VIA MEDICA

REVIEWS

Anaesthesiology Intensive Therapy
2015, vol. 47, no 1, 77–81
ISSN 1642–5758
DOI: 10.5603/AIT.2015.0007
www.ait.viamedica.pl

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

Michał Stankiewicz-Rudnicki, Tomasz Gaszyński, Wojciech Gaszyński

Department of Anaesthesiology and Intensive Therapy, Medical University in Łódź, Poland

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

Anaesthesiology Intensive Therapy 2015, vol. 47, no 1, 77–81

The parameters commonly used to assess the efficacy of mechanical ventilation in patients treated in intensive care units such as arterial blood gas (ABG), capnometry and parameters of respiratory mechanics (e.g., peak inspiratory pressure (PIP), plateau pressure (Pplat), static and dynamic compliance) describe the condition of the entire lungs. However, these measurements do not provide information about the diverse functions of their individual parts. To date, ventilation distribution in the lungs and the effects of various ventilation modes on it have been assessed using computed tomography, magnetic resonance imaging and positron emission tomography (PET) [1–6]. None of the abovementioned methods can be used as a bedside examination necessary to dynamically assess the effectiveness of therapeutic interventions such as recruitment manoeuvres (RMs) and variable values of positive end-expiratory pressure (PEEP). On the other hand, bedside ultrasound examination capable of detecting foci of atelectasis and providing assessment at various PEEP values is a subjective method that requires much experience [7, 8].

The technology of electrical impedance tomography (EIT) currently available commercially offers bedside visualisation of lung ventilation and dynamic changes of regional ventilation distribution.

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 F_IO_2 configurations to achieve a desirable PaO_2 and plateau pressure below 30 cm H_2O. 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 by Gattinoni 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 H_2O and a decrease in pressure support (PS) by 4 cm H_2O 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 manoeuver in which the plateau pressure was increased by 5 cm H_2O every 15 min was superior to a short-term manoeuver to maintain the positive pressure of 40 cm H_2O 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

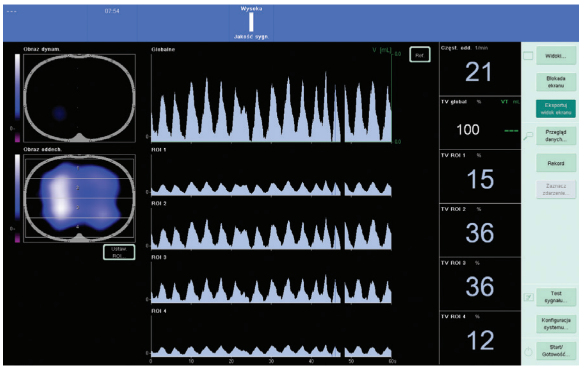

Figure 1. Proper ventilation distribution on EIT imaging of healthy lungs in the supine position. White colour — the area of best aeration, blue colour — less aerated area, black regions — lack of ventilation

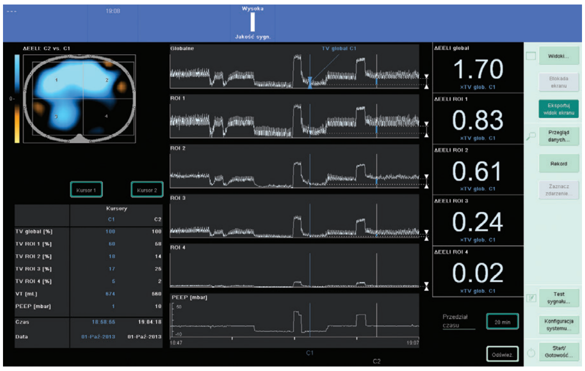

Figure 2. EELI changes after using PEEP of 10 cmH_2O in a patient with severe hospital-acquired pneumonia. The lung images are analysed using the 4 quadrant configuration. Blue colour — increased EELI (i.e. increased FRC). Yellow colour – decreased EELI (and FRC)

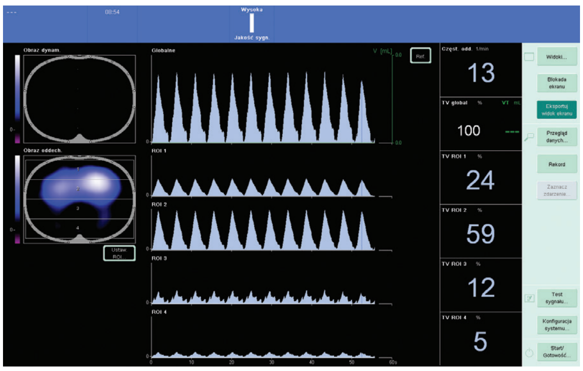

Figure 3. Dorsal atelectasis in an ARDS patient in the supine position with near symmetric involvement of both lungs

with severe fungal pneumonia fulfilling the criteria of ARDS prone position significantly changed ventilation distribution in favour of dorsal lung regions as the nondependent ones in this position. No such effect was observed when, instead of proning, a recruitment manoeuvre (PEEP 15 cm H_2O, peak pressure 40 cm H_2O) was performed in a supine position [26].

