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Electrical impedance tomography for diagnosis and monitoring of pulmonary function disorders in the intensive care unit — case report and review of literature

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Abstract

The aim of this paper is to describe the possibility of using Electrical Impedance Tomography (EIT) as a treatment monitoring tool in the ICU. It was based on case report and literature review. A 19-year-old female was admitted to ICU due to severe acute respiratory distress syndrome. Despite aggressive treatment there was no improvement. We decided to use EIT in the monitoring of treatment because of difficulties in transporting the patient to the radiology department in order to perform a control CT scan. After identifying the causing factor (*Pneumocyctis jiroveci*), EIT monitoring was maintained to assess the effectiveness of targeted microbial treatment. In the following days, we observed an improvement of regional ventilation of the upper and middle segments of the left lung that corresponded well with laboratory test results, especially arterial blood gas analysis. The use of Electrical Impedance Tomography enables non-invasive, bedside, continuous assessment of regional lung ventilation. It is possible to use it in both mechanically ventilated and spontaneously breathing patients. It allows efficient and dynamic monitoring of the course of the therapeutic process. Interpretation of the results is relatively easy to learn and does not require specialist knowledge. Moreover, it is possible to use EIT in those cases where other methods are of high risk or contraindicated.

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Acute respiratory distress syndrome (ARDS) is one of the major causes of hospitalisation in intensive care units. The lung parenchyma in ARDS is characterised by substantial heterogeneity, which creates favourable conditions for uneven regional distribution of ventilation [1]. Beside the atelectatic areas, which are not involved in gas exchange, there are the portions of normal ventilation. The atelectatic areas are predominantly located in the dorsal parts [2–4]. This nonhomogenous structure of the lungs is mainly responsible for their more severe injury during mechanical ventilation [4] while increased vascular resistance of pulmonary capillaries leads to increased right ventricular afterload. This increase can ultimately result in acute right ventricular failure, which markedly worsens the prognosis of ARDS patients [5, 6].

The majority of patients with ARDS require invasive mechanical ventilation. Non-invasive ventilation (NIV) can be used only in a small proportion of such cases [7]. Irrespective of the type of respiratory support, the efficacy of treatment has to be continuously monitored in all patients. In everyday clinical practice, monitoring involves arterial and mixed venous blood gasometry, capnometry and evaluation of parameters of ventilation mechanics. All the above parameters reflect the functional status of the lungs as a whole and not of their individual segments. The available and clinically useful tests enabling the assessment of regional pulmonary ventilation include computed tomography, magnetic resonance imaging and ultrasound examinations, all of which are static. In 2011, a novel method for continuous

imaging of regional pulmonary ventilation was introduced, i.e. electrical impedance tomography (EIT).

EIT enables quick visualisation of regional pulmonary ventilation. This method involves measurements of lung electrical resistivity based on the phenomenon of lung parenchyma resistivity to an electrical impulse, which increases with its aeration [8, 9]. A belt of electrodes is wrapped around the thoracic cavity; one pair of electrodes generates a slight, undetectable intensity (about 5 mA) current while the remaining electrodes record the electric potential. The tissue resistivity is calculated as a ratio of intensity to voltage [10]. Thanks to this method, data about the cross-sectional thoracic resistivity are obtained, hence the degree of aeration of individual pulmonary portions. The image is then analysed by dividing the pulmonary area into 4 layers in the dorsal-ventral system or sectors denoted as regions of interest (ROI) 1 to 4. The degree of aeration of a given region in a particular phase of the respiratory cycle is displayed on a monitor as various colours. White denotes the highest aeration regions while black is the colour of an unventilated region. The numerical values visible on the screen indecate the percentage of total resistivity increases (total ventilation) per individual layers or sectors.

