Assessment of regional ventilation in acute respiratory distress syndrome by electrical impedance tomography

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Abstract

Mechanical ventilation in acute respiratory distress syndrome (ARDS) incurs a risk of ventilator-associated lung injury (VALI) from inhomogeneous conditions and different properties of dependent and non-dependent lung regions at risk of atelectasis and overdistension, respectively. Electrical impedance tomography (EIT) offers regional ventilation assessment to optimise treatment with mechanical ventilation. This article provides an overview of scientific literature on the application of impedance tomography in acute respiratory distress syndrome. It also presents the results of EIT studies in different clinical situations that may be of use in implementing impedance tomography for treating ARDS.

Key words: acute respiratory distress syndrome, overdistension, electrical impedance tomography, positive end-expiratory pressure, recruitment manoeuvre, ventilator-associated lung injury

WHY SHOULD REGIONAL DISTRIBUTION OF VENTILATION BE MONITORED IN ACUTE RESPIRATORY DISTRESS SYNDROME (ARDS)?

To date, there is no model of optimal mechanical ventilation in ARDS. Two ventilation strategies compete — lung protective ventilation according to the ARDS.net protocol and open-lung strategy (OLS), as first defined by Lachmann [9, 10]. OLS involves a recruitment manoeuvre to aerate the atelectatic areas and individual selection of PEEP to maintain this effect [11]. The ARDS.net protocol is based on the selection of predefined PEEP and FIO2 configurations to achieve a desirable PaO2 and plateau pressure below 30 cm H2O. A common element of both strategies is the use of PEEP with low tidal volume ventilation (LTV), i.e., 6 ml per kg of ideal body weight [12].

It has been demonstrated that not only PEEP but also LTV can lead to distension of pulmonary alveoli, which is a risk factor of their injury caused by mechanical ventilation (VALI, ventilator-associated lung injury) [13, 14] as a result of lung non-homogeneity in ARDS. Although ARDS is an inflammatory disease of the entire lungs, the distribution of atelectatic areas not involved in gas exchange, is uneven [14]. They coexist with the areas poorly or even normally aerated defined byGattinoni as “baby lung” [15]. The greatest...
magnitude of atelectasis is observed in the areas of dependent lungs, i.e., located gravitationally inferiorly [16]. There is a paradox in the treatment of ARDS—recruitment of atelectatic lung alveoli can simultaneously lead to excess inflation of well-ventilated parts (non-dependent lungs) [17, 18]. Therefore, imaging of ventilation distribution in ARDS should answer the following questions:

1. What is the lung aeration image in a patient ventilated with low volumes?
2. What is the effect of a recruitment manoeuvre on functionally diverse parts of lungs in ARDS?
3. What is the optimal value of PEEP to reduce the risk of re-collapse of alveoli and improve their distension to favour even ventilation?

**PHYSICAL PRINCIPLES OF ELECTRICAL IMPEDANCE TOMOGRAPHY**

Electrical impedance tomography (EIT) is based on measurements of electrical resistance of the lungs. A belt of electrodes (16 or 32, depending on the device) is attached around the patient’s thorax, of which one pair generates an electrical current of low, imperceptible intensity of approximately 5 mA, and the remaining one records the electrical potential. The location of emission electrodes is changed one by one around the thorax. Based on the intensity/voltage ratio, the tissue resistance is calculated through which the current has travelled at a subsequently changed configuration of electrode direction.

The higher the lung resistance, the better the aeration [19]. It has been demonstrated that an increase in lung volume from the residual volume to the vital capacity volume can result in an increase in electrical resistance by more than double [20]. Electrical impedance tomography provides information about thoracic resistance on each section and thereby, degree of their aeration.

Amongst several scientific EIT devices, two have been approved for clinical application and are commercially available. The PulmoVista 500 (Drager, Medical GmbH, Germany) has been on the market since 2011 and the Swisstom BB2 (Swisstom/Maquet, Switzerland) has been available since March 2014.

**EIT TO MONITOR REGIONAL VENTILATION IN ARDS**

In EIT, results of electrical resistance measurements corresponding to the degree of lung aeration are coded with colours. PulmoVista 500 uses the Newton-Raphson sophisticated reconstruction algorithm enabling the presentation of resistance in the form of an image, similar to computed tomography. Subsequently, the image is analysed by dividing the lungs into 4 dorso-abdominal layers (Fig. 1) or 4 sectors (Fig. 2), two in each lung. The numerical values indicate the percentage of total increased resistance (total ventilation) corresponding to each layer or sector. In healthy lungs using the 4-layer configuration (ROI, regions of interest), a similar ventilation distribution is observed in the two inner (ROI 2, ROI 3) and two outer (ROI 1, ROI 4) layers (Fig. 1).

In ARDS, the nondependent lung areas are predominantly ventilated while the dependent segments are atelectasis with visible loss of ventilation in the EIT image [16]. This causes the disorders of ventilation-perfusion ratio and unoxygenated blood leak (Fig. 3).

The results of several studies have been published so far in which EIT was used as a device to assess ventilation in ARDS patients [21–24]. The first attempts to apply EIT for optimisation of PEEP were made by Hinz and colleagues [21] in 2005 using a prototype monitor of electrical impedance in patients meeting the criteria of acute lung injury (ALI). This study demonstrated that increasing values of PEEP lead to expansion of atelectatic alveoli. It was assumed, however, it was not possible to detect their distension using the EIT technology. It appeared possible when in the process of an incremental increase in PEEP, loss of ventilation is observed in the regions ventilated with lower positive pressure values [22].

