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Research article

The influence of reference electrode in electrical impedance tomography

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ABSTRACT

Background: Some electrical impedance tomography (EIT) devices equip reference electrodes. In practice, it is not uncommon to observe high contact impedance for the reference electrode. The influence of bad contact reference electrode on data quality is unknown. The study aimed to investigate the influence of reference electrode on EIT image reconstruction.

Methods: Thirty lung healthy volunteers were prospectively examined with EIT. The subjects were spontaneously breathing in supine position. Three scenarios were constructed: 1. Normal measurement; 2. Reference electrode disconnected without recalibration; 3. Reference electrode disconnected, and the measurement restarted after recalibration of the system. EIT-based parameters measuring spatial and temporal ventilation distributions were calculated and compared. A so-call deviation score was calculated to assess the differences in EIT parameters between scenarios 2 and 1, between 3 and 1.

Results: The absolute differences for all parameters were significantly higher than zero ($p < 0.01$ for all parameters and scenarios). Deviation score for scenario 2 was 4.5 ± 3.5. Four subjects had a deviation score of 0 in scenario 2 and five subjects had a score of 1. The deviation in scenario 3 was higher (6.1 ± 3.1). No subjects had a score of 0 and only two subjects had a score of 1.

Conclusions: For EIT systems that equips with reference electrode, it is important to ensure the proper contact and functionality of the reference electrode. The EIT data quality would remain unchanged in only a small portion of subjects.

1. Background

Electrical impedance tomography (EIT) is a novel technique that monitors ventilation and perfusion distribution in the lung [1, 2]. A set of electrodes are attached around the thorax (typically 16 or 32 electrodes) and imperceptible small currents are injected into the thorax during the measurement. The resultant voltages are measured and, subsequently, relative impedance changes are reconstructed to represent the air and blood changes within the measurement plane. Several commercial EIT devices are available on the market with different electrode settings and current injection patterns. Some require an extra off-plane electrode as a reference (e.g. PulmoVista500 from Dräger Medical, Lübeck, Germany) whereas the others have no such requirements (e.g. LuMon from Sentec, Therwil switzerland). Since the current-injecting electrodes are close to each other on the body surface, the measured potential differences could be limited. With the additional reference electrode, a common reference

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point for all voltage measurements is created. Besides, with the voltage measurements between the current-injecting electrodes and the reference electrode, the electrode-skin contact impedances could be better assessed.

PulmoVista500 is one of the widely used EIT devices [3]. The reference electrode is connected to a traditional ECG electrode, which might have various quality depending on the manufacturers and storage environment. Besides, the attachment and detachment of the cable to the electrode may increase the contact impedance over time. In practice, it is not uncommon to observe high contact impedance for the reference electrode (e.g. Figure 1). Up to now, the influence of bad contact reference electrode on data quality is unknown. The study aimed to investigate the influence of reference electrode on EIT image reconstruction.

2. Methods

2.1. Subjects and measurements

A total of 30 lung healthy volunteers were prospectively examined with EIT (all males; age, 25.9 ± 1.3 years; height, 176.8 ± 6.0 cm; weight, 75.2 ± 10.8 kg). The study was approved by institutional ethics review boards of the first affiliated hospital of Guangzhou Medical University, Guangzhou (201704). All participants signed the written consent form prior to the study.

To evaluate the influence of reference electrode, three scenarios were constructed: 1. Normal measurement with the reference electrode connected; 2. Reference electrode disconnected during measurement and the

