Measurement of lung function using Electrical Impedance Tomography (EIT) during mechanical ventilation

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Abstract. The consistency of regional lung density measurements as estimated by Electrical Impedance Tomography (EIT), in eleven patients supported by a mechanical ventilator, was validated to verify the feasibility of its use in intensive care medicine. There were significant differences in regional lung densities between the normal lung and diseased lungs associated with pneumonia, atelectasis and pleural effusion (Steel-Dwass test, p < 0.05). Temporal changes in regional lung density of patients with atelectasis were observed to be in good agreement with the results of clinical diagnosis. These results indicate that it is feasible to obtain a quantitative value for regional lung density using EIT.

1. Introduction
   Mechanical ventilation is necessary in intensive care medicine. Though management of respiration with mechanical ventilation can improve the prognosis for acute phase patients, it has recently been known to induce ventilator-induced lung injury (VILI) or a ventilator-associated lung injury (VALI). Also, acute respiratory distress syndrome (ARDS) is associated with inhomogeneous lesions in the lungs. Therefore, there is a need for local regional monitoring of lung lesions at the bedside. Electrical impedance tomography (EIT) has been tried for the monitoring of lung lesions of patients [1-4]. Brown et al have suggested a measurement method of calculating absolute lung resistivity [5] and of lung density [6] from EIT data sets. However, the clinical feasibility of these methods has not been studied on patients connected to a mechanical ventilator.

   In this paper, regional lung density and lung disease in patients undergoing mechanical ventilation are compared, in order to verify the clinical feasibility of determining lung density from EIT data sets.

2. Method
   2.1 Determination of lung density using absolute lung resistivity
      Absolute lung resistivity ($\text{AbR}$) was determined using the method devised by Brown et al [5]. In summary, this method returns the best estimate of the absolute value of lung tissue resistivity by comparing the measured EIT data to computed data sets. Lung Filling Factor ($\text{FF}$) is the ratio by
volume of air to condensed matter within the lung tissue. A function between $AbR$ and $FF$ was provided using a numerical lung model developed by Nopp et al [7]. If we know the density of the condensed matter of the lungs then we can relate $FF$ to the overall density of lung tissue (Lung density: $LD$) as follows:

$$LD = \frac{\text{Lung Weight}}{\text{Air Volume} + \text{Tissue Volume}} \quad (1)$$

$$FF = \frac{\text{Air Volume}}{\text{Tissue Volume}} \quad (2)$$

Substituting from equation (1) into equation (2)

$$LD = \frac{\text{Lung Weight}}{FF \cdot \text{Tissue Volume} + \text{Tissue Volume}} = \frac{\rho_r}{FF + 1} \quad (3)$$

and

$$FF = \frac{\rho_r}{LD} - 1 \quad (4)$$

We will use $\rho_r = 1050 \text{kg} \cdot \text{m}^{-3}$ [8]

$AbR$ was determined as a function of $FF$ from the Nopp model [6] and hence related to $AbR$.

2.2 Measurement of regional lung density using absolute lung resistivity

EIT data was measured 207 times in total from 11 male patients connected to a mechanical ventilator in the intensive care unit at Kitasato University Hospital. Table 1 shows the patients’ profiles.

Lung densities were estimated for four lung regions defined as right anterior, left anterior, right posterior and left posterior as shown in Fig.1. The 828 lung regions were grouped into four categories, namely normal lung (332) and three pulmonary diseases that were pneumonia (104), atelectasis (274) and pleural effusion (87), on the basis of clinical diagnosis based on X-ray and CT images. The lung densities for these four categories were statistically compared using the Steel-Dwass test ($p < 0.05$). In addition, continuous changes in regional lung densities were measured for eight days from one patient and were compared with the clinical diagnosis.

The study was approved by the university ethics committee and informed consent was obtained from the patient’s relative.

![Fig. 1 Definition of lung regions at the level of the EIT electrode plane.](image)
Table 1  Patients’ profiles  (N=11)

| Height (cm) | 165±0.04 |
| BMI | 23.0±3.3 |
| Gender (M : F) | 11:00 |
| RASS index | -4.27±1.0 |

Table 2  Numbers of measurements, position, and pulmonary disease divided four areas (Eleven cases, 207 measurement, and 828 lung areas).

| Posture       | Total |
|---------------|-------|
| Supine        | 101   |
| Right lateral decubitus | 48    |
| Left lateral decubitus | 51    |
| Others        | 7     |

| Lung area       | RA | LA | RP | LP | Total |
|-----------------|----|----|----|----|-------|
| Normal          | 129| 100| 33 | 70 | 332   |
| Pneumonia       | 15 | 71 | 12 | 6  | 104   |
| Atelectasis     | 46 | 12 | 122| 65 | 274   |
| Pleural effusion| 4  | 21 | 27 | 35 | 87    |
| Total           | 194| 204| 194| 205| 797   |

RA: Right anterior, LA: Left anterior, RP: Right posterior and LP: Left posterior.

BMI; Body Mass Index
RASS; Richmond Agitation and Sedation Scale
CPA; Cardio Pulmonary Arrest

3. Results

Table 2 gives statistics on the EIT measurements that were made in the clinically diagnosed groups. Approximately half of the EIT data were measured in the supine position and 40% of regional lung areas were diagnosed as normal.

Figure 2 shows the relationship between pulmonary disease and the measurements of lung density in the supine position. There were significant differences in regional lung density between the four groups (p < 0.05), except for pneumonia and atelectasis, and the mean values of the regional lung densities in the three pulmonary diseases were higher than for those in normal lung. In addition, when the posture of the patients was changed from supine to the left lateral decubitus position, there was a significant difference in the regional lung densities between pneumonia and atelectasis but no significant difference between atelectasis and pleural effusion (Fig.3). Similar results were also obtained for the right lateral decubitus position.

Furthermore, regional lung density measurements in one patient diagnosed as having atelectasis decreased day by day (Fig.4). At Day 1, no obvious activity of the alveoli in the right lung had been observed by the clinician. The results indicated that only the left lung was working and the chest X-ray, taken on the same day, was in good agreement with this result. On the other hand, activity of the alveoli in the right anterior of the lung had clearly increased and the chest X-ray was in agreement with this on Day 8. Lung densities in the right lung decreased from higher values on Day 1 to the values measured from normal lung regions as shown Fig.3 (221±49.4 kg·m⁻³).
4. Discussion

Statistical differences were found between the regional lung densities of normal and pulmonary diseases. However, there were no significant differences between pneumonia and pleural effusion in the supine position. To discriminate both diseases, measurement in the left lateral decubitus position was also needed. The reason for the observed large changes in regional lung density associated with pleural effusion was considered to be the movement of lung water with changes in posture of the patient. Furthermore, regional lung density measurements in one patient diagnosed as having atelectasis decreased day by day (Fig.4). This trend was observed to be in good agreement with the results of clinical diagnosis based on X-ray and CT images.

These results indicate that it is feasible to obtain a quantitative value for regional lung density using the EIT technique with no risk of exposure to harmful radiation as in X-ray and CT. EIT may be a useful technique for daily monitoring of the lung function of patients in an intensive care unit, although the CT has the advantage of providing much better anatomical diagnosis.

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