Review article

Electrical Impedance Tomography - Watch the lungs breathe!

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Abstract

Electrical Impedance Tomography (EIT) is a relatively new noninvasive tool in the management of patients on mechanical ventilators. It is a simple, user-friendly and radiation-free investigation to study the regional ventilation and distribution of ventilation particularly in patients with Acute Respiratory Distress Syndrome (ARDS). It empowers the clinician to take necessary steps for the management of collapsed, non-aerated regions of the lungs, to prevent regional overdistension of lungs which results in Ventilator Induced Lung Injury (VILI) and for early detection of pneumothorax. This is a short review focusing the basic principles, clinical applications and current evidence in the effectiveness of this modality in the routine respiratory care.

Keywords: Electrical Impedance Tomography, mechanical ventilation, respiratory monitoring.

Introduction

Imaging modalities such as 128-slice computerised tomogram (CT) scanners, functional Magnetic Resonance Imaging methods (f-MRI), or 3 Dimensional ultrasound scanning are excellent tools. However, their use has limitations and logistic issues for routine use in a hypoxaemic ventilated patient in the ICU to study the regional distribution of ventilation. Introduced in 1984 by Barber and Brown Electrical impedance tomography (EIT) is a noninvasive, radiation-free monitoring modality for real-time imaging of ventilation induced lung changes.[1] It is unique and is used for bedside monitoring of real time noninvasive measurements of regional lung volume changes.[2] EIT is helpful as a monitoring tool in a variety of applications in critical care medicine, including but not limited to monitoring of ventilation distribution,[3] assessment of lung overdistension,[4] atelectasis[5] and detection of pneumothorax.[6]

Working principle of EIT

EIT works by injection of high frequency and low amplitude electrical currents, through 16 or 32 electrodes applied around the thorax, in a belt like fashion to obtain images of a cross section of the lungs (*Figure 1*).[7]

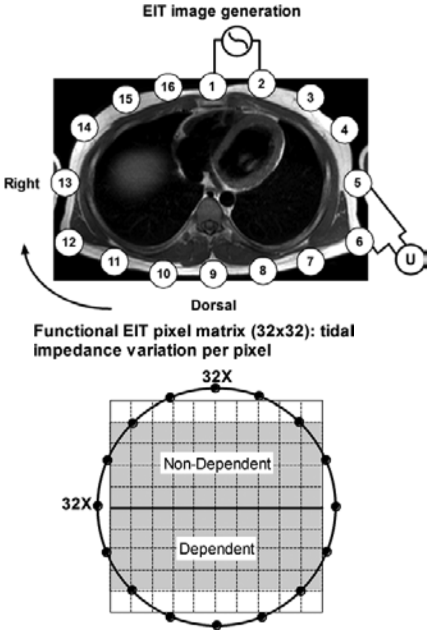

Figure 1: Top: Principle of electrical impedance tomography (EIT) Bottom: functional EIT image (fEIT). Electrical excitation currents are injected between pairs of adjacent surface electrodes (1 to 16); the resulting voltages are measured between the other electrodes (U). The ventral to dorsal oriented Regions of Interest (ROIs) are marked in gray in the right panel.(Adapted from: Ido G Bikker, Steffen Leonhardt, Dinis Reis Miranda, Jan Bakker and Diederik Gommers. Bedside measurement of changes in

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lung impedance to monitor alveolar ventilation in dependent and nondependent parts by electrical impedance tomography during a positive end-expiratory pressure trial in mechanically ventilated intensive care unit patients. Critical Care 2010 14:R100)

The method is based on the principle that resistance of the lung tissue to passage of an electrical impulse increases with its aeration. Sixteen pairs of electrodes placed on an elastic band fastened around the thorax measure the changes in thoracic tissue impedance in response to the electrical impulse emitted by two consecutive electrodes. Impulse emission is continuously moved around the thoracic cavity. The device performs 50 measurements per second, which in the respiratory cycle lasting 3 seconds generates 150 dynamically changing images.[8] The modality has undergone tremendous modification over time from the prototype Sheffield Mark 1 to the modern Pulmovista 500. Issues of resolution and reconstruction artifacts have been addressed by improved algorithms and filtering. In modern EIT equipment, bioimpedance measurements are performed by an electrode belt containing 16 electrodes, wrapped around the chest wall. In addition, another reference electrode must be attached to a central point on the body, preferably on the abdomen. This ensures that all measurements at different electrode pairs are referenced to the same electric potential. In modern equipment, cardiac related impedance changes are filtered and eliminated displaying only the ventilation related impedance changes focusing on the end expiratory lung volumes. Measurement of relative impedance changes cancels out the necessity to consider the thoracic shape into account as in absolute impedance measurements although it cannot represent consolidation due to pre-existing lesions, pleural effusion *etc.* At a frequency of 10 kHz, the electrical impedance of the chest is around 2–4 Vm, and the average impedance of the lung is around 10 Vm. During inspiration, lung impedance changes up to 300% from 7.2 to 23.6 Vm, but the chest wall impedance remains relatively constant.[9] PulmoVista 500 uses a Finite Element Method (FEM) based linearised Newton-Raphson reconstruction algorithm to convert the 208 voltages of a frame into an ellipsoid EIT image instead of Sheffield back projection algorithm which is limited to round shapes. Gaussian filtering is another technological enhancement in modern EIT equipment, for improving the quality of image. Details of physical laws governing EIT are beyond the scope of this review but available in a review by Mouloud A Denai *et al.*[10]