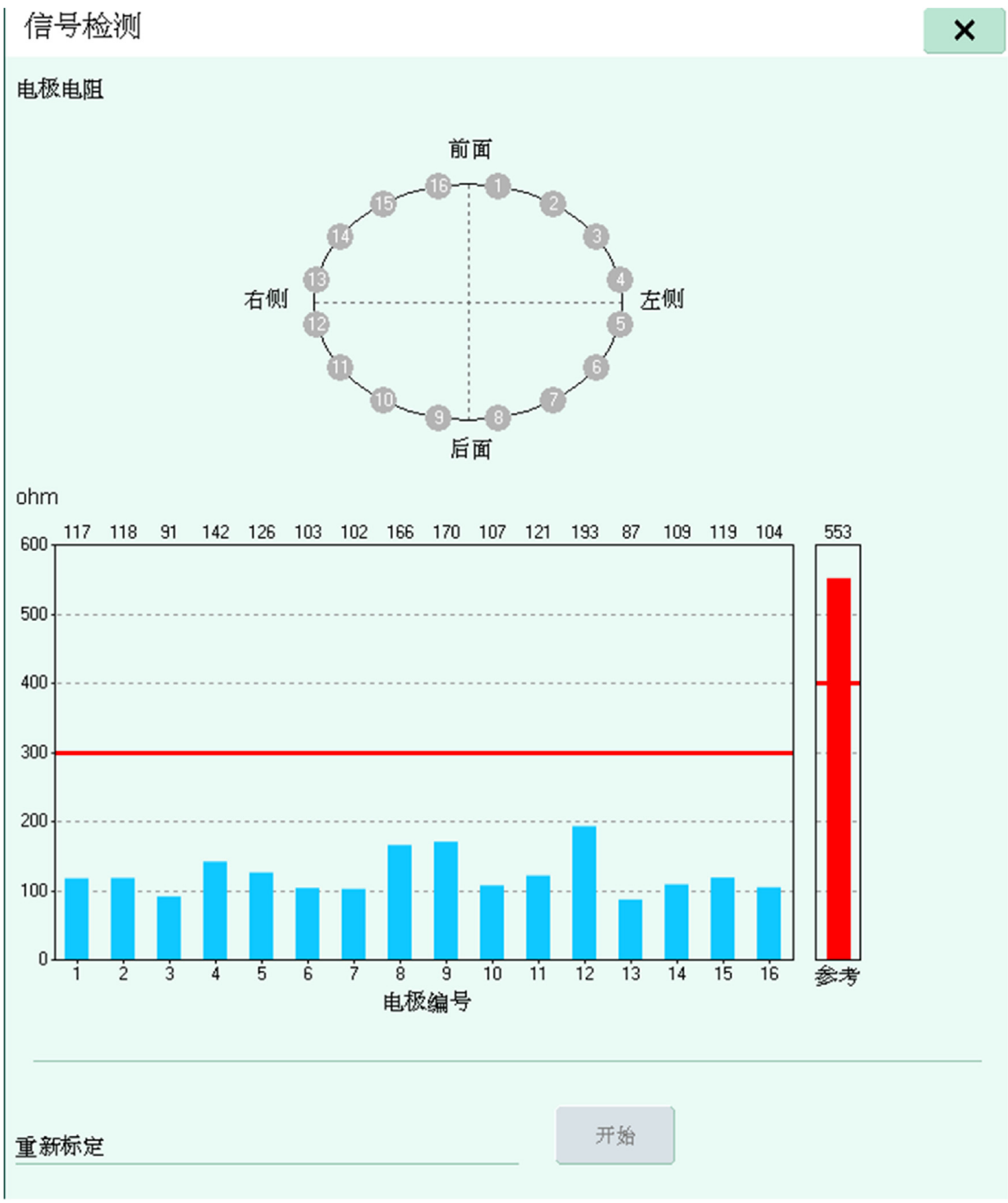

Figure 1. An example of contact impedance measurement showing reference electrode-skin contact impedance was above the preset threshold.

Table 1. EIT parameter thresholds derived from a previous study [8].

EIT parameters from [8]	SD from [8]	EIT parameters for current study	1.96*SD (~95% CI)
CoV [%]	1.70	CoV	3.33
TV_D [%]	5.40/2 (2 ROIs)	ROIs	5.29
GI	0.04	GI	0.08
RVD_{SD}	2.00	RVD_{SD}	3.92

SD, standard deviation; CI, confidence intervals; CoV, center of ventilation; TV_D, tidal variation in dorsal regions; GI, the global inhomogeneity index; RVD_{SD}, standard deviation of regional ventilation delay; ROIs, regions of interest.

user did not notice; 3. Reference electrode disconnected, the user stops and restarts the measurement (recalibration of the system while reference electrode is still disconnected). The subjects were spontaneously breathing in supine position. EIT measurement was performed with PulmoVista 500. An EIT electrode belt with 16 electrodes was placed around the thorax in the fourth intercostal space and one reference electrode was placed at the subjects' abdomen for the scenario 1. For each scenario, measurement was recorded for 2 min with a frame rate of 20 Hz.