CASE REPORT

A 19-year-old female patient was admitted to the ICU with symptoms of respiratory failure in the course of interstitial pneumonia of unknown aetiology. The symptoms occured about two weeks prior to admission in the form of general malaise, sore throat and an/the elevated temperature of 38°C. The general practitioner (GP) initially administered symptomatic antipyretic treatment, (paracetamol 500 mg every 12 h, inosine 1 g every 8 h). Due to the lack of improvement, intensified symptoms of infection, fever and markedly deteriorated condition of the patient, the GP administered empiric antibiotic therapy (amoxicillin 875 mg + clavulanic acid 125 mg every 12 h) along with anti-inflammatory, as well as antipyretic treatment (ibuprofen 200 mg every 6 h). Despite the management used, the symptoms of dyspnoea intensified and an X-ray showed fine macular densities in the form of interstitial lesions in the medial and inferior field of the left lung. Having considered the results and the patient's deteriorating condition, the patient was referred to the Department of Lung Diseases. During the first 24 hours post admission, the patient developed symptoms of acute respiratory failure with hypoxia and increasing respiratory acidosis. Therefore, she was transferred to the ICU. On admission to the ICU, the patient was conscious, with increased dyspnoea at rest, tachypnoea with a marked respiratory effort and cyanosis. Crackles and rattling sounds were auscultated over the lung fields, more intense on the left side.

Despite the passive oxygen therapy administered through a face mask (flow O_2 10 L min^{-1}), the symptoms of respiratory failure were confirmed by arterial blood acid-base balance testing: SpO_2 88–90%, PaO_2 53 mm Hg, $PaCO_2$ 29 mm Hg, pH 7.51. Mechanical ventilation was applied (FiO_2 0.5, PIP 25 cm H_2O, PEEP 8 cm H_2O) using the non-invasive method of continuous positive airway pressure (CPAP). Furthermore, monitoring of regional lung ventilation was initiated with EIT using a PulmoVista 500 (Drager, Medical GmbH, Germany).

The first EIT visualisation demonstrated markedly limited ventilation of the lung parenchyma predominantly involving the superior and medial field and, to a lesser extent, the inferior field of the left lung (Fig. 1). The image was consistent with the X-ray picture taken earlier. Based on the EIT image and considering the patient's deteriorating clinical condition and elevated inflammatory parameters (C-reactive protein [CRP] 22.11 mg L^{-1}, procalcitonin (PCT) 0.071 ng L^{-1}, WBC 18.13 G L^{-1}, neutrophils 12.68 G L^{-1} (84.5 %), once the material for bacteriological testing was collected, she was subjected to broad-spectrum empiric antibiotic therapy (ceftriaxone 2g every 12 h, clarithromycin 500 mg every 12 h), antiviral therapy (oseltamivir 75 mg every 12 h) and antifungal therapy (fluconazole 400 mg during the first 24 hours and then 200 mg every 24 h). Moreover, screening for HIV was performed (anti-HIV antibodies — negative).

