SIGNA VITAE 2018; 14(SUPPL 1): 21-23

Electrical impedance tomography as ventilation monitoring in ICU patients

STJEPAN BARISIN, MD PHD[1,2], HELENA OSTOVIC, MD[1,2], MARKO PRAZETINA, MD[1], NATASA SOJCIC MD[1], IVAN GOSPIC, MD[1], NIKOLA BRADIC, MD[1,3]

[1]Clinical Department of Anesthesiology, Reanimatology and Intensive Care, University Hospital Dubrava, Zagreb
[2]Faculty of Medicine, JJ Strossmayer University Osijek
[3]Department of Biomedical Sciences, University North, Varazdin

Adress of corresponding author:
Assist. Prof. Stjepan Barišin, MD, PhD
Dubrava University Hospital
Clinical Department of Anesthesiology, Reanimatology and Intensive Care
Av. Gojka Suska 6, HR-10000 Zagreb
e-mail: abarisin@kbd.hr

ABSTRACT

Electrical impedance tomography (EIT), as a monitoring tool of regional lung ventilation, is radiation-free imaging with high temporal resolution. The most important purpose of EIT is to visualize the distribution of tidal volume in different lung regions especially between dependent (dorsal in supine patients) and non-dependent (ventral in supine patients) regions.
Many clinical studies evaluated the applicability of PulmoVista® 500 (Dräger Medical GmbH, Lübeck, Germany) and similar EIT devices in estimating optimal PEEP after recruitment maneuvers (RM) in lung healthy patients and acute respiratory distress syndrome (ARDS), ventilation distribution in cystic fibrosis, COPB, pneumonia and respiratory diseases syndrome in infants.

Keywords: Electrical impedance tomography – EIT, regional ventilation, lung monitoring

INTRODUCTION

Impedance is an abstract physical variable that describes the resistivity or conductivity characteristics of an electric circuit in the presence of different tissues and organs. For instance, muscle and blood are good conductors, but fat and bone are poor ones. The inspiration of imagining the thorax with electricity is based on the existence of these dissimilar electrical properties of different tissues. Thoracic bioimpedance is influenced by two cyclic mechanisms: ventilation and perfusion. Impedance of the lung varies on a large scale from residual volume to total lung capacity. The increasing amount of air during inspiration leads to an increase in tissue impedance that is proportional to the inspired gas volume. In humans, an inspiration maneuver from residual volume to total lung capacity amplifies regional impedance by around 300% (1). To perform bioimpedance measurements, an electrode belt containing 16 electrodes is placed around the chest wall at the5th intercostal space. PulmoVista 500 determines the distribution of intra-thoracic bioimpedance by applying an alternating electrical current. There are an active pair of electrodes and a separate pair of electrodes for voltage measurements and measuring the resulting surface potentials at the remaining 13 electrode pairs. Subsequently, the adjacent electrode pair is used for the next current application and another 13 voltage measurements are performed. The location of the injecting andmeasuring electrode pairs successively rotates around the entire thorax. The resulting 208 values, also called a frame, are used to reconstruct one cross-sectional EIT image. It consists of a matrix of 32 × 32 pixels with a frame rate of 20 images per second and 40 EIT images per breath will be generated (2). Therefore it is capable of continuously measuring the change of impedance in every pixel which actually represents gas exchange in the corresponding lung fragment.

CLINICAL APPLICATIONS

HEALTHY LUNGS

Although mechanical ventilation is an established method to replace or assist a patient's breathing, research is still required on "lung protective ventilation" (LPV) in order to reduce ventilator-associated/induced lung injury (VALI/VILI). Controversies persist as to the use of higher or lower levels of PEEP and as to whether recruitment maneuvers (RM; dynamic, transient increase in transpulmonary pressure which is directly proportional to the reopening of lung units) should be performed during the perioperative period (3). EIT is used as a prospective regional ventilation tool to improve decision-making at the bedside and to assist in the adjustment of "optimal" PEEP values that balances between over-distension (hyperinflation) and under-ventilation (atelectasis) (4).
A study performed by Silva et al. (5), in which10 anesthetized patients with healthy lungs mechanically ventilated under volume-controlled mode were observed. A standardized incremental PEEP trial was performed. There was no difference between PEEP level determined by EIT and ventilation measurement. In a second study that included 49 morbidly obese patients who underwent general anesthesia during laparoscopic bariatric surgery, it was revealed that a PEEP level of 10 cm H2O preceded by a RM improves respiratory compliance and oxygenation but does not eliminate atelectasis induced by general anesthesia (6). Spooner et al. (7) have found a statistically significant rise in end-expiratory lung volume during head-of-bed elevation at20° and 30° in 20 postoperative cardiac surgery patients except in the anterior region. There were no significant changes in hemodynamics and oxygenation when head of bed was elevated to 30°. Based on those findings they recommended that mechanically ventilated patients should be positioned with head-of-bed elevation.