2.2. EIT data analysis

The finite element method based linearized Newton–Raphson reconstruction algorithm was used to convert the recorded data into EIT images [4]. The image reconstruction was achieved with software provided by the manufacturer (EIT Data Review Tool 63, Dräger Medical, Lübeck, Germany).

Functional EIT (fEIT) was calculated by subtracting the end-expiration from the end-inspiration image, which represents the variation during tidal breathing (TV).

$$TV_i = \Delta Z_{i,Ins,n} - \Delta Z_{i,Exp,n} \quad (1)$$

where TV_i is the pixel i in the fEIT image; $\Delta Z_{i,Ins}$ and $\Delta Z_{i,Exp}$ are the pixel values in the raw EIT image at the end-inspiration and end-expiration, respectively. Zero was assigned to TV_i if $TV_i < 0$.

To evaluate the influence of reference electrode on EIT data analysis, the following EIT-based parameters characterizing spatial and temporal heterogeneities were calculated for each breath during the measure ments:

Center of ventilation (*CoV*) depicted ventilation distribution influenced by gravity (relative impedance value weighted with location in anteroposterior co-ordinate) [5]. The calculation is described in Eq. (2):

$$CoV = \sum (y_i \times TV_i) \Big/ \sum TV_i \times 100\% \quad (2)$$

where TV_i is the tidal variation in the fEIT image for pixel i (same as the one in Eq. 1), and y_i is the pixel height and of pixel i scaled so the bottom of the image (dorsal) is 100% and the top (ventral) is 0%.

The fEIT images were divided into four regions of interest (ROIs). Depending on the way how the ROIs were divided, two types of settings were constructed: ROI_{layers}, four horizontal anterior-to-posterior segments with equal height; $ROI_{quadrants}$, four quadrants corresponding to right ventral, left ventral, right dorsal and left dorsal lung regions.

The global inhomogeneity (*GI*) index was calculated from the tidal EIT images to summarize the ventilation heterogeneity [6]. The calculation is described in Eq. (3):

$$GI = \sum_{l \in lung} \left| TV_l - Median(TV_{lung}) \right| \Big/ \sum_{l \in lung} TV_l \quad (3)$$

where *TV* denotes the value of the differential impedance in the tidal images; TV_l is the pixel in the identified lung area; Pixel l is considered as lung region if $TV_l > 20\% \times \max(TV)$. TV_{lung} are all the pixels representing the lung area. High *GI* index implies high variation among pixel tidal impedance values.

The regional ventilation delay (*RVD*) index characterizes the regional ventilation delay as pixel impedance rising time compared to the global impedance curve [7], which may assess tidal recruitment/derecruitment (calculated as described in Eq. 4).

$$RVD_l = t_{l,40\%} \Big/ T_{inspiration,global} \times 100\% \quad (4)$$

where $t_{l,40\%}$ is the time needed for pixel l to reach 40% of its maximum inspiratory impedance change. $T_{inspiration,\ global}$ denotes the inspiration time calculated from the global impedance curve. To assess the distribution of RVD, Muders et al. proposed to use standard deviation of the pixel values [7], as described in Eq. (5):

$$RVD_{SD} = \sqrt{\frac{1}{L} \sum_{l \in lung} \left(RVD_l - mean(RVD_{lung})\right)^2} \quad (5)$$

where L is the total number of pixels identified as lung area.