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_2O [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_2O 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_2O. The healthy lungs, on the other hand, reacted with increased impedance in abdominal regions when PEEP was reduced from 15 to 10 cm H_2O, which demonstrates that a PEEP of 15 cm H_2O 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 manoeuver and PEEP on lung ventilation in patients undergoing general anaesthesia for laparoscopy. A PEEP of 10 cm H_2O 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_2O, 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_2O [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 scheme to determine the optimal PEEP in the pig ARDS model 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.

ACKNOWLEDGEMENTS

1. The authors declare no financial disclosure.
2. The authors declare no conflict of interest.

References:

1. *Yoshida T, Rinka H, Kaji A et al.:* The impact of spontaneous ventilation on distribution of lung aeration in patients with acute respiratory distress syndrome: airway pressure release ventilation versus pressure support ventilation. Anesth Analg 2009; 109: 1892–1900.
2. *Fumagalli R, Marcolin M, Mascheroni D, Torresin A:* Relationships between lung computed tomographic densitiy, gas exchange, and PEEP in acute respiratory failure. Anesthesiology 1988; 69: 824–832.
3. *Chiumello D, Marino A, Brioni M et al.:* Visual anatomical lung CT scan assessment of lung recruitability. Intensive Care Med 2013; 39: 66–73.
4. *Thieme SF, Hoegl S, Nikolaou K et al.:* Pulmonary ventilation and perfusion imaging with dual-energy CT. Eur Radiol 2010; 20: 2882–2889. doi: 10.1007/s00330-010-1866-8.
5. *Mugler JP III, Altes Talissa A, Ruset Iulian C et al.:* Simultaneous magnetic resonance imaging of ventilation distribution and gas uptake in the human lung using hyperpolarized xenon-129. Proc Natl Acad Sci USA 2010; 107: 21707–21712.
6. *Bellani G, Messa C, Guerra L et al.:* Lungs of patients with acute respiratory distress syndrome show diffuse inflammation in normally aerated regions: a [18F]-fluoro-2-deoxy-D-glucose PET/CT study. Crit Care Med 2009; 37: 2216–2222.
7. *Yang JX, Zhang M, Liu ZH, Ba L, Gan JX, Xu SW:* Detection of lung atelectasis/consolidation by ultrasound in multiple trauma patients with mechanical ventilation. Clin Ultrasound J 2009; 1: 13–16.
8. *Stefanidis K, Dimopoulos S, Tripodaki ES et al.:* Lung sonography and recruitment in patients with early acute respiratory distress syndrome: a pilot study. Crit Care 2011; 15: R185. doi: 10.1186/cc10338.
9. *Brower RG, Matthay MA, Morris A et al.:* Ventilation with lower tidal volumes as compared with traditional tidal volumes for acute lung injury and the acute respiratory distress syndrome. N Engl J Med 2000; 342: 1301–1308.
10. *Lachmann B:* Open up the lung and keep the lung open. Intensive Care Med 1992; 18: 319–321.
11. *Meade MO, Cook DJ, Guyatt GH et al.:* Ventilation strategy using low tidal volumes, recruitment maneuvers, and high positive end-expiratory pressure for acute lung injury and acute respiratory distress syndrome — a randomized controlled trial. JAMA 2008; 99: 637–645.
12. *Spieth PM, Güldner A, Gueldner A, Carvalho AR et al.:* Open lung approach vs acute respiratory distress syndrome network ventilation in experimental acute lung injury. Br J Anaesth 2011; 107: 388–397. doi: 10.1093/bja/aer144.
13. *Maunder RJ, Shuman WP, McHugh JW, Marglin SI, Butler J:* Preservation of normal lung region in adult respiratory distress syndrome: analysis by computed tomography. JAMA 1986; 255: 2463–2465.
14. *Terragni PP, Rosboch G, Tealdi A et al.:* Tidal hyperinflation during low tidal volume ventilation in acute respiratory distress syndrome. Am J Respir Crit Care Med 2007; 175: 160–166.
15. *Gattinoni L, Pesenti A:* The concept of "baby lung". Intensive Care Med 2005; 27: 404–415.
16. *Gattinoni L, Caironi P, Pelosi P, Goodman LR:* What has computed tomography taught us about the acute respiratory distress syndrome? Am J Respir Crit Care Med 2001; 164: 1701–1711.
17. *Puybasset L, Gusman P, Muller JC et al.:* Regional distribution of gas and tissue in acute respiratory distress syndrome. III. Consequences for the effects of positive end-expiratory pressure. Intensive Care Med 2000; 26: 1215–1227.
18. *Gattinoni L, Carlesso E, Cadringher P et al.:* Physical and biological triggers of ventilator-induced lung injury and its prevention. Eur Respir J 2003; 22: 15s–25s.
19. *Harris ND, Suggett AJ, Barber DC, Brown BH:* Applications of applied potential tomography (APT) in respiratory medicine. Clin Phys Physiol Meas 1987; 8 Suppl A: 155–165.
20. *Nebuya S, Mills GH, Milnes P et al.:* Indirect measurement of lung density and air volume from electrical impedance tomography (EIT) data. Physiol Meas 2011; 32: 1953–1967.
21. *Hinz J, Moerer O, Neumann P, Dudykevych T, Hellige G, Quintel M:* Effect of positive end-expiratory-pressure on regional ventilation in patients with acute lung injury evaluated by electrical impedance tomography. Eur J Anaesthesiol 2005; 22: 817–825.
22. *Bikker IG, Leonhardt S, Reis MD, Bakker J, Gommers D:* Bedside measurement of changes in lung impedance to monitor alveolar ventilation in dependent and non-dependent parts by electrical impedance tomography during a positive end-expiratory pressure trial in mechanically ventilated intensive care unit patients. Crit Care 2010; 14: R100, doi: 10.1186/cc9036.
23. *Mauri T, Bellani G, Confalonieri A et. al.:* Topographic distribution of tidal ventilation in acute respiratory distress syndrome: effects of positive end-expiratory pressure and pressure support. Crit Care Med 2013; 41: 1664–1673. doi: 10.1097/CCM.0b013e318287f6e7
24. *Blankman P, Hasan D, van Mourik MS, Gommers D:* Ventilation distribution measured with EIT at varying levels of pressure support and neurally adjusted ventilatory assist in patients with ALI. Intensive Care Med 2013; 39: 1057–1062. doi: 10.1007/s00134-013-2898-8
25. *Wolf GK, Gomez-Laberge C, Kheir JN et al.:* Reversal of dependent lung collapse predicts response to lung recruitment in children with acute lung injury. Pediatr Crit Care Med 2012; 13: 509–515. doi: 10.1097/PCC.0b013e318245579c.
26. *Karsten J, Meier T, Heinze H:* Bedside measurement of electrical impedance tomography and functional capacity during position therapy in a case of acute respiratory failure. Appl Cardiopulm Pathophysiol 2011; 15: 81–86.
27. 27. *Bein T, Ploner F, Ritzka M, Pfeifer M, Schlitt HJ, Graf BM:* No change in the regional distribution of tidal volume during lateral posture in mechanically ventilated patients assessed by electrical impedance tomography. Clin Physiol Funct Imaging 2010; 30: 234–240. doi: 10.1111/j.1475-097X.2010.00933.x
28. *Bikker IG, Preis C, Egal M, Bakker J, Gommers D:* Electrical impedance tomography measured at two thoracic levels can visualize the ventilation distribution changes at the bedside during a decremental positive end-expiratory lung pressure trial. Crit Care 2011; 15: R193. doi: 10.1186/cc10354.

