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Effects of pleural effusion drainage in the mechanically ventilated patient as monitored by electrical impedance tomography and end-expiratory lung volume: A pilot study

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ABSTRACT

Purpose: In patients with pleural effusion (PLE) monitored by Electrical Impedance Tomography (EIT) an increase in end-expiratory lung impedance (EELI) is observed following evacuation of the PLE. We aimed at differentiating the effect of fluid removal from lung reaeration and describe the change in ventilation distribution.

Materials and methods: Mechanically ventilated patients were monitored by EIT during PLE evacuation. End-expiratory lung volume (EELV) was measured concurrently. We included a calibration maneuver consisting of an increase in positive end-expiratory pressure (PEEP) by 5 cm H_2O. The ratio ΔEELI/ΔEELV was used to compare changes of EELI and EELV in response to the calibration maneuver and PLE evacuation. At the same time we assessed distribution of ventilation using changes in tidal variation.

Results: PLE removal resulted in a 6–fold greater increase in ΔEELI/ΔEELV when compared to the calibration maneuver ($r = 0.84$, $p < .05$). We observed a relative increase in ventilation in the area of the effusion (mean 7.1%, $p < .006$) and an overall shift of ventilation to the dorsal fraction of the lungs (mean 8%, $p < .0002$).

Conclusions: The increase in EELI in the EIT image after PLE removal was primarily due to the removal of the conductive effusion fluid.

1. Introduction

Critically ill patients frequently have a disorder of the distribution and volume of body fluids, one manifestation of which is pleural effusion (PLE) formation [1]. According to observational studies 50% to 60% of mechanically ventilated patients develop pleural effusion [2]. PLE may affect pulmonary mechanics and gas exchange, but the consequences are variable and individual. They are determined by anatomical conditions, coexisting pathologies of the pulmonary parenchyma, and the rate of effusion development. The impact of PLE on the clinical outcomes of critically ill patients is unclear and thus the clinical value of fluid evacuation is uncertain [3,4]. The reference method for PLE diagnosis is computed tomography (CT). However, in the intensive care unit ultrasound is routinley used as an excellent and reliable means of assessing the lungs, pleural cavities and PLE [5]. The accuracy of ultrasound in PLE detection is 93% when compared to CT [6].

Electrical impedance tomography (EIT) is a well-known diagnostic method that provides a planar view of the conductivity of the evaluated environment. It is a bed-side, non-invasive, inexpensive, and radiation-free imaging modality that offers real-time information about the investigated area [7,8]. In clinical practice functional EIT (fEIT) is typically used [8]. fEIT calculates changes in tissue conductivity between a set baseline and the current time frame. Therefore only relative impedance changes expressed in arbitrary units (A.U.) are observable and areas of constant impedance (like pleural effusion) are not easily analyzed. The use of EIT to monitor ventilation and the effect of treatment interventions is common [8-10].

The first study on the effect of changes of thoracic fluid content on thoracic electrical impedance was published over 40 years ago [11] but those dealing with EIT and the presence or the removal of PLE are rare [10,12-15]. A recent study showed a possible diagnostic tool that could help detect pleural effusion using out-of-phase impedance changes [16]. After removal of pleural effusion a significant increase of end-expiratory lung impedance (ΔEELI) has been observed in spontaneously ventilating as well as mechanically ventilated patients [16,17]. The clinical value of such information is uncertain however, because ΔEELI could result not only from increased aeration of lung tissue which was previously compressed by the effusion but also from the removal of the conductive fluid itself.

The aerated lung tissue in ventilated patients corresponds to end-expiratory lung volume (EELV) and its manipulation through changes in positive end-expiratory pressure (PEEP) which is commonly used as a means of improving oxygenation and ventilation mechanics. In

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other words, changes in EELV correspond to variations in lung aeration. In several trials a good to moderate correlation between ΔEELI and change in end-expiratory lung volume (ΔEELV) was decribed [18,19].

For these reasons we designed a study that combines EIT monitoring with concurrent EELV measurement before, during and after elimination of pleural effusion in mechanically ventilated patients. Our objective was to determine whether EIT could be used for assessment of lung re-aeration after PLE evacuation. Concurrently we attepmted to determine the relative contribution of lung aeration and fluid removal on the change in EELI.

2. Material and methods

We performed a prospective interventional study in the intensive care unit (ICU) of The Military University Hospital in Prague. It was approved by the Ethics committee (RN 108/9–107/2016) and registered in ClinicalTrials.gov (NCT03231072). The requirement for written informed consent was waived by the ethics committee. Patients were recruited from January 2017 to March 2018.

