**Evaluation of Electrical Impedance Tomography in the Measurement of PEEP-Induced Changes in Lung Volume**

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**Study objectives:** A new noninvasive practical technique called electrical impedance tomography (EIT) was examined for the measurement of alveolar recruitment.

**Design:** Prospective clinical study.

**Setting:** ICU of a general hospital.

**Patients:** Acute respiratory failure (ARF) patients.

**Measurements:** The ventilation-induced impedance changes (VICs) of the nondependent and the dependent part of the lung were determined by EIT as a measure of tidal volume distribution. By the use of an impedance ratio (IR), defined as the VIC of the nondependent part of the lung divided by the VIC of the dependent part of the lung, the ventilation performances in both parts of the lung were compared to each other.

**Results:** Between patients, the VIC of the nondependent part of the lung was significantly lower in the patients with a level of positive end-expiratory pressure (PEEP) of > 10 cm H$_2$O than in patients with a PEEP of < 5 cm H$_2$O (p < 0.05). A significantly lower IR (± SD) was found in the group with PEEP of > 10 cm H$_2$O than in the group with PEEP between 0 and 5 cm H$_2$O (1.28 ± 0.58 vs 2.99 ± 1.24, respectively; p < 0.01). In individual patients, the VIC of the whole lung increased when the PEEP level was increased. The VICs of the nondependent part of the lung and of the dependent part of the lung showed significant increases at a PEEP of 10 cm H$_2$O compared to a PEEP of 0 cm H$_2$O (p < 0.05). Also the IR decreased in individual patients when the PEEP was increased; a significant decrease was found at 10 cm H$_2$O compared to 0 cm H$_2$O (1.67 ± 1.24 vs 2.23 ± 1.47, respectively; p < 0.05).

**Conclusions:** The decrease in IR indicates an increase in VIC in the dependent part of the lung above the nondependent part of the lung. The increase in VIC can be regarded as an increase in lung volume, implying alveolar recruitment in the dependent part of the lung. The same results also have been shown in earlier reports by CT scan. Since EIT is far more practical than CT scanning and also is a bedside method, EIT might help in the adjustment of ventilator settings in ARF patients.

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**Key words:** acute lung injury; electrical impedance; positive end-expiratory pressure; recruitment; tomography

**Abbreviations:** ARF = acute respiratory failure; EIT = electrical impedance tomography; IR = impedance ratio; LIS = lung injury score; PEEP = positive end-expiratory pressure; VIC = ventilation-induced impedance change; $V_t$ = tidal volume

In patients with acute respiratory failure (ARF), positive end-expiratory pressure (PEEP) often is applied to improve arterial oxygenation. By applying PEEP, changes in lung volume can be accomplished by recruitment of alveoli. However, the measurement of alveolar recruitment is difficult. A possible approach with which measure the amount of alveolar recruitment is CT scanning. Information about the recruitment of alveoli can be obtained from the static images constructed at different PEEP levels. However, the major disadvantage of CT scanning is the impossibility of using it frequently at the bedside. Furthermore, data are only provided by static images. A dynamic bedside method measuring changes in lung volume in different regions of the lung could be of value in the management of critically ill patients. Electrical impedance tomography (EIT) might provide such data. EIT is noninvasive and can...
be applied in clinical practice. The technique has been shown to provide dynamic images of regional ventilation. The impedance changes that are measured can be visualized in a two-dimensional image. By selecting different lung regions of interest, regional differences in the impedance changes can be measured, and, therefore, lung volume can be inferred. It has been shown that ventilation-induced changes in electrical impedance measured by EIT have a linear relationship with tidal volume (VT) in individual subjects. However, between different subjects that have all been ventilated with the same VT, the ventilation-induced impedance changes may differ due to the influence of the amount of lung parenchyma and lung edema. Therefore, the main contribution of EIT would appear to be the ability to determine independently the nondependent and dependent lung contribution to VT in an ARF patient.