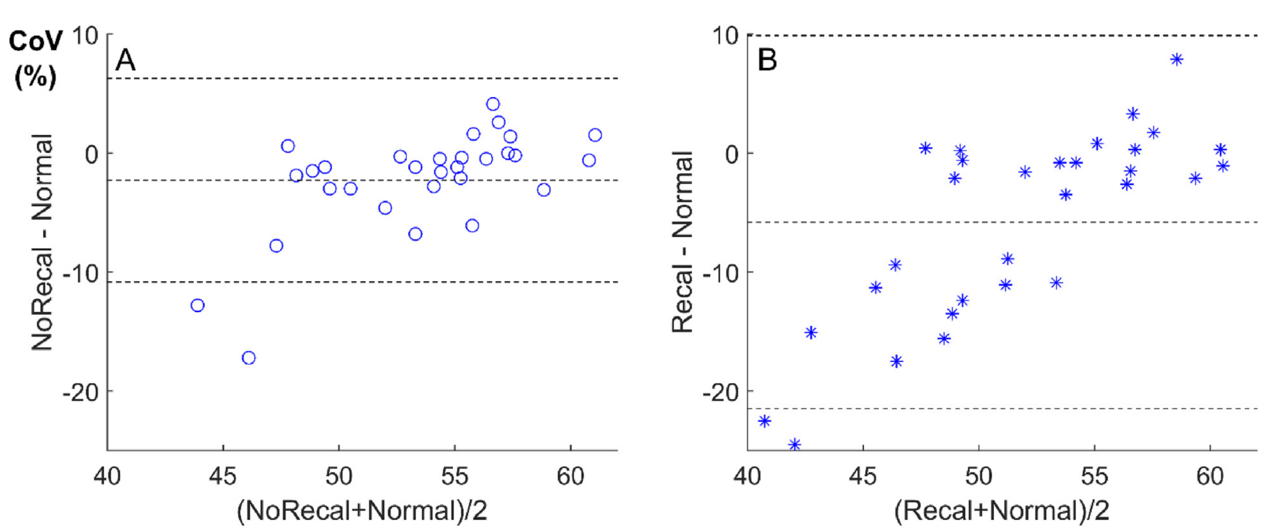

Figure 2. Bland-Altman plots comparing the center of ventilation (CoV) between scenarios 2 (A), 3 (B) and scenario 1.

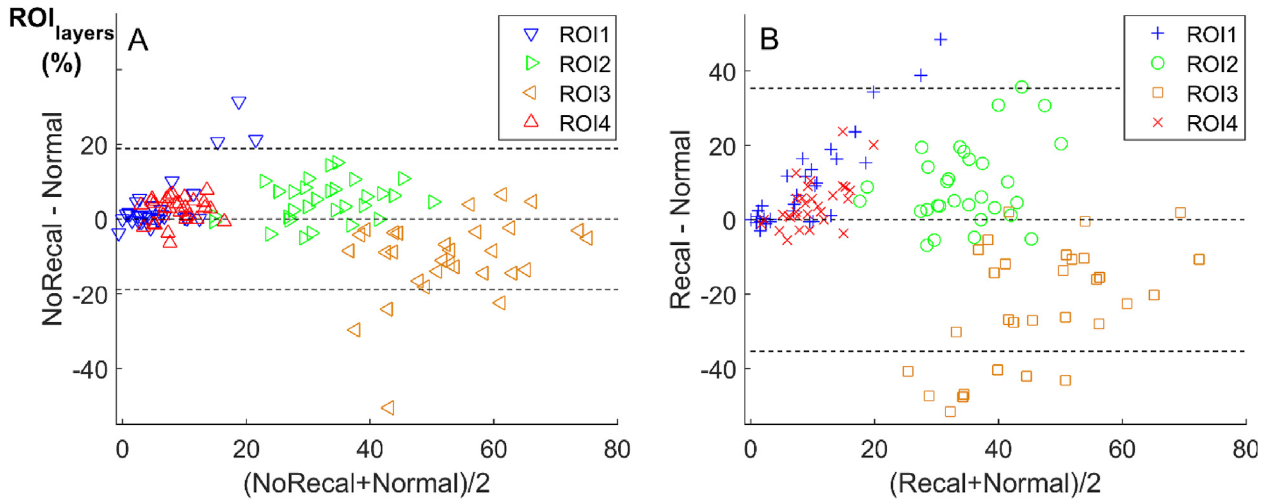

Figure 3. Bland-Altman plots comparing the four regions of interest (ROIs) between scenarios 2 (A), 3 (B) and scenario 1, which are four horizontal anterior-to-posterior segments with equal height.