During the subsequent hours of treatment, the presence of influenza A (including AH1N1) and B virus was excluded. Likewise, the results of blood and sputum cultures were negative. Due to elevated parameters and lack of improvement of the patient`s condition, which was also reflected in EIT monitoring, the sputum was sampled and cultured for antigens of atypical bacteria (*Mycoplasma pneumoniae*, *Legionella pneumophila*, *Chlamydia sp.*, *Pneumocystis jiroveci*). The results confirmed the presence of Pneumocystis jirovec and cysts. Treatment with trimethoprim/sulfamethoxazole was initiated (960 mg every 4 h). After five days of treatment, the patient`s condition and
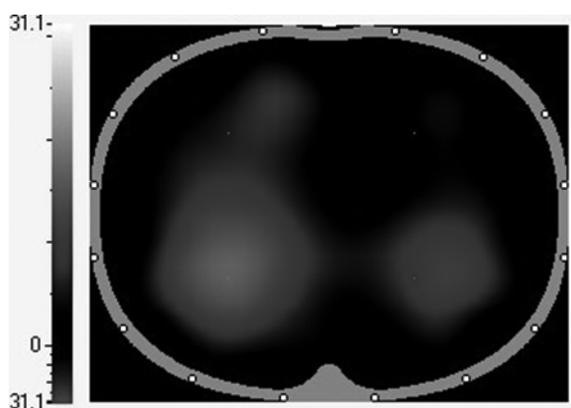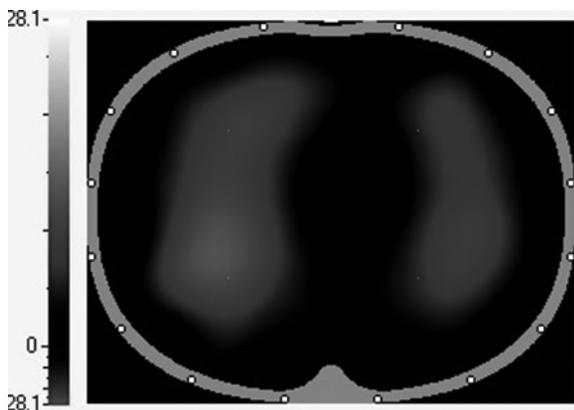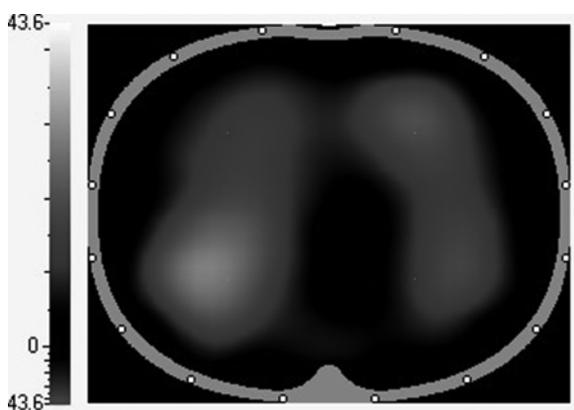

Figure 1. EIT scan at onset of NIV-CPAP

Figure 2. EIT scan 48 hours after the initiation of targeted therapy

Figure 3. EIT scan on discharge

gasometric parameters markedly improved (PaO$_2$ 63 mm Hg, PaCO$_2$ 34 mm Hg, pH 7.46). Moreover, the inflammatory parameters normalised (CRP 1.9 mg L^{-1}, WBC 7.14 G L^{-1}, neutrophils 3.99 G L^{-1} [55.9 %]). The above changes strictly correlated with EIT imaging (Figs 2, 3), demonstrating a gradual improvement of aeration of individual lung fields; based on the above findings, the parameters of NIV-CPAP were gradually reduced (FiO$_2$ 0.21, PIP 12 cm H$_2$O, PEEP 4 cm H$_2$O) until the complete withdrawal of ventilation and subsequent provision of periodic passive oxygen therapy.

On day 9, the patient was transferred to the Department of Lung Diseases to continue the treatment and a diagnostics of the causes of an atypical bacterial infection. On discharge, the patient's respiration was efficient (SpO$_2$ 94–96%), gasometry was normalised (PaO$_2$ 85 mm Hg, PaCO$_2$ 36 mm Hg, pH 7.43), while inflammatory parameters and bacteriological results were negative.

DISCUSSION

The modern methods of lung imaging enable to diagnose and verify the therapeutic management in many respiratory diseases. Both computed tomography and magnetic resonance imaging have been commonly used providing very good quality and high-resolution images. In many cases, they allow to determine the causes of disease, provide a quick reliable diagnosis and suitable management. However, they also have their limitations. They are not safe in all groups of patients due to the use of X -rays or a magnetic field.

Contraindications for CT are associated with the Atomic Energy Act, as well as the directive of the Minister of Health and mainly include pregnancy or suspected pregnancy and allergy to contrast media (whenever used). Absolute contraindications for magnetic resonance imaging are implanted electric and electronic devices, in particular pacemakers, insulin pumps, hearing aids, neurostimulators, intracranial metal clips or metallic bodies in the eye.