A recent study published by Mauri and co-workers [23] compared the involvement of dependent (dorsal) lung regions in total ventilation of ARDS patients ventilated according to pressure support ventilation (PSV). An increase in PEEP by 5 cm H₂O and a decrease in pressure support (PS) by 4 cm H₂O independently favoured the recruitment of atelectatic lung parts and even ventilation distribution.

A similar observation was made by Blankmann et al. showing that lower inspiration support, both in PCV and neurally adjusted ventilatory assist mode (NAVA), provided better conditions of ventilation in dependent regions [24]. EIT imaging demonstrated that improvement of aeration of dependent lung sectors could be achieved by recruitment with positive end-expiratory pressure or by increased involvement of the diaphragm in initiation of inspiration [23, 24].

Wolf, who evaluated the extent of atelectasis using EIT in a group of children with newly diagnosed ARDS, found that a gradual recruitment manoeuvre in which the plateau pressure was increased by 5 cm H₂O every 15 min was superior to a short-term manoeuver to maintain the positive pressure of 40 cm H₂O over 40 seconds. Moreover, he demonstrated a positive correlation between the extent of atelectasis in dependent parts and the response of lungs to the recruitment manoeuvre [25].

An important element of ARDS treatment is positioning therapy. However, reports on the use of EIT for ARDS treatment in positions other than supine are sparse. According to a report presented by Karsten [26] describing a patient...
Otherwise, Regensburg and colleagues did not demonstrate significant changes in the distribution of ventilation in ARDS patients due to gradual changes in body positioning from supine to the lateral position with 60° tilting to the right and left at constant PEEP of 12 cm H$_2$O [27].

The same therapeutic interventions attempted in ARDS patients were analysed using EIT in other clinical situations, particularly in patients undergoing general anaesthesia with muscle relaxants, which can alter ventilation distribution similar to ARDS [22, 28, 29]. This observation enables the extrapolation of these findings to clinical practice in ARDS.

Bikker [22] performed PEEP decrementation from 15 to 0 cm H$_2$O in two groups of ICU patients, those with healthy lungs and with confirmed pathologies [22]. In patients with lung pathology, PEEP reduction led to decreased impedance (ventilation) both in dependent, dorsal regions and abdominal regions, which is consistent with progressive derecruitment and indicates that the optimal value of PEEP is at least 15 cm H$_2$O. The healthy lungs, on the other hand, reacted with increased impedance in abdominal regions when PEEP was reduced from 15 to 10 cm H$_2$O, which demonstrates that a PEEP of 15 cm H$_2$O was too high and induced distension of alveoli located abdominally. Another study published by the same author proved that derecruitment and excessive distension of alveoli in response to variable PEEP could be observed in the supradiaphragmatic and electrodes positioned higher on the thorax [28].

EIT was also used to assess the modifying effects of a recruitment manoeuvre and PEEP on lung ventilation in patients undergoing general anaesthesia for laparoscopy. A PEEP of 10 cm H$_2$O proved sufficient for reversing the ventilation distribution changes resulting from general anaesthesia yet was too low to prevent adverse effects of pneumoperitoneum [29].

Furthermore, there were attempts to optimise PEEP in obese patients using the assessment of end-expiratory lung impedance (EELI), which corresponds to functional residual capacity (FRC) [30, 31]. Measurements of EELI using EIT reflects changes in regional lung volume and can be an alternative to determinations of impedance changes in the respiration cycle (Fig. 2). Three values of PEEP were compared, i.e., 10, 15 and 20 cm H$_2$O, and the end-expiratory impedance was examined for each. Stabilisation of EELI values indicated the optimal PEEP. The above criteria were met by the value of 15 cm H$_2$O [30]. (Fig. 2).

Animal models of induced ALI/ARDS also provide relevant data concerning the usefulness of EIT for assessment of changes occurring in lungs during mechanical ventilation in ARDS. A study published in 2013 demonstrated that two methods of determining the optimal PEEP based on parameters of total lung function and on values of regional compliance estimated with EIT gave comparable results [32].
According to another study, the recruitment of atelectatic regions was possible only after the previous lung extension in the nondependent part [33]. Since a key aim of ventilation in ARDS is extension of atelectatic lungs without distension of alveoli, the study findings demonstrated that recruitment has to be supplemented by gradual reductions in PEEP below the value resulting in distension. The above schedule determines the optimal PEEP in the pig ARDS model, which was applied by Wolf and colleagues who directly compared the efficacy of ventilation according to the ARDS net protocol and ventilation guided by impedance tomography [34]. The authors performed mechanical ventilation based on the assessment of regional compliance of dependent lung parts. It was calculated by dividing the respiratory volume of the model by the number of pixels over the dorsal sector of the EIT image. Impedance tomography-guided ventilation can improve the lung compliance as well as gas exchange and reduce the severity of mechanical ventilation-associated histopathological markers of lung injury compared to the commonly used ARDS.net protocol [34].

The findings of studies carried out to date have indicated that electrical impedance tomography is a valuable bedside examination to assess lung ventilation. The information regarding regional distribution of ventilation in ALI/ARDS patients can help to reconcile the need for prevention of atelectasis and the necessity to protect the lungs against injuries caused by mechanical ventilation.

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