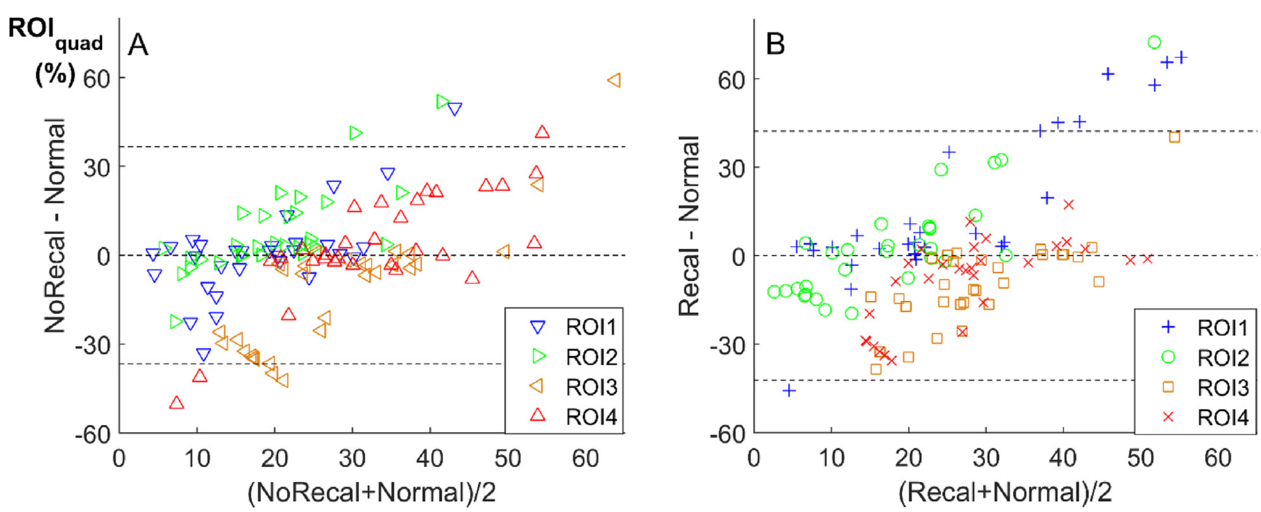

Figure 4. Bland-Altman plots comparing the four regions of interest (ROIs) between scenarios 2 (A), 3 (B) and scenario 1, which are four quadrants corresponding to right ventral, left ventral, right dorsal and left dorsal lung regions.

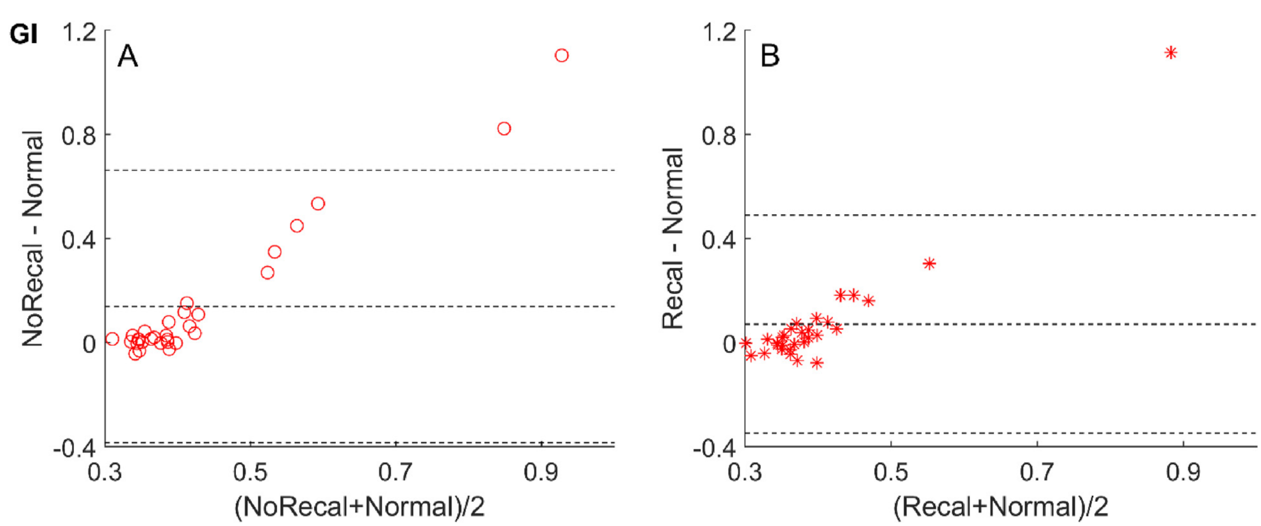

Figure 5. Bland-Altman plots comparing the global inhomogeneity index (GI) between scenarios 2 (A), 3 (B) and scenario 1.