An important issue, especially in intensive care units, is the procedure or method itself. The transport of critically ill patients poses a risk of severe complications. The study findings demonstrate that the incidence of complications during intra-hospital transport ranges from 5.9 to 66% [11–13]. The major risks relate to the central nervous, cardiovascular and respiratory systems. Disorders of these systems can develop quickly, without initial symptoms and lead to sudden cardiac arrest. Moreover, during the majority of transports, there are periods when the patient's condition is supervised only clinically, despite optimal equipment, e.g. while moving a patient from bed to a wheelchair. An essential problem during intra-hospital transportation from an ICU is mechanical ventilation, which is usually administered according to regulations which differ from those in the ICU (different mode of ventilation of a portable transport ventilator or ventilation using a self-expandable bag). A change in the mode of ventilation and the equipment used for it can cause blood oxygenation disorders [14, 15]. According to Waydhas [16], in about half of patients blood oxygenation deteriorates after the change of devices and mode of ventilation while in 20% of patients the gas exchange returns to baseline parameters after 24 hours and not sooner. Moreover, the transportation of mechanically ventilated patients itself is considered an independent risk factor for ventilator-associated pneumonia [17].

In view of the MRI/CT contraindications described above and the difficulties regarding transportation, the risk-benefit ratio should be taken into account. Furthermore, during treatment of pneumonia or ARDS, therapeutic management should be verified by repeating the examination, which substantially limits the use of MRI/CT as bedside methods deemed safe for patients. For this reason, these methods are rarely used to evaluate and monitor regional distribution of lung ventilation during treatment of respiratory diseases. US imaging, on the other hand, requires appropriate experience and is highly subjective [18, 19].

EIT is the newest technology used for lung imaging. The method is based on measurements of the lung's electrical

resistivity, and is characterised by high time usu resolution, which enables following the changes in a real time the changes in real time [20]. As EIT is non-invasive and virtually causes no adverse side effects (lack of radiation, no transport required), the method has become an attractive alternative to computed tomography, magnetic resonance imaging or ultrasound examinations. Many comparative medical trials have proved that the EIT results are reliable and repeatable [21–29].

Electrical impedance tomography has already been used to evaluate mechanical ventilation in patients with acute respiratory distress syndrome [30–32]. The parameters obtained by EIT have been applied to observe the regional lung response to the recruitment manoeuvre [33], to regulate PEEP [34, 35], VT [36] and FiO_2 [37]. The method allows to adjust optimal parameters of ventilation in severe cases of ARDS to ensure appropriate blood oxygenation. Moreover, it provides information about the side effects of mechanical ventilation enhanced by some diseases, i.e. ARDS, COPD, lung cancer, cystic fibrosis or ageing-associated processes [38–40]. Electrical impedance tomography has also been used to detect pleural oedema [41, 42], changes in respiratory parameters after aspiration [43] and to evaluate one-lung ventilation [44]. Furthermore, EIT has been applied to evaluate regional perfusion of the pulmonary tissue, cardiac output and interactions between these parameters [45–47]. This bedside examination is safe and can be used in children and newborns. Indeed, it has been found that end-expiratory lung volume (EELV) increases and stabilises in newborns treated with surfactant [48]. Finally, EIT enables monitoring of lung volume changes during oscillatory ventilation in preterm infants [49, 50].

As any other method, electrical impedance tomography has its limitations. It is contraindicated or poses high risks in obese patients (BMI > 50 kg m^{-2}), those with tissue oedema, motor hyperexcitability, skin wound or lesions in the region where electrodes are attached, implantable active cardiac devices (pacemaker, cardioverter-defibrilator), during electrotherapy in which the placement of electrodes is risky (e.g. in patients with spinal cord injuries), during monitoring exceeding 24 hours, and during drainage of the pleural cavities.

SUMMARY

The use of electrical impedance tomography enables non-invasive bedside continuous monitoring of the aeration of individual portions of lung fields, both in mechanically ventilated and spontaneously breathing patients. The method is not used to visualise the structural changes in respiratory diseases (lung emphysema, bronchiectasis, tumours). However, since it is less harmful and easy to perform, EIT enables effective dynamic monitoring of the therapeutic

process. Moreover, it is relatively easy to learn how to interpret its results and no specialist knowledge is required. The method can be applied in cases where other methods pose high risks or are contraindicated, e.g. in pregnant women.

In our case, the use of electrical impedance tomography contributed to a quick and correct diagnosis. However, the biggest asset of EIT is its safety and low-invasiveness while monitoring the efficacy of treatment.

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