Correlation with CT Scan

Spatial resolutions of EIT images are inferior to CT images. In 16-electrode systems, resolution is estimated to be 12% of the thoracic diameter for regions in the periphery of the lung and 20% for central regions. By using 32-electrode systems, this resolution can be improved to 6–10% of the thoracic diameter, which corresponds to approximately 1.5–3cm in the cross-sectional plane. The spatial resolution in the craniocaudal direction corresponds to a slice thickness of approximately 7–10 cm.[7] This can be improved either by increasing the number of electrodes or by improving hardware but the temporal resolution which results in as much as 50 images per second, can display the inflation and deflation of lungs in real time better than CT images.

Clinical applications

Setting of PEEP

Setting PEEP optimally is a tradeoff between lung collapse and overdistension. The information provided by global parameters of lung function, such as blood gas values, dynamic respiratory indices, best compliance method and slope of the static pressure-volume (P/V) curve does not consider regional inhomogeneity of the lung, and therefore may be sometimes misleading. EIT provides an efficient, user friendly and risk free method to set the PEEP *(Figure 2)*.

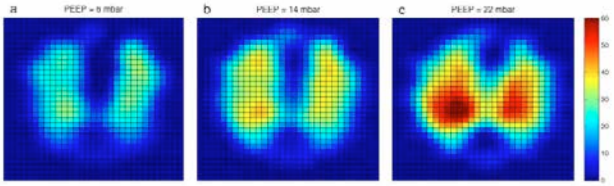

Figure 2: Tidal ventilation distribution in EIT images at different PEEP levels. (a) 6 mbar. (b) 14 mbar. (c) 22 mbar. The tidal images were the differences of relative impedance between end-inspiration and end-expiration in electrical impedance tomography (EIT). High ventilated regions are marked in red, while low ventilated regions are marked in blue. (Adapted from :Zhanqi Zhao, Daniel Steinmann, Inéz Frerichs, Josef Guttmann,

Knut Möller. PEEP titration guided by ventilation homogeneity: a feasibility study using electrical impedance tomography. Crit Care. 2010; 14(1): R8.)

In a retrospective study Zhanqi Zhao *et al*[11], studied 10 anaesthetised patients with healthy lungs under mechanical ventilation. Ventilation distribution was monitored by EIT. A standardised incremental PEEP trial was conducted. During the PEEP trial, *'optimal'* PEEP level for each patient was determined when the lungs showed most homogeneous distribution of air, indicated by the lowest Global Inhomogeneity Index (GI index) value.[12]

Two well recognised methods for setting PEEP, *i.e.*, the maximum global dynamic compliance[13] and SLICE method[14] were included for comparison based on the maximum global dynamic compliance and the intra-tidal compliance-volume curve. They found that no significant differences in the results were observed between the GI index method (12.2 ± 4.6 mbar) and the dynamic compliance method (11.4 ± 2.3 mbar, $P > 0.6$), or between the GI index and the compliance-volume curve method (12.2 ± 4.9 mbar, $P > 0.6$). Global inhomogeneity (GI) index based on EIT was an index developed by the same group of investigators to quantify the tidal volume distribution within the lung using a formula.

In 2010, Dargaville *et al* applied EIT during an incremental and decremental PEEP trial to identify the PEEP level at which the most homogeneous distribution of regional compliance (Crs) and ventilation occurs in healthy, injured and surfactant-treated lungs.[15] They found that most uniform distribution of regional tidal ventilation was noted during PEEP decrements after lung recruitment, at varying PEEP levels. Comparing different studies on various methods of setting the PEEP in an excellent review, Zhao *et al* proposed to combine indices of lung mechanics, blood gas analysis and imaging techniques to titrate PEEP. Besides, application of PEEP should be complemented with other strategies such as low tidal volume body positioning, recruitment manoeuvre, to achieve the best outcome for the patient.[16]

Assessment of lung recruitment

Lung recruitment by various techniques are employed to re-inflate collapsed alveoli in patients with ARDS namely sigh, sustained inflation, incremental and decremental PEEP, to name a few of them. Whatever be the modality used, it was difficult to assess the efficacy of the manoeuvre at the bed side at real time except by global indices and clinical improvement in vital parameters. The clinician was blind to the de-recruitment after procedures such as endotracheal suction, bronchoscopy, positioning *etc.* EIT provides an excellent tool in this regard. On an experimental model in pigs, Beraldo *et al*[17] found a good correlation between EIT and CT estimates of lung atelectasis during decremental PEEP trials after a maximal lung recruitment manoeuvre.