29. *Karsten J, Luepschen H, Grossherr M et al.:* Effect of PEEP on regional ventilation during laparoscopic surgery monitored by electrical impedance tomography. Acta Anaesthesiol Scand 2011; 55: 878–886. doi: 10.1111/j.1399-6576.2011.02467.x.
30. *Erlandsson K, Odenstedt H, Lundin S et al.:* Positive end-expiratory pressure optimization using electric impedance tomography in morbidly obese patients during laparoscopic gastric bypass surgery. Acta Anaesthesiol Scand 2006; 50: 833–839.
31. *Hinz J, Hahn G, Neumann P:* End-expiratory lung impedance change enables bedside monitoring of end-expiratory lung volume change Intensive Care Med 2003; 29: 37–43.
32. *Bikker IG, Blankman P, Specht P, Bakker J, Gommers D:* Global and regional parameters to visualize the 'best' PEEP during a PEEP trial in a porcine model with and without acute lung injury. Minerva Anestesiol 2013; 79: 983–992.
33. *Gómez-Laberge C, Rettig JS, Smallwood CD, Boyd TK, Arnold JH, Wolf GK:* Interaction of dependent and non-dependent regions of the acutely injured lung during a stepwise recruitment manoeuvre. Physiol Meas 2013; 34: 163–177. doi: 10.1088/0967-3334/34/2/163.
34. *Wolf GK, Gómez-Laberge C, Rettig JS et al:* Mechanical ventilation guided by electrical impedance tomography in experimental acute lung injury. Crit Care Med 2013; 41: 1296–1304. doi: 10.1097/CCM.0b013e3182771516.

Corresponding author:
Michał Stankiewicz-Rudnicki, MD
Department of Anaesthesiology and Intensive Therapy
Medical University in Łódź
ul. Kopcińskiego 22, 90–153 Łódź, Poland
e-mail: mic.str@gmail.com

Received: 9.01.2014
Accepted: 6.09.2014