Once likely pleural effusion was identified in a patient on mechanical ventilation it was assessed by ultrasound, Ultrasonix Sonix Touch (Ultrasonix Medical Corporation, Richmond, Canada). If the distance from chest-wall to lung parenchyma was over 30 mm and the attending physician indicated fluid removal the patient could be enrolled in the study. We included patients in which the PLE developed in the course of acute disease. Patients suffering from pneumonia, ARDS, or those with lung contusion or lung tumor complications were excluded as well as those that would require excessive sedation or even muscle relaxation to ensure ventilator synchrony during measurement.

All patients were in the supine position with the upper half of the body elevated by 20° and were sedated with propofol and sufentanil. Patients received synchronized intermittent mandatory ventilation via a cuffed endotracheal tube using an Engström Carestation ventilator (GE Healthcare, Madison, Wisconsin) that enables measurement of end-expiratory lung volume (EELV) by oxygen wash-in/wash-out technique. Tidal volume was set to 6–7 ml/kg of ideal body weight. Other ventilator settings remained the same as before the study except for the EIT calibration maneuver (ECM), which was carried out by PEEP elevation of 5 cm H_2O for 5 min before and after PLE removal. EELV was measured before, during, and after each EIT calibration maneuver with six measurements in total. The point of drainage was identified by ultrasound and infiltrated with local anaesthetic (trimecaine), with consideration to the intended location of the EIT belt. The selection of drainage set or chest tube and its insertion was performed by the attending physician. The 16-electrode belt was placed at the level of the 4-6th intercostal space at the parasternal line and connected to the PulmoVista 500 system (Dräger Medical, Lübeck, Germany). EIT recording with a scan rate of 50 Hz was started and continued throughout the procedure (Fig. 1). As soon as fluid ceased to appear in the collection system, the drainage was considered to be complete for the purposes of our measurements. The procedure itself took one hour on average. The fluid was routinely examined according to the attending physician's orders. All interventions were completed without complications.

Analysis of the raw EIT data was done offline by Dräger EIT Data Analysis Tool 6.1. (Dräger Medical, Lübeck, Germany), Microsoft Excel 2010 (Microsoft, Seattle, WA, USA) and Matlab (MathWorks, Inc., Natick, Massachusetts, USA). The selection of the baseline for fEIT data reconstruction has a substantial effect on evaluation of EELI and thus EELV, therefore a single baseline for EIT data reconstruction was selected for each patient at a minimum impedance value during the EIT recording segment before fluid evacuation [20]. We used the default regions-of-interest (ROI) in layers and quadrants that the Dräger software offers, which were applied to the whole image. The end-expiratory lung impedance (EELI) was defined as the average of the end-expiratory global impedance values of 10 consecutive breaths in a specific time span. Ventilation was calculated using the tidal variation (TV) of impedance, defined by the software's breath-detection algorithm as the average difference between the maximum and minimum impedance values achieved during the 10 measured breaths. The ventilation change (ΔTV) in a specific fraction of the lung or ROI was calculated as the relative change of TV in percent. The lung adjacent to the PLE was arbitrarily defined as ipsilateral.

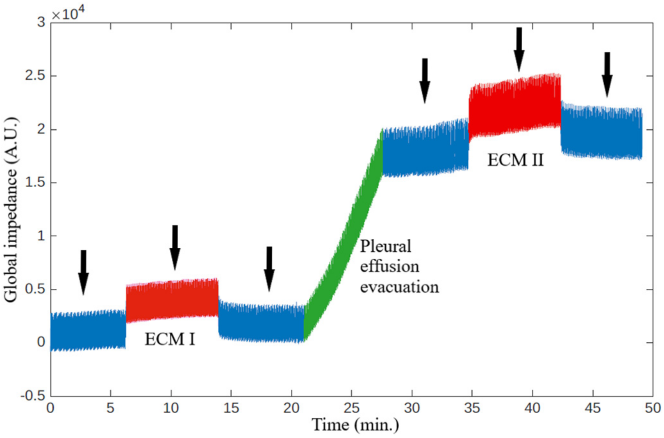

Fig. 1. EIT record of global impedance (i.e. end-expiratory lung impedance, EELI) of one patient during the entire course of measurement with study protocol events labeled. Black arrows—EELV measurement; Red sections—EIT calibration maneuvers (ECM I and II); Green section—evacuation of pleural effusion. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

3. Data analysis

Results were evaluated using a two-tailed Student's *t*-test for the comparison of two continuous variables. Normality of data was tested using the Kolmogorov-Smirnov test. Comparison of categorical variables was done using the chi-square test. Correlations between variables were assessed using Pearson's r coefficient. The limit of statistical significance was defined as $p = .05$. STATISTICA 13.5 software (TIBCO Software Inc., Palo Alto, CA, USA) was employed in statistical evaluation. Results are presented as mean ± standard deviation (SD).