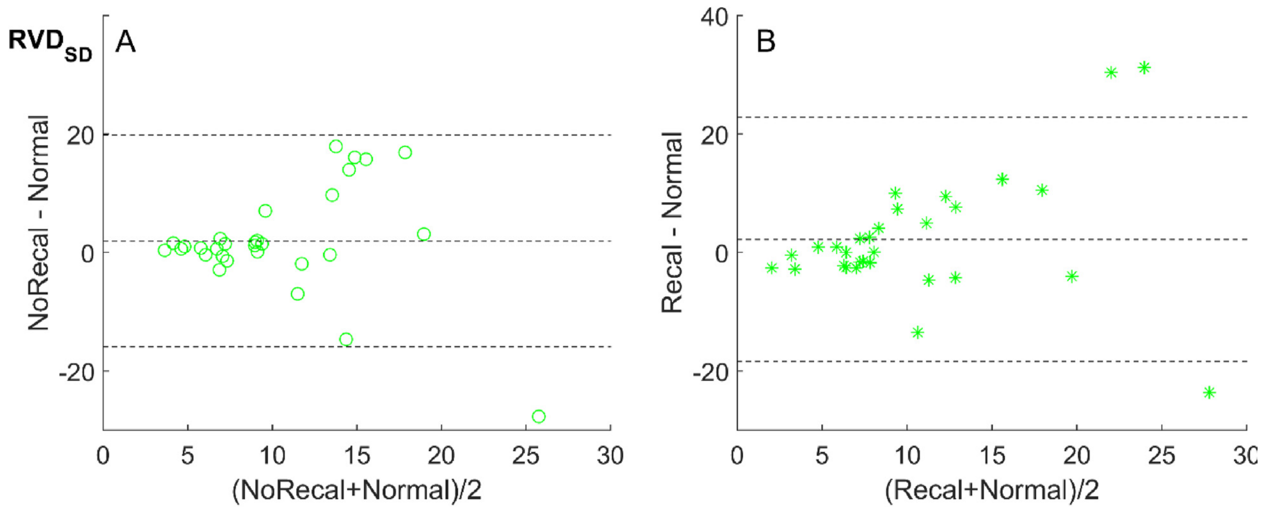

Figure 6. Bland-Altman plots comparing the regional ventilation delay (RVD) between scenarios 2 (A), 3 (B) and scenario 1.

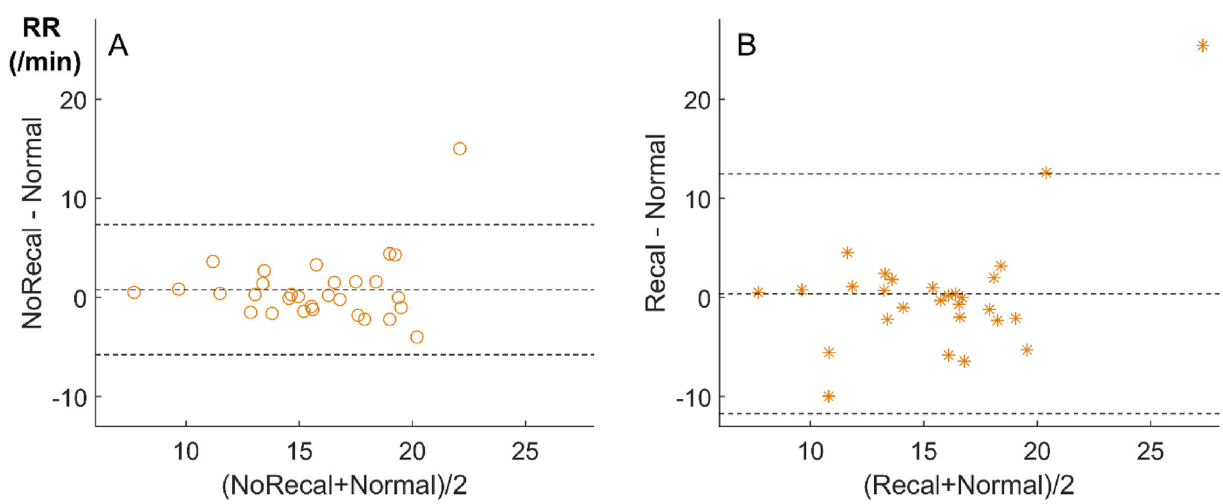

Figure 7. Bland-Altman plots comparing the respiratory rate (RR) between scenarios 2 (A), 3 (B) and scenario 1.

Besides, respiratory rate (*RR*) was derived from the EIT data to examine whether the rhythm for both respiratory related signals were identified correctly.

