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Multi-Electrode Impedance Method for Detection of Regional Ventilation

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Abstract. By means of computer simulation and experiment, we investigated the feasibility of simultaneously measuring the transfer impedance changes in the right apex, left apex, right base and left base of the lungs using the multi-electrode impedance method. To obtain the transfer impedance in each region, while suppressing the effects of other regions, changing the amplitude and polarity of the applied current must localize the high sensitivity areas in the interest region. Twelve current and eight voltage electrodes were equidistantly arranged on the anterior and posterior chest walls. The amplitudes and polarities of the currents that were simultaneously applied to the current electrodes, and which provided the appropriate sensitivity distribution, were theoretically obtained. The effects of the localized sensitivity distribution were verified by comparing the simulation results of the investigated method with the results of the conventional four-electrode method. From the results of the computer simulation, we developed multi-electrode impedance pneumography and applied it to healthy adult volunteers who were both in sitting position and in left decubitus. We found that the measurement results were physiologically reasonable.

1. Introduction
Currently, RI scintigraphy is primarily used to evaluate the regional ventilation in lung. However, it is almost impossible to continuously monitor pulmonary physiological changes for a long duration by this method. Therefore, in this study, we propose a multi-electrode impedance method [1] (MEIM) for lengthy and non-invasive monitoring the pulmonary physiological changes of patients under intensive care. To measure the regional impedance change in the lung, the sensitivity in the interest region must be high and localized. In measuring impedance by MEIM, currents are simultaneously applied to 12 current electrodes arranged on the chest walls, and the regional transfer impedance changes $\Delta Z$ are sagittally detected as differential voltage changes between pairs of voltage electrode arranged on the chest wall in the same region. The sensitivity distribution (SD) is theoretically calculated by Geselowitz’s (1971) sensitivity theorem [2]. From the results of the computer simulation, we developed multi-electrode impedance pneumography and applied it to health adult volunteers. In this paper, we discuss the feasibility of this method and the superiority of MEIM, both theoretically and experimentally, for the simultaneous measurements of $\Delta Z$ in the right apex ($RA$), left apex ($LA$), right base ($RB$) and left base regions ($LB$) of the lungs.
2. Simulation studies

2.1. Theory

In order to measure $\Delta Z$ in $RA$, $LA$, $RB$, and $LB$ of lung, we equidistantly arranged twelve current electrodes on the right and left upper, middle, and lower sites on the anterior and posterior chest walls as shown in Figure 1. Eight voltage electrodes were equidistantly arranged on the same level as the current electrodes on $RA$, $LA$, $RB$, and $LB$ sites as shown in Figure 1. Because the currents simultaneously applied to the current electrodes arranged on the anterior and posterior, the currents flow sagittally as shown by the red arrows in Figure 1. The red and blue circles in the figure are the current and voltage electrodes, respectively. The amplitudes of all currents are identical. Because the polarity of the adjacent current electrode pair is opposite to that of the current supplied to the pair at the interest region, as shown in Figure 1, a zero sensitivity region is produced in the boundary between the right and left lungs, and consequently, the high sensitivity area in the region of interest (RI) is localized. Two pair of current electrodes arranged on the right and left middle sites of the chest wall are used to isolate the apex and base. We can simultaneously obtain $\Delta Z$ in right apex, left apex, right base and left base of the lung by measuring the voltage difference sagittally as shown in Figure 1. We assume that the spatial conductivity changes of the four regions are $\Delta g_{RA}$, $\Delta g_{LA}$, $\Delta g_{RB}$, and $\Delta g_{LB}$, respectively. The $\Delta Z$ at $RA$ is theoretically given by the following equation (1). $L_I$ is the electric field that is generated by the unit current supplied to all the current electrode pairs and is referred to as the lead vector. The lead vector $L_V$ is the electric field that is generated by the unit current supplied to the voltage electrode pair in RI. Therefore, the dot product of $L_I$ and $L_V$ gives the sensitivity. $L_{I-RA}$, $L_{I-RB}$, $L_{I-LA}$, and $L_{I-LB}$ are the lead vectors in $RA$, $RB$, $LA$ and $LB$, respectively. $L_{V-RA}$, $L_{V-RB}$, $L_{V-LA}$ and $L_{V-LB}$ are the lead vectors at $RA$, $RB$, $LA$ and $LB$, respectively, produced by the current supplied to the voltage electrode pair at the $RA$. From the superposition theorem, $\Delta Z$ in the other regions can be expressed by equations similar to equation (1).

$$
\Delta Z_{RA} = \int_{V_{RA}} -\Delta g_{RA} L_{I-RA} \cdot L_{V-RA-RB} dv + \int_{V_{RB}} -\Delta g_{RB} L_{I-RB} \cdot L_{V-RB-RB} dv
+ \int_{V_{LA}} -\Delta g_{LA} L_{I-LA} \cdot L_{V-LA-LA} dv + \int_{V_{LB}} -\Delta g_{LB} L_{I-LB} \cdot L_{V-LB-LB} dv
$$

(1)