4. Results

A total of 19 patients was included in the study. Of these, 4 were additionally excluded due to interference with the ventilator despite sedation and 2 discarded during data processing for inconsistent measurements and poor EIT image quality. There were 8 women and 5 men in the evaluated group, other characteristics are detailed in Table 1.

Table 1
Basic patient characteristics.

Parameter	
Age (years)	64 ± 15 (32–82)
Height (cm)	166 ± 11
Weight (kg)	64 ± 14
PEEP (cm H_2O)	7 ± 2
Tidal volume (ml)	476 ± 50
Pmax. (cm H_2O)	21 ± 5
Respiratory rate (per min.)	15 ± 2
Effusion site left (n)	7
Main diagnosis (n)	
Sepsis	6
Trauma	2
Abdominal tumor resection	3
Other	2

PEEP—positive end-expiratory pressure; P-max—peak inspiratory pressure; n—number of patients. Values are expressed as mean ± standard deviation with range for age only.

Table 2
Changes in EELI and EELV, summary.

	EIT calibration maneuver I	EIT calibration maneuver II	PLE evacuation
ΔEELI (A.U.)	2244 ± 1216	3495 ± 2462	6947 ± 3436
ΔEELV (ml)	423 ± 136	385 ± 115	240 ± 107
ΔEELI/ΔEELV (A.U./ml)	5.5 ± 2.8	9.2 ± 6.2	35.2 ± 22.6

EIT calibration maneuver I and II (PEEP increase by 5 cm H_2O) prior to and after fluid evacuation; ΔEELI—change in expiratory lung impedance; ΔEELV—end-expiratory lung volume change; PLE—pleural effusion.
Results are presented as mean ± standard deviation.

4.1. Global ventilation

An overview of ΔEELV and ΔEELI measurements is given in Table 2. The volume of drained fluid was 625 ± 204 ml, with a range of 380–1100 ml. After PLE removal we observed a ΔEELI of 6947 ± 3436 A.U. and at the same time a ΔEELV of 240 ± 107 ml. There was a correlation of drained volume to ΔEELV ($r = 0.60$, $p < .05$) as well as to ΔEELI ($r = 0.52$, $p < .05$). ΔEELI was inversely proportional to chest circumference ($r = -0.70$, $p < .05$) and grew in the area where the PLE was localised (Fig. 2). We found no effect of PLE drainage on airway resistance or dynamic compliance.

We calculated the ratio ΔEELI/ΔEELV (A.U./ml) to follow the association between ΔEELI and ΔEELV during the EIT calibration maneuver and after PLE removal and compared the values for both cases. Results are in Table 2. The ratio of ΔEELI/ΔEELV (A.U./ml) after evacuation of the fluid was on average 6.4 times greater than during ECM I and, as shown in Fig. 3, the ratios were correlated ($r = 0.84$, $p < .05$).

The global TV before PLE evacuation was 2546 ± 963 A.U., after the withdrawal of the fluid it was 2915 ± 1093 A.U. corresponding to an increase of TV in 12 patients (429 ± 340 A.U.), in 1 patient a decrease was observed. The change in global TV in response to both calibration maneuvers was variable (from −800 to +500 A.U.).

4.2. Local ventilation

There was a relative increase of TV of 7.1% ± 7.6% ($p < .006$) in quadrant ROI 3 or 4 where the maximum of the PLE was previously localised. In 11 patients we observed an overall increase in ipsilateral lung ventilation up to 10% of TV, but in 2 cases the trend was reversed (7.3 and 4.4%, respectively). The lateral redistribution of TV after PLE removal however, was not statistically significant ($p = .92$).