2.3. Statistical analysis

Data analysis was performed using MATLAB 8.5 (The MathWorks Inc., Natick, USA). The Lilliefors test was used for normality testing. For normally distributed data, results were expressed as mean ± standard deviation. The parameter values calculated for scenarios 2 and 3 were compared to that obtained from scenario 1. An arbitrary threshold of 20% differences in *RR* and *HR* higher than 20% with respect to scenario 1 were considered significant. In a previous study, standard deviation of the EIT-based parameters in healthy volunteers were calculated [8]. The values were used to set thresholds for individual parameters (Table 1). A so-call deviation score was calculated. For each parameter, if its value in scenarios 2 or 3 was over the corresponding threshold, deviation score for this subject and this scenario increased by 1. In total 12 parameters were compared so the highest deviation score was 12 for each subject.

For overall comparison, Bland-Altman plot was used to show the agreements. Paired t test was used to test whether the absolute differences between the scenarios 2 and 1, between 3 and 1 were significantly higher than zero. A p value <0.05 was considered statistically significant.

3. Results

The differences between the scenarios 2 and 1, between 3 and 1 for all evaluated EIT parameters were plotted in Figures 2, 3, 4, 5, 6, and 7. The absolute differences for all parameters were significantly higher than

Table 2. Number of subjects whose parameter values were over the preset threshold in the corresponding scenarios.

EIT parameters	Scenario 2 (No Recalibration)	Scenario 3 (Recalibration)
CoV	7	14
$ROI_{Layers}1$	6	14
$ROI_{Layers}2$	15	17
$ROI_{Layers}3$	20	27
$ROI_{Layers}4$	7	14
$ROI_{Quadrants}1$	11	16
$ROI_{Quadrants}2$	13	19
$ROI_{Quadrants}3$	17	18
$ROI_{Quadrants}4$	15	16
GI	9	6
RVD	10	15
RR	6	8

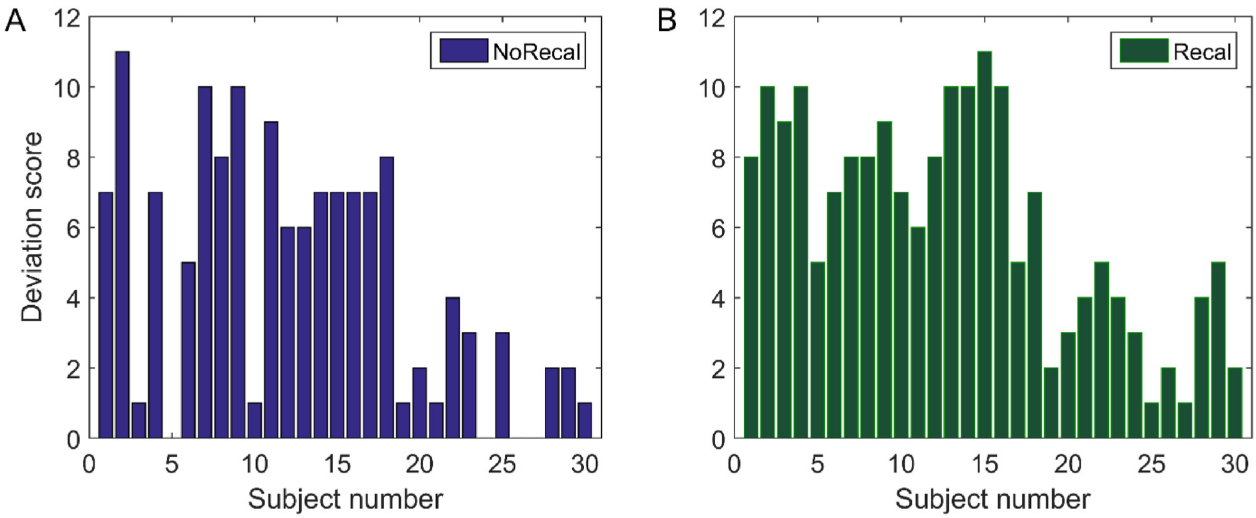

Figure 8. Deviation score for subjects in scenarios 2 (A, no recalibration) and scenario 3 (B, recalibration).

zero ($p < 0.01$ for all parameters and scenarios). Compared to normal measurements, ventilation distribution tended to distribute towards ventral regions (Figures 2A and 2B, CoV being smaller; Figures 3A and 3B, increase occurred in ROI2; However, in Figures 4A and 4B, the increase in ROI1 and ROI2 was not predominant). The ventilation distribution became less homogeneous (Figures 5A and 5B) and regional delay slightly increased (Figures 6A and 6B). Although the differences in respiratory rate were close to zero, but the variation among subjects was large (Figures 7A and 7B). Table 2 showed the number of subjects whose parameter values were over the preset threshold in the corresponding scenarios.