2.2. Simulation model and results

To obtain SD by MEIM, simulation studies are carried out with the cuboid-model, the conductivity $g$ of which is uniform. The cuboid-model consists of 729 points and 512 cubic elements. SD is
calculated by the 3-D finite element method. Figure 2-(b) shows one of the calculated SD for the measurements of $\Delta Z$ in RA of the lung. Arranging two pairs on the right and left apex and base can produce the zero sensitivity regions (ZS) in the boundaries between the right and left apex and base of the lungs. Two pair of current electrodes arranged on the right and left middle sites of the chest wall produces ZS between apex and base lungs. For comparison, SD obtained by the conventional four electrode method is shown in Figure 2-(a). The upper and lower diagrams of Figure 2-(b) respectively show SD on the cross section through the center of the anterior and posterior chest walls and on the sagittal plane over the voltage electrode pair arranged on the anterior and posterior chest wall as depicted in Figure 2-(c). Table 1 shows the rate of the influence of $\Delta g$ in each of the four regions to $\Delta Z_{RA}$ when the influence of $\Delta g$ in the RA region is 100%. For comparison, the table shows the corresponding rates to $\Delta Z_{RA}$ measured by the conventional four electrode method. The two results indicate that the regional conductivity changes in RI can be effectively detected. From the geometrically symmetry of electrode arrangement, the three other regions have the same sensitivity distribution characteristics as previously described.

| Region    | Four electrode method | Multi-electrode method |
|-----------|------------------------|------------------------|
| Right apex| 100%                   | 100%                   |
| Right base| 12.5%                  | 2.6%                   |
| Left apex | 17.8%                  | -9.7%                  |
| Left base | 5.1%                   | -1.3%                  |

3. Experiment

3.1. Hardware design
The MEIM system consists of 12 floating-type constant-current sources (six positive and six negative) outputting 37 $\mu$A at 10kHz and four voltage detectors (differential amplifiers). All the current electrodes are connected to the floating-type constant-current sources while the voltage pickup electrodes are connected to the differential amplifiers, SN ratios of which are greater than 75dB.

3.2. Electrode arrangement
Tidal volume measurements by the MEIM system were conducted on 12 healthy volunteer students between 18 and 22 years old, with their informed consent. For monitoring, the tidal volume was simultaneously measured by the spirogram. The electrode arrangement on the human body shown in Figure 3 is the same as that of the simulation model. Furthermore, as in the simulation, $\Delta Z$ was simultaneously obtained for the four regions in the sitting position and left decubitus.

![Figure 3. Multi electrode arrangement](image)

![Figure 4. $\Delta Z$ and tidal volume waveforms in left decubitus](image)
3.3 Experimental results

Figure 4 and Table 2, 3 and 4 show one of the experimental results. Figure 4 shows the relationship between the tidal volume and the \( \Delta Z \) waveform in the left decubitus. The waveforms from top to bottom in figure are the simultaneous measurement results at \( LA, RA, LB, \) and \( RB \). The amplitude of \( \Delta Z \) is an indicator of the regional lung activity; in fact, it is proportional to the ventilation volume in each region. The \( \Delta Z \) waveforms in each region correlate well with the tidal volume waveform. Table 2 shows the correlation factors of the tidal volume and \( \Delta Z \) in each region. The factors are over 0.95% in all four regions. The results indicate that \( \Delta Z \) waveform reflects the variation in the ventilation volume of each region. We define the ratio of the value of \( \Delta Z \) in other regions and the value of \( \Delta Z \) in right base as the activity contribution rate to the regional ventilation volume (AC). Table 3 shows AC of each lung in each posture. The amplitudes of \( \Delta Z \) waveforms at the base are slightly greater than those at the apex in the sitting position. However, there is no difference between AC of the left and right lungs at both the apex and the base. In the left decubitus, AC by the apex of the left lung is significantly greater than that by the apex of the right lung. There is no difference between AC by left and right base.

| Posture      | Left apex | Right apex | Left base | Right base |
|--------------|-----------|------------|-----------|------------|
| Sitting position | 0.93      | 0.90       | 1.02      | 1.00       |
| Left decubitus    | 1.14      | 0.92       | 1.01      | 1.00       |

Table 4 shows the ratios of the total value of \( \Delta Z \) in left apex and base and the total value of \( \Delta Z \) in right apex and base, to the tidal volume (i.e., AC). In the sitting position, there is no difference between the contributions in the apex and base of the lungs. It is clear that AC of the left apex of the lungs is greater than that of the right apex in the left decubitus.

| Posture      | Apex | Base |
|--------------|------|------|
| Sitting position | 1.00 | 1.02 |
| Left decubitus    | 1.24 | 1.01 |

4. Discussion

In order to effectively measure the regional transfer impedance, high sensitivity region must be localized by the appropriate SD. From the computer simulation results, it has been found that the proposed MEIM system can be used to obtain reasonably localized high sensitivity area in RI and to carry out simultaneous and independent measurements of regional \( \Delta Z \). The results of simultaneous sagittal measurements of \( \Delta Z \) in both the sitting position and left decubitus were found to be physiologically reasonable. Thus, from the theoretical and experimental study, it is clear that the proposed MEIM can be used to simultaneously and independently detect the physiological changes in a particular region of the lungs.

References
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