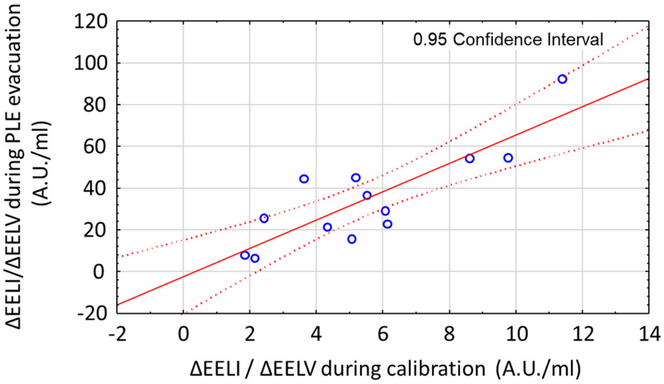

Fig. 3. The correlation between ΔEELI/ΔEELV ratio (A.U./ml) during EIT calibration maneuver I and after pleural effusion evacuation.

Concerning anteroposterior ventilation distribution, after PLE evacuation there was a shift of TV to the dorsal lung fraction, i.e. layers ROI 3 and 4, of 8% ± 5.5% ($p < .0002$), after ECM I 9% ± 5.5% ($p < .0002$) and ECM II 4% ± 2.7% ($p < .0002$).

Layers ROI 2 and 3 represent the middle parts of the lungs which initially contained 78.8% ± 6,8% of global TV, followed by a small decrease after effusion removal of 2.7% ± 3.5% ($p < .03$) shifting towards ROI 4.

5. Discussion

We showed that the increase in global impedance following effusion evacuation does not fully correspond to the improvement of lung aeration but is largely influenced by the removal of the conductive pleural fluid. Therefore, the functional EIT itself is not a suitable tool for evaluating the impact of PLE evacuation on lung aeration.

The increase of EELV immediately after effusion evacuation was about one third of the volume of the evacuated effusion, which is similar to earlier published data [21]. Although the increase in EELV was more pronounced during the calibration maneuvers the change in EELI per unit change in EELV, i.e. the ratio ΔEELI/ΔEELV, was 4–6 times greater after effusion evacuation (Table 1). If the observed change in EELI after effusion evacuation corresponded only to changes in lung tissue aeration—as with the calibration maneuver—the corresponding increase in EELV would be larger than the effusion volume. The strong influence of the removal of conductive material is supported by the fact that EIT

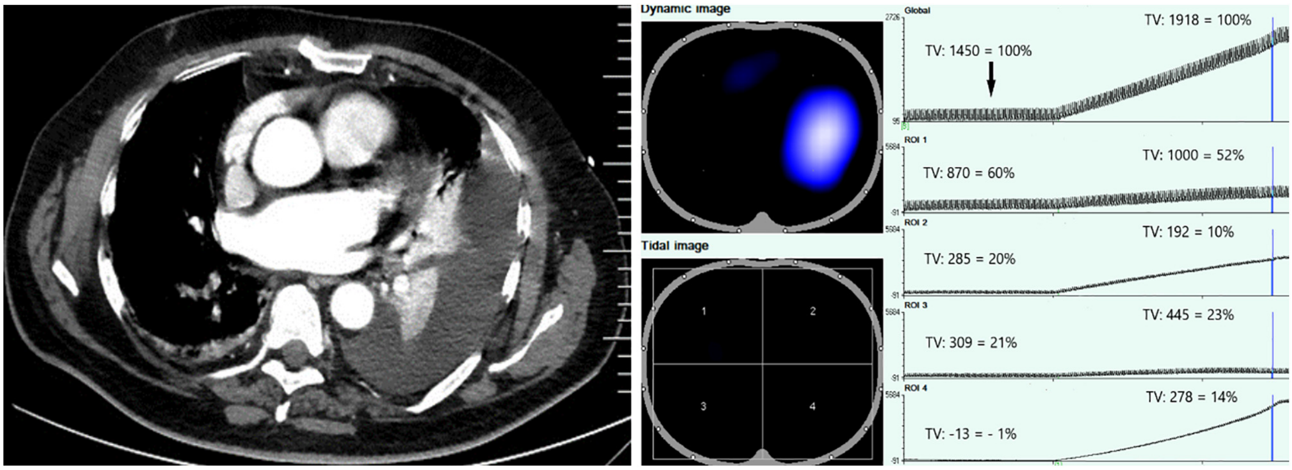

Fig. 2. Left: CT scan, left-sided pleural effusion, patient with urosepsis. Right: the same patient, EIT record, before and during evacuation of PLE, PulmoVista 500 system, modified. Region-of-interest (ROI) in quadrants. Black arrow—time of tidal variation (TV) distribution (%) in ROI before evacuation. Vertical blue line—time of the dynamic image in the upper left corner and corresponding TV distribution (%) in ROI after PLE evacuation. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is very sensitive to even a small evacuated fluid volume and a steep increase of impedance was visible in the area that anatomically corresponded to the PLE site (Fig. 2).