Deviation score for scenario 2 was 4.5 ± 3.5. Four subjects had a deviation score of 0 in scenario 2 and five subjects had a score of 1 (Figure 8A). The deviation in scenario 3 was higher (6.1 ± 3.1). No subjects had a score of 0 and only two subjects had a score of 1 (Figure 8B).

4. Discussion

In the present study, the influence of reference electrode on EIT data analysis was evaluated in 30 subjects and two scenarios. For the device we evaluated (PulmoVista 500), when the reference electrode felt off or defected, data analysis in 70% of subjects deviated from the ideal measurement setting in 2 or more evaluated parameters (deviation score $\geq$2). If the user noticed the malfunction of reference electrode and restart the calibration without fixing the contact issue, over 93% of the subject data deviated significantly.

Electrode contact impedance influences the system performance since the common mode rejection ratio is a function of electrode gain accuracy. It may also influence the current distribution near the boundary and introduce artefacts [9]. Electrode movement would introduce baseline shifts, which influence long-term monitoring. Previous studies attempted to remove the motion artifacts using advance data processing algorithms (e.g. [10]). Time-difference image reconstruction may reduce the requirement of knowing the exact contact impedance of each electrode. Besides, attempts have been proposed to calculate the contact impedance via active electrodes [11] or mathematically using complete electrode model [12]. Certain electrodes may tend to have insufficient skin contact in certain positions (e.g. sitting, standing, lateral). Pressing the corresponding electrodes would be one solution. Developing algorithm that overcomes the missing electrodes would be another approach. A reference electrode establishes a common point for voltage measurement so that it may be used to calculate the contact impedance. However, it may also add complexity to EIT measurement (e.g. preparation time, risk of bad contact). There are already many cables connected to the patient in the ICU. Reducing the size and the number of cables is essential. Some EIT devices digitalize the voltage signals directly at the electrodes so that the cable connecting the subject and the monitor is minimized, whereas the other devices might use wireless connection to avoid any connection cables [13]. Nevertheless, for EIT systems that equips with reference electrode, it is important to ensure the proper contact and functionality of the reference electrode. The EIT data quality would remain unchanged in only a small portion of subjects. We could not establish any factors that could predict whether the data quality was acceptable beforehand. We acknowledge that we only simulated the on or off status of the reference electrode. In practice, the contact impedance might be higher than the preset threshold (400 Ω) but not as extreme as the scenarios in the study. We suspected that if the contact impedance was slightly higher than the threshold, the EIT images could be still acceptable, which was not explore in the current study.

To evaluate the influence of contact impedance on EIT data, we calculated several commonly used EIT-based parameters [8]. The reason why we compared EIT image-based indices instead of the voltage measurements was that these indices were clinically well-accepted and served the purpose of clinical applications, which were the ultimate goal of the EIT measurement. Whether the reference electrode influences the surface voltage measurement plays only an indirect role.

One limitation of the study was the thresholds for the deviation score calculation. The thresholds of EIT parameters were derived from a previous study. Whether they were ideal to quantify the deviation between scenarios was not validated. Besides, we did not test the location of the reference electrode. Whether it has influence on data quality is unknown.

5. Conclusions

Reference electrode does influence on EIT data quality, and it is important to ensure the electrode's proper contact and functionality.

Declarations

Author contribution statement

LS, LY and ZZ were involved in study design, data collection, analysis, and interpretation, and manuscript writing.

ZL, WH and ZG were involved in data collection and revised the manuscript critically.

Y Li, Y Lu, FF and MD were involved in data interpretation and revised the manuscript critically.

All authors read and approved the final manuscript.

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Data availability statement

Data included in article/supp. material/referenced in article.

Declaration of interest's statement

The authors declare no competing interests.

Additional information

No additional information is available for this paper.

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Not applicable.

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