The objective of the present study is to show whether the regional impedance changes measured by dynamic imaging using EIT in critically ill patients will reflect the change in alveolar recruitment induced by PEEP. For this purpose, the study was divided into two parts.

In the first part of the study (Part 1), differences between patients at different levels of PEEP were investigated; in the second part (Part 2), the intraindividual differences in impedance changes were investigated at different levels of PEEP.

**Materials and Methods**

**Patients in Part 1**

The study was performed in the ICU of the ZCA hospital in Apeldoorn, The Netherlands. Twenty consecutive patients with noncardiogenic ARF were included. The diagnosis was based on the presence of respiratory distress with dyspnea and tachypnea, hypoxemia (PaO₂ of < 200 mm Hg), and bilateral and diffuse opacities on the chest roentgenogram in the absence of an elevated pulmonary capillary wedge pressure (< 18 mm Hg). Patients were mechanically ventilated with pressure control ventilation (Servo 900C; Siemens-Elema AB; Solna, Sweden). The levels of PEEP and the fraction of inspired oxygen were chosen according to clinical requirements. The lung injury score (LIS) was computed as described by Murray et al., using the number of quadrants involved on the chest roentgenogram, the arterial PaO₂/fraction of inspired oxygen ratio, the level of PEEP, and the quasi-static compliance (the VT divided by pause pressure minus total end-expiratory pressure), with each item scored from 0 to 4. The mean of the scores gives the LIS.

**Study Design of Part 1**

In the first part of the study, EIT measurements were performed with the electrodes attached at the third intercostal level determined in the midclavicular line. Two EIT measurements were recorded for 60 s each, with a 30-s interval between the measurements. During and in between the measurements ventilator settings were not changed.

**Technical Aspects of EIT**

In this study, EIT measurements were made using the Sheffield Applied Potential Tomograph (Model DAS-01P Portable Data Acquisition System, Mark I; IBEES; Sheffield, England), which has been described previously. Briefly, EIT is a technique that produces 2-day images of physiologic changes in impedance by means of 16 standard ECG electrodes that are placed around the object measured. An alternating current (50 KHz; 5 mA peak to peak) is injected between a circulating pair of adjacent electrodes, and the remaining electrodes are used to measure impedance. When all electrodes are used as injecting electrodes, one data collection cycle is completed. In order to minimize artifacts in the present study, 10 data collection cycles were averaged to obtain one image or frame. During the entire measurement a sequence of frames at 1.13-s intervals was recorded. The Sheffield Applied Potential Tomograph generates difference images to a reference set. Therefore, only physiologic processes that cause changes in impedance can be imaged.

In the thorax, major changes in impedance occur due to the inspiration and expiration of air. Therefore, in the sequence of images, the change in impedance due to the inflation of air can be visualized and studied. After defining a region of interest in the 2-day image, the impedance changes occurring over time are plotted in a curve and numerical values are obtained. Because the reconstruction algorithm of the EIT is based on differences in impedance, the average impedance change has no unit and is expressed as an arbitrary unit.

**Image Analysis with EIT**

In the present study, the total image (788 pixels), comprising the upper and the lower parts of the lung, was studied by dividing the EIT image along the midline into nondependent (394 pixels) and dependent (394 pixels) parts of the lung. From the obtained curves, the maximal difference in impedance between inspiration and expiration (so-called ventilation-induced impedance change [VIC]) was calculated. An impedance ratio (IR) was used in this study to investigate differences between the nondependent part of the lung and the dependent part of the lung. The IR was defined as the VIC of the nondependent part of the lung divided by the VIC of the dependent part of the lung.

**Statistical Analysis**

Data are presented as the mean ± SD. Differences during separate levels of PEEP were analyzed by using the Mann-Whitney test. Also, analysis of variance was used to compare the differences in IR between three categories of PEEP (0 to 5, 5 to 10, and > 10 cm H₂O).