Meier *et al*[18], used EIT to monitor regional tidal volume during a PEEP titration manoeuvre in surfactant depleted pigs. They could detect the development of regional lung collapse and of regional lung recruitment before global changes in lung mechanics were appreciated. Additionally, they showed good correlation of ventilation estimated by EIT and CT. In 2007, Luepschen *et al* showed that the centre of gravity of ventilation images shifts dorsally during lung recruitment and ventrally during lung collapse.[19]

Earlier Frerichs *et al* in an experimental study with 16 newborn piglets demonstrated that EIT assists in displaying the effects of acute lung injury, lung recruitment, surfactant administration, and mechanical ventilation strategy. Lung injury was found to displace the ventilation ventrally, and lung recruitment restores it to the normal position. After surfactant administration, centre of ventilation was seen shifting ventrally, but if surfactant administration is followed by a recruitment manoeuvre it remains in the pre-injury position.[20]

In a recent experimental study using anaesthetised pigs, Thomas Muders *et al* showed that the regional-ventilation-delay can be noninvasively measured by electrical impedance tomography during a slow inflation volume of 12 mL/kg and visualised using ventilation delay maps. Their data suggest that the impedance tomography-based analysis of regional-ventilation-delay inhomogeneity provides a good estimate of the amount of tidal recruitment and may be useful to individualise ventilator settings.[21]

EIT in ARDS management

In Acute Respiratory Distress Syndrome (ARDS) EIT helps in setting PEEP, assess recruitment, detect de-recruitment early, to take necessary steps to re-recruit the lungs, and detection of pneumothorax. In a research by Wrigge H *et al*, they compared EIT measures to dynamic CT in 18 pigs, divided into three groups (control, direct, and indirect lung injury). In this study, EIT helped in real-time monitoring of regional ventilation distribution. During a slow inflation, regional recruitment was detected by using the time delay between beginning of inspiration and initiation of regional inflation (ventilation delay index).[22] Hinz *et al* monitored 20 mechanically ventilated patients with acute lung injury/acute respiratory distress syndrome (ARDS) during tidal breathing and showed that the characteristics of regional impedance over time was markedly heterogeneous and significantly different from that of the whole lung.[23] Wolf *et al* studied the feasibility of real-time electrical impedance tomography to guide lung protective ventilation in an animal model of ARDS by inducing Lung injury in 12 Yorkshire swine with saline and augmented tidal volume. The control group (n = 6) was ventilated using ARDS net guidelines, and the electrical impedance tomography-guided group (n = 6) was ventilated using EIT guidance. PaO_2/FIO_2 ratio was found to be higher and oxygenation index was found to be lower in the EIT-guided ventilation group, and the presence of hyaline membranes and airway fibrin was significantly reduced in the EIT-guided ventilation group. However, interleukin-8 level obtained by bronchoalveolar lavage did not differ between the groups. The upper and lower 95% limits of agreement between electrical impedance tomography and computed tomography were ± 16%.[24]

Endotracheal suction induced de-recruitment is often underestimated. EIT is helpful in detecting de-recruitment induced by suction, bronchoscopy and ventilator disconnection. Wolf *et al* studied six children with ARDS, on pressure controlled ventilation and continuously monitored with EIT. They demonstrated that lung volumes decreases by 5.3 ml/kg after three suctioning manoeuvres. Unexpectedly, they found that the most dorsal regions of the lung were the least affected by de-recruitment which they attributed to preexisting atelectasis.[25]

Lindgren *et al* found that endotracheal open system suctioning induced more collapse of the lung and decrease in regional lung compliance when compared to closed-system suctioning.[26] In another study, the same authors used EIT to assess lung collapse during bronchoscopic suctioning in patients mechanically ventilated with acute lung injury. They showed that bronchoscopic suctioning leads to a decrease in lung aeration and compliance irrespective of open or closed suctioning system.[27]

Other uses of EIT

Detection of pneumothorax and pleural effusion

Costa *et al* studied characteristic changes in the EIT signals associated with pneumothoraces and developed an algorithm for their detection. They prospectively evaluated this algorithm for its sensitivity and specificity in detecting pneumothoraxes in real time.[28] Pneumothoraces as trivial as 20 ml could be detected (sensitivity of 100% and specificity 95%) which could be distinguished from PEEP induced parenchymal overdistension or recruiting manoeuvres. Their location also was correctly identified in all cases, with a total delay of only three respiratory cycles.