According to global tidal variation we observed mainly an increase in ventilation after PLE removal while in the course of calibration maneuvers this trend was not apparent. This is probably due to the fact that PEEP elevation influences more the whole lung and the response at the cross section of EIT belt is therefore quite variable.

Our results further showed a significant increase in ventilation in the quadrants previously occupied by the effusion. This may indicate definite lung re-aeration [16] but a concurrent dorsal shift of already ventilated lung tissue cannot be distinguished. The effusion evacuation led to a small shift in ventilation to the dorsal fraction of the lungs but the maximum ventilated regions (layers ROI 2 and 3) of the lungs remained almost unchanged. Interestingly, we did not observe a statistically significant shift of ventilation towards the ipsilateral lung.

These changes may contribute to the discussion of the clinical importance of PLE removal because the main outcome criteria such as mortality or length of ICU stay are not significantly influenced [26]. If removal of effusion does not substantially alter the ventilation distribution, then the area of the lung exposed to positive pressure during mechanical ventilation is almost the same after PLE evacuation and the incidence of ventilator induced lung injury (VILI) should not be affected.

The observed ventilation redistribution can also be explained by the fact that the EIT image is made up of the volume of tissue extending ± 10 cm from the tomographic plane depending on the EIT type [27] and thus also shows parts of the lungs where there is less or no surrounding exudate. The belt position could be important as well in patients whose diaphragm level is unusual due to high intraabdominal pressure [28].

A trend towards increased aeration (EELI) was apparent during ECM II (Fig. 1) and remained in the final phase of the EIT record. We could expect a more pronounced increase of EELI several hours apart but this would require further research. It is likely that performing the classic recruitment maneuver following effusion evacuation would result in greater aeration of previously compressed lung tissue and greater participation in ventilation. It could therefore be convenient to include some form of distension routinely after PLE removal that could improve aeration and thus further improve oxygenation.

The actual underlying pathology and pleural fluid characteristics may have an effect on lung expansion and residual fluid volume. The re-expansion corresponds with ΔEELV which was included in our measurements and in this sense the results (the ratio ΔEELI/ΔEELV) takes into account the degree of re-expansion.

This study is to our knowledge the first to combine the use of EIT and EELV measurements during PLE evacuation to evaluate the effect of fluid removal and lung aeration. Ensuring synchrony with the ventilator and maintaining constant ventilatory parameters were prerequisites for consistent measurement, particularly of EELV and its changes.

EELV was used in this study as a surrogate of lung aeration changes. To calibrate EELV measurement using EIT, the PEEP maneuvers were conducted. Several studies confirmed the linear relationship between EELV measured by an independent method with EELI measured by EIT and induced by PEEP maneuvers [18] and suggest EIT as a suitable method for PEEP-induced EELV measurement [19]. Even though several authors documented that the EELV/PEEP relationship might not always be linear [22] and might be affected by the position of the EIT belt [23], the PEEP maneuvers can be used for EELV measurement calibration, especially when the PEEP changes used for calibration are small [24,25].

It turned out that the second calibration maneuver led to smaller ΔEELV than the first one (Table 2). After the PLE evacuation the lung partly re-expanded and EELV increased by one third of the volume of the drained fluid (240 ± 107 ml). We can therefore assume that the recruitable volume of the lungs that could be influenced by moderate PEEP elevation (i.e. ECM) was reduced and so was delta EELV during the second calibration maneuver.

Our study has several limitations. Above all, it should be noted that EELV is a global ventilation parameter, while EIT measurements are focused only on the cross-section within the wide plane of the belt. The re-aeration could be scanned but not quantified by ultrasound. The most accurate method for assessing regional re-aeration would probably be to compare the CT scan at the EIT belt level. Secondly, the small patient group had to be further reduced to assure consistent data for evaluation. Finally, patients were monitored only for a short time after the evacuation of most effusions and lacked long-term follow up for comparison and measurement of residual effusion volume and lung re-expansion.

6. Conclusion

In summary, the influence of pleural effusion evacuation on lung aeration in mechanically ventilated patients cannot be effectively evaluated by EIT alone. The steep increase of end-expiratory lung impedance in the course of pleural effusion evacuation was largely caused by the loss of conductive electrolyte (i.e. the pleural effusion) adjacent to the EIT belt. Improved aeration of lung tissue had only a relatively minor effect.

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