ARDS

ARDS is the sudden failure of the respiratory system and is associated with a very high mortality rate (27–45% from mild to severe). Cyclic opening and closing of alveoli in ARDS patients increases ventilation heterogeneity and, thus, the risk for VILI. The application of an RM and the administration of PEEP reduce the risk of hypoxemia. An adequate PEEP and low tidal volume are critical to reduce the mortality rate (4). Hsu et al. (8) found a significant correlation between the end-expiratory lung impedance measured by Pulmovista 500 and PaO2/FiO2 ratio in 19 mechanically ventilated ARDS patients after RM (8).
Investigators from Boston Children's Hospital reported that respiratory system compliance from EIT and ventilator measurements had a correlation coefficient of 0.80 during RM in 9 pediatric patients with ARDS (9). A prospective observational study compared EIT images of 18 ICU patients with ARDS during a decremented PEEP trial after RM. In another study, ICU patients were divided in 2 groups: 13 responders and 5 non-responders. Responders were patients who had a PaO2 + PaCO2 > 400 mmHg after RM. In responders, it was shown that lowering the PEEP level resulted in a decrease of recruited and over-distended pixels in ventral regions and a decrease of over-distended pixels in dorsal regions. However, there was no significant difference of recruited and over distended pixels during PEEP titration in all regions in non-responders (10).
EIT is also capable of measuring impedance changes during the cardiac cycle and therefore it can calculate ventilation - perfusion mismatch which differed significantly in dorsal (dependent) regions before and after RM in 20 consecutive ARDS patients (11). EIT measurements showed that tidal volume will be distributed more equally using a mode of ventilation that involves more spontaneous diaphragm activity in patients with and without ARDS (12).

CYSTIC FIBROSIS

Cystic fibrosis (CF) is the most frequent inherited metabolic disease in Caucasians, mainly affecting the lung and digestive system. The gold standard for evaluation of parenchymatous changes is a low-dose high resolution computed tomography (HRCT). However, these techniques expose patients to harmful ionizing radiation at a young age. EIT delivers information about
global and regional ventilation and has high temporal resolution. Several studies were conducted comparing EIT with lung imaging and lung function tests. Lehman et al. (13) found a high and statistically significant correlation between spirometry and global EIT results ($r2=0.71–1.0$, $P<0.001$) in 11 pediatric patients with cystic fibrosis and their healthy controls. In a study of 5 CF patients, ratios of maximum expiratory flows at 25% and 75% of vital capacity (MEF25/MEF75) with respect to relative impedance change were calculated for regional areas in EIT images. Regional airway obstruction identified in the MEF25/MEF75 maps was similar to that found in CT (14). In 10 adult patients with CF, simultaneous spirometry and EIT measurements were made at two thoracic levels. CF patients exhibited significantly different EIT measurements and a significantly higher degree of ventilation inhomogeneity in the 3rd intercostal space compared to the 5th intercostal space than lung-healthy controls (15).

PNEUMONIA AND COPD

A study performed on 24 adult patients with community-acquired pneumonia revealed that EIT detects right-sided and left-sided ventilation disorders due to pneumonia in correspondence to chest X-ray (16). In 2017, 19 pediatric patients with unilateral pneumonia were enrolled in a prospective observational study which revealed significant agreement between EIT and chest radiography in identifying the affected lung (left or right) (17). Several very interesting studies were performed using Goe MF II EIT device (EIT - Group Göttingen, Göttingen Germany) that is comparable with PulmoVista® 500 (18). EIT measurements showed more homogeneously distributed ventilation during HFOV than during initial CMV in 10 patients with acute exacerbations of COPD and hypercapnic respiratory failure (19). In 11 high-frequency ventilated premature infants with respiratory distress syndrome (RDS) endotracheal tube suction was performed. EIT revealed that changes in lung volume were heterogeneously distributed (20). A similar study included 15 preterm infants with RDS investigated the correlation between respiratory inductive plethysmography during a stepwise recruitment procedure. End-expiratory lung volume changes measured by both techniques were significantly correlated in 12 patients (mean $r = 0.93 \pm 0.05$) (21).
Fourteen ALI/ARDS patients were included into the study by Kunst et al. (22) with a significant correlation between changes in extravascular lung water (EVLW) as measured by the thermal dye double indicator dilution techniques and EIT ($R=0.85$; $p<0.005$). EIT with reduced spatial resolution showed a strong correlation between thoracic resistivity and removed pleural fluid in 11 patients with pleural effusion (23).

CONCLUSION

The limitation of the EIT scan in ICU patients is in the low spatial resolution when compared with radiographic imaging techniques. Secondly, EIT is recommended for functional but not solely anatomic lung imaging. The resolution of the EIT method requires the use of self-adhesive electrodes which have to be placed on the entire chest circumference.
Numerous clinical studies, which were performed to investigate the applicability and significance of lung EIT in clinical practice, showed EIT potential benefits. Its value has been observed in the management of acute diseases as well as in continuous monitoring of complicated clinical conditions for optimizing ventilator therapy. Its paramount advantage is due to its high temporal resolution and lack of ionizing radiation which makes it suitable for repeated and long-term applications, especially in infants. The EIT technique is more widely being considered as a future tool for evaluation of the immediate effects of a change in ventilation in ICU patients.

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