Hahn G *et al* studied the combined use of dynamic and absolute images for the diagnosis of pneumothorax and pleural effusion.[29] They studied five pigs and showed reproducible results with the development of pneumothorax causing regional increase in absolute impedance and decreased ventilation, whereas pleural effusions produced a regional decrease in impedance and decreased ventilation. However this area is to be explored by further studies.

Endotracheal tube placement by EIT

In a study by Steinmann *et al* regional ventilation was studied by EIT in 40 patients ventilated through left-sided double lumen tubes (DLTs) for one lung ventilation (OLV) during thoracic surgery.[30] EIT was recorded during two-lung ventilation before induction of anaesthesia, after DLT placement and during OLV in the supine, and subsequently in the lateral position. EIT measurements were made before and after verification of correct DLT placement by fibreoptic bronchoscopy (FOB). EIT accurately displayed distribution of ventilation between left and right lung. All cases (n=5) of initially misplaced DLTs in the contralateral right main bronchus were detected by EIT. However, EIT did not allow prediction of FOB-detected endobronchial cuff misplacement requiring DLT repositioning. Furthermore, after DLT repositioning, distribution of ventilation, as assessed by EIT, did not change significantly (all $P > 0.5$).

To study ventilation distribution in various clinical settings

EIT was used to study the ventilation distribution associated with different positions in patients on continuous positive airway pressure (CPAP) by Angela F *et al.*[31] They investigated 22 subjects. Measurements were made in sitting and supine position without CPAP and in supine with a CPAP of 7 cmH_2O. Functional residual capacity (FRC) was measured with the oxygen washin-washout method. Ventilation distribution was recorded with EIT. FRC was observed to reduce by 16% from the sitting to the supine position. Ventilation distribution showed a trend towards ventral lung regions. In the supine position, application of CPAP increased the FRC but did not change the ventilation distribution. Thomas Bein *et al* assessed the distribution of regional lung ventilation during moderate and steep lateral posture using EIT in mechanically ventilated patients.[32] They assessed the distribution of regional lung ventilation during moderate and steep lateral posture using electrical impedance tomography (EIT) in mechanically ventilated patients. They found that a change in lateral positions did not induce a significant change in regional tidal volume distribution. In right lateral positions, a broader variation of V_T with a trend towards an increase in the dependently positioned lung was observed in comparison with supine position.

To study ventilation perfusion balance

EIT has been used to study ventilation-perfusion ratio (V/Q ratio) by some investigators. Tanaka *et al*[33] described a fuzzy modeling technique for heart and lung segmentation using electrical impedance tomography. Freichis *et al* compared EIT and CT images to study pulmonary perfusion. Their results indicate that EIT imaging of lung perfusion is feasible when an electrical impedance contrast agent (hypertonic saline) is used.[34] Anneli *et al* studied the V/Q ratio in porcine model.[35] Six mechanically ventilated, anaesthetised pigs in the supine position were studied at baseline, after inflation of a balloon in the inferior cava to reduce cardiac output and after an increased positive end-expiratory pressure (PEEP) of 20 cmH_2O (PEEP 20) to increase pulmonary aeration. EIT measurements were performed at the midthoracic level to measure the amplitude of impedance changes related to ventilation (ZV) and perfusion (ZQ), both globally and in four defined regions of interest (ROI) extending from the ventral to dorsal distance. Significant positive and negative correlations were demonstrated between fractional alveolar dead space ($r2 = 0.63$ [regression coefficient]) and venous admixture ($r2 = 0.48$), respectively, and the global ZV/ZQ ratio. This field is under ongoing research.

Limitations of EIT

Although EIT is a wonderful tool in respiratory care, it has its own limitations. One of these limitations is the relatively low image resolution of EIT. Although improvements in image quality can be expected with the development of advanced image reconstruction algorithms,[36] the spatial resolution of EIT images can never match the resolution of CT images.[37] The limitation of individual application of electrodes in different planes has been overcome by development of electrode belts applied around chest wall. EIT is complementary rather than a replacement for conventional imaging techniques.

Conclusion

EIT is a radiation-free, real-time bedside monitoring tool to assess the regional ventilation distribution and to focus on the region of interest (ROI) and its dynamic changes during ventilation. It assists the clinician to adopt necessary steps to improve regional ventilation. It has been validated over years and still being validated for routine clinical use. Despite the limitations, EIT is likely to complement other imaging modalities such as CT scan and ultrasound for the care of ventilated patients in coming future.

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