**Patients in Part 2**

Six patients who underwent elective abdominal surgery were included in the study. Patients were mechanically ventilated with volume-control ventilation (Servo300; Siemens-Elema AB). The baseline ventilatory settings were a VT of 8 ml/kg and a respiratory rate of 17 breaths/min. Each patient was measured at four different levels of PEEP (0, 5, 10, and 15 cm H₂O). The inspiratory plateau pressure was said not to exceed 35 cm H₂O. Patients with a history of chronic pulmonary disease were excluded, since the impedance signal may be confounded by relatively poorly ventilated areas in emphysematous lungs. Dur-
ing all the measurements, patients were in the supine position. The protocol had been approved by the local ethics committee, and informed consent was obtained from the patient or the closest relative to each patient.

Study Design of Part 2

The second part of the study was performed as described by Gattinoni et al. Each patient was measured at four different PEEP levels (0, 5, 10, and 15 cm H₂O). Each PEEP was maintained for 5 to 10 min before repeated EIT measurements were obtained. EIT measurements were made at the basis of the lungs, as described by Gattinoni et al. All other ventilatory settings were kept constant throughout the procedure. After the measurements were completed, PEEP was increased by 5 cm H₂O and the same procedure was repeated.

Image Analysis with EIT

Also in this study, the total image (788 pixels), comprising the upper and the lower parts of the lung, was studied by dividing the EIT image along the midline into nondependent (394 pixels) and dependent parts (394 pixels) of the lung. The VIC and IR were calculated.

Statistical Analysis

Data are presented as the mean ± SD. The paired Wilcoxon signed rank test was used to investigate intraindividual differences at different PEEP levels.

RESULTS

Part 1

All patients had ARF resulting from sepsis. Sources of sepsis were abdominal (7), pulmonary (12), and urinary tract infections (1). All patients were measured once. Patients were separated into three groups according to the level of PEEP necessary for their clinical requirements. Five patients were receiving PEEPs between 0 and 5 cm H₂O (group A), six patients between 5 and 10 cm H₂O (group B), and nine patients > 10 cm H₂O (group C).

The VIC of the nondependent part of the lung was significantly lower in group C than in group A (p < 0.05). No significant difference values for the VIC in the dependent part of the lung were found between groups C and A. A significantly lower IR was found in group C than in group A (1.28 ± 0.58 vs 2.99 ± 1.24, respectively; p < 0.01; Fig 1). A significantly higher LIS was present in group C than in group A (2.86 ± 0.37 vs 1.55 ± 0.41, respectively; p < 0.005).

Part 2

In three of the six patients, PEEP was not increased to 15 cm H₂O as inspiratory plateau pressure exceeded 35 cm H₂O. In all patients, the VIC of both parts of the lung increased significantly with increasing PEEP. The VIC of the nondependent part of the lung showed a significant increase at a PEEP of 10 cm H₂O compared to a PEEP of 0 cm H₂O (p < 0.05). Also, the VIC of the dependent part of the lung showed a significant increase at a PEEP of 10 cm H₂O compared to a PEEP of 0 cm H₂O (p < 0.05). No significant difference was found for
the VIC of the nondependent and the dependent parts of the lung at a PEEP of 5 cm H₂O compared to a PEEP of 0 cm H₂O. In all six patients, the IR decreased when the PEEP was increased (Fig 2). A significant decrease in IR was found at a PEEP of 10 cm H₂O compared to a PEEP of 0 cm H₂O (1.67 ± 1.24 vs 2.23 ± 1.61, respectively; p < 0.05).

**DISCUSSION**

The objective of this study was to investigate the use of EIT for measuring alveolar recruitment during mechanical ventilation at different levels of PEEP in ARF patients by comparing the regional impedance changes of the nondependent and dependent parts of the lung. First, interindividual differences in ARF were investigated, and thereafter the intrathree individual differences were examined in patients undergoing elective abdominal surgery. The latter group was chosen because it is known that in those patients collapse of alveoli occurs at the dorsal parts of the lungs and results in differences between the nondependent and dependent parts of the lung.

