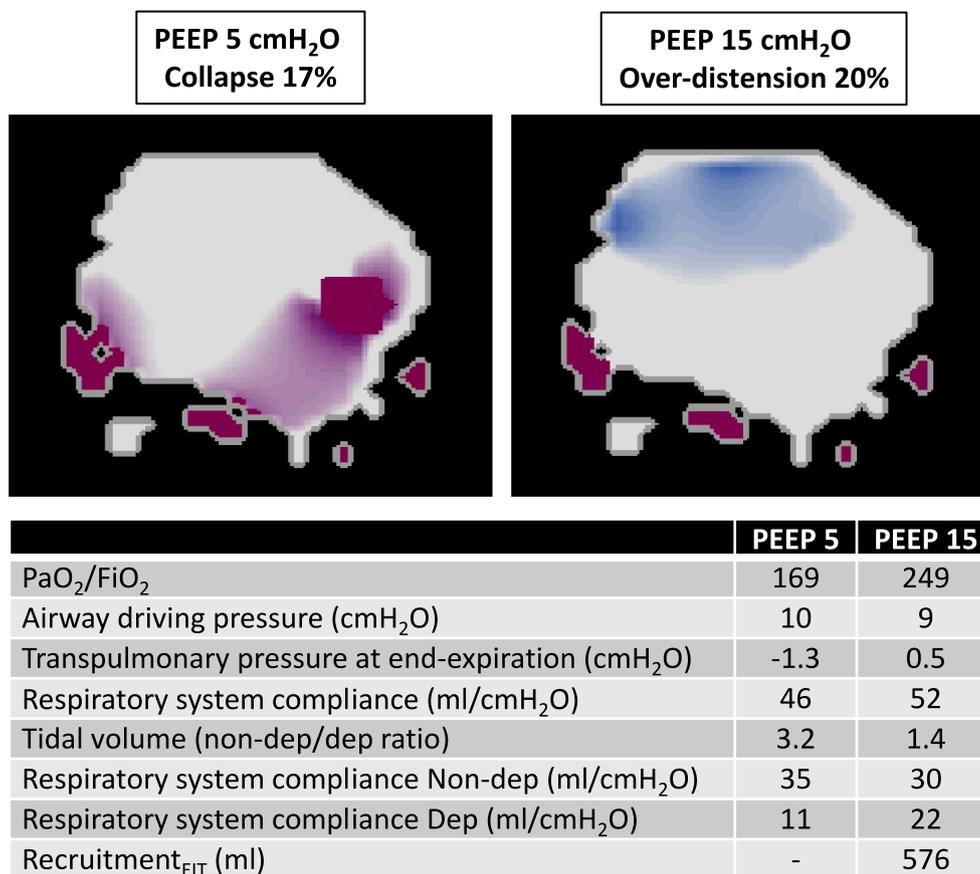
Fig. 1 Data from a patient with moderate ARDS undergoing volume-controlled ventilation monitored by electrical impedance tomography (EIT) at PEEP 5 and 15 cmH$_2$O. In the upper panel, pixel-level respiratory system compliance was calculated to assess decreased value at lower PEEP (collapse) or at higher PEEP (overdistension). Values are expressed as percentage of collapsed or overdistended units. Note the regional distribution of collapse in the dependent region and overdistension in the non-dependent one. The lower table reports classic respiratory monitoring + transpulmonary pressure and EIT data from the same patient at the two PEEP levels: at higher PEEP, oxygenation and respiratory system compliance improve yielding lower driving pressure; PEEP 15 also afforded positive transpulmonary pressure at end expiration, increased ventilation homogeneity, higher compliance of the dependent region, and clinically relevant recruitment measured by EIT—all indicating enhanced lung protection. Finally, please note the 14% decrease of non-dependent lung compliance, indicating higher risk of dynamic overdistension

Conclusions

Despite the aforementioned limitations that should be carefully considered to avoid misinterpretation, EIT conveys unique dynamic physiologic measures, which could represent a significant step forward for the advanced respiratory and cardiovascular monitoring of critically ill patients.

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