In the first part of the study, a significantly lower VIC in the nondependent part of the lung was found in patients at high levels of PEEP compared with those at low levels of PEEP, whereas in the dependent part of the lung no difference was found. The lower VIC in the nondependent part of the lung is influenced by the decrease in lung volume due to an increase in the severity of ARF. In our study, a significantly higher LIS was found in the group at high PEEP levels, indicating the increase in severity of ARF. The significant increase in IR at higher PEEP levels suggests an increase of Vt in the dependent part of the lung, and thus alveolar recruitment at higher levels of PEEP. However, VIC is not solely determined by the Vt, but also by the amount of lung parenchyma and lung edema. Therefore, in the second part of the study, intrathree individual PEEP-induced changes were measured by EIT.

To keep the amount of extravascular lung water or the severity of ARF from having an influence on the measurements, the time between the increase of PEEP and the measurement was designated to be 10 min, as it is known that the increase in lung volume is fast, but the effect of PEEP on extravascular lung water is small within this time period. The significant intrathree individual increase in VIC of both lungs by increasing PEEP suggests the increase of total alveolar volume by PEEP. The finding in the second part of the study that ventilation in the dependent part of the lung showed a significant increase in impedance change at higher PEEP levels indicates that an increase in lung volume due to the recruitment of alveoli or the distension of already expanded lung units occurs in the dependent part of the lung. The significant increase in impedance change in the dependent part of the lung by applying PEEP suggests the same finding: recruitment or opening of alveoli in this part of the lung. The IR, a ratio for the difference between the nondependent and the dependent parts of the lung, decreased significantly at a PEEP of 10 cm H₂O compared to 0 cm H₂O, indicating that the mentioned alveoli recruitment in the dependent part of the lung is higher than that in the nondependent part. This effect was significant at PEEP levels of > 5 cm H₂O.

To show regional differences in lung volume by a technique that can be used frequently at the bedside and is noninvasive may offer great possibilities. First, by using information about the recruitment of the alveoli in the nondependent part of the lung, ventilator settings may be determined, and individual ventilator settings may have beneficial effects on mortality. Second, with the possibility of using EIT frequently, ventilator settings can be adapted as often as possible. Third, increasing PEEP may decrease the compliance of the alveoli in the upper part of the lung due to overstretching of the alveoli. To what extent the EIT signal indicates the amount of stretching, and thus indirectly the risk of volutrauma and barotrauma, needs to be explored. Further research is needed to explore this field.

Several disadvantages exist when using EIT. First, EIT has a moderate spatial resolution. A maximal spatial resolution, given as 10% of the electrode array diameter, indicates that two points that are 2 cm from each other can be seen as two individual points. Therefore, EIT can only compare global regions and not regions having great anatomical precision. Because, in this study, only differences between the nondependent and dependent halves of the lung are important, this lack of definition is less relevant. Second, blood volume changes in the thorax may induce impedance changes. Because the impedance changes due to ventilation are much higher than those of lung perfusion (300% vs 3%, respectively), the impedance change measured can be considered to be due to the volume of air. By averaging 10 cycles in each image, the perfusion will be averaged and its influence will be further minimized.

Notwithstanding these disadvantages, the results of this study revealed a gradient from the nondependent to the dependent part of the lung that is similar to the results found by Gattinoni et al by CT scan. This underlines the assumption that EIT can measure the recruitment of alveoli, although no blood gas measurements were performed at the different levels of PEEP in the second study. The major
advantage of EIT over CT is its much easier applicability. Not only can EIT be used frequently next to the bedside, EIT also is noninvasive, inexpensive, uses no radioactive beaming, and can show the dynamic changes of lung volume over time. However, at this moment, no well-defined clinical studies on EIT are available. The demonstrated similarity between EIT and CT scan is promising. In conclusion, the use of EIT in the measurement of regional alveolar recruitment seems promising and may, therefore, be helpful in the adjustment of mechanical ventilation in ARF patients.

REFERENCES