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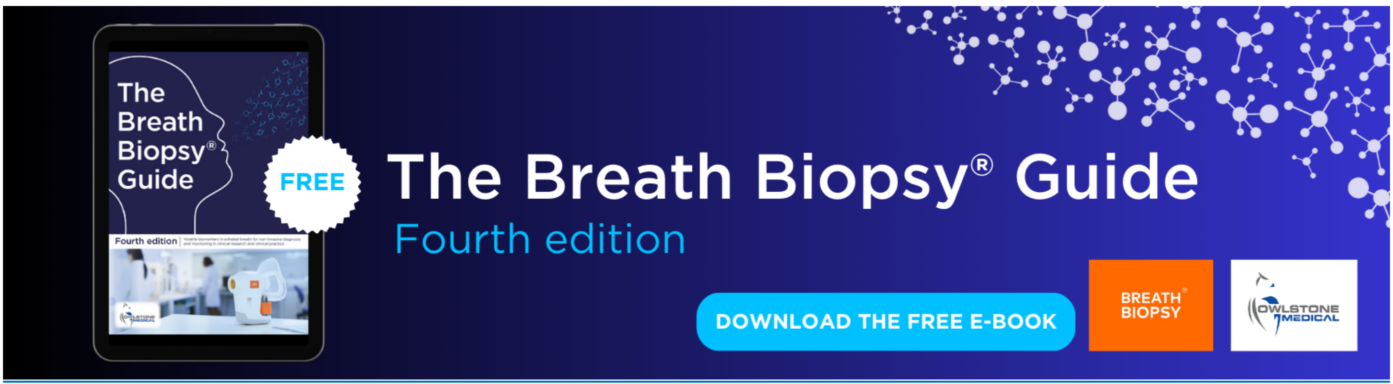

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Regional ventilation distribution before and after laparoscopic lung parenchymal resection

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Keywords: ventilation distribution, electrical impedance tomography, laparoscopic lung parenchymal

Abstract

Objective. The aim of the present study was to evaluate the influence of one-sided pulmonary nodule and tumour on ventilation distribution pre- and post- partial lung resection. *Approach.* A total of 40 consecutive patients scheduled for laparoscopic lung parenchymal resection were included. Ventilation distribution was measured with electrical impedance tomography (EIT) in supine and surgery lateral positions 72 h before surgery (T1) and 48 h after extubation (T2). Left lung to global ventilation ratio (F_l), the global inhomogeneity index (GI), standard deviation of regional ventilation delay (RVD_{SD}) and pendelluft amplitude ($A_{pendelluft}$) were calculated to assess the spatial and temporal ventilation distribution. *Main results.* After surgery (T2), ventilation at the operated chest sides generally deteriorated compared to T1 as expected. For right-side resection, the differences were significant at both supine and left lateral positions ($p < 0.001$). The change of RVD_{SD} was in general more heterogeneous. For left-side resection, RVD_{SD} was worse at T2 compared to T1 at left lateral position ($p = 0.002$). The other EIT-based parameters showed no significant differences between the two time points. No significant differences were observed between supine and lateral positions for the same time points respectively. *Significance.* In the present study, we found that the surgery side influenced the ventilation distribution. When the resection was performed on the right lung, the postoperative ipsilateral ventilation was reduced and the right lung ratio fell significantly. When the resection was on the left lung, the ventilation delay was significantly increased.

1. Introduction

Lung parenchymal resection is a common surgery for emphysema, pulmonary nodule, cancer, and many other lung diseases. Whether the surgery is conducted with minimally invasive or open procedures plays an important role to the clinical outcomes (Bhagat *et al* 2020). The types of resection (e.g. lobectomy, wedge resection) may also have influences (Asamura *et al* 2017, Divisi *et al* 2020, Nakagawa *et al* 2021). Patients usually experience partial loss of lung function after surgery (Feng *et al* 2022). Risk factors and prediction for postoperative lung functions are studied previously (Fan *et al* 2023, Tsubokawa *et al* 2023). Various techniques including routine physiotherapy and ventilation support are proposed to improve the patients' outcomes (Lucangelo et al 2009, Malik et al 2018).

In recent years, lung protective ventilation strategies during the perioperative period have been adopted to improve perioperative oxygenation and reduce postoperative pulmonary complications (Joe et al 2023, Park et al 2023). Electrical impedance tomography (EIT) is one of the bedside tools to optimize ventilator settings and lung protective ventilation strategies. Small imperceptible alternative currents are injected into the thorax and the corresponding surface voltages are measured (Frerichs et al 2017). The relative impedance changes are calculated, which are proportional to the air and blood volume changes within the chest. With this rationale it provides continuous images of pulmonary ventilation and shows regional ventilation change. In the context of peri-operative procedures, EIT has been proposed to assess the regional lung functions (Lasarow et al 2021, Becher et al 2022), ventilator settings during one-lung ventilation (Liu et al 2019, Zha et al 2023), peri-operative ventilation distribution and recovery after thoracic surgery (Zhao et al 2021, Lin et al 2022), pulmonary rehabilitation program and inspiratory muscle activities (Li et al 2023). In a previous study, we observed that regional ventilation distribution might not recover easily even after minimally invasive surgery (Zhao et al 2021). During laparoscopic lung parenchymal resection, one-lung ventilation is applied. Patient is in lateral position with the non-surgery side as gravity-dependent regions. Previous studies have indicated that lateral position changes ventilation distribution due to gravity and disease status (Karagiannidis et al 2015, Wang et al 2021, Oh et al 2022). It was unclear how the laparoscopic lung resection changed the ventilation distribution.

The aim of the present study was to evaluate the influence of one-sided pulmonary nodule and tumor on ventilation distribution pre- and post- lung resection.

2. Methods

The prospective observational study was approved by the Second Affiliated Hospital of Air Force Medical University (NO. K202212-13). Written informed consent was obtained from all patients or their legal representatives prior to the study.

2.1. Patients and protocol

A total of 40 consecutive patients scheduled for laparoscopic lung parenchymal resection from September to December 2022 were included (age 58.23 ± 13.46 years, height 166.95 ± 6.61 cm, weight 64.13 ± 9.53 kg, male: female 21:19). The patients had the American Society of Anesthesiologists (ASA) classification I–II. One-sided pulmonary nodule or tumor was confirmed with CT prior to the surgery.

The procedure of surgery followed strictly the internal protocols. After general anesthesia, dual lumen tracheal catheter was inserted and the patient was kept in a lateral position with the surgical side facing upwards. All operations were performed with two-port thoracoscopy. Targeted resection was performed based on the location of the patient's pulmonary lesions. All patients were sent to the general ward after surgery. Exclusion criteria were: age >90 or <20 years; rejection to the patient consent form; in pregnancy and lactation period; epileptic re-accumulation; acute brain injury; acquired immunodeficiency; highly contagious diseases; large area of burns on the chest surface and other contraindication to the use of EIT (pacemaker, automatic implantable cardioverter defibrillator, and implantable pumps). Further, patients with unstable vital signs before surgery were also excluded (heartbeat >150 or <60 beats per minute, respiratory rate >30 or <10 breaths per minute, systolic blood pressure <90 mmHg or mean arterial pressure <70 mmHg).

Ventilation distribution was measured with EIT in supine and surgery lateral positions at 2 time points: 72 h before surgery (T1, pre-operative period, baseline), 48 h after extubation (T2, post-extubation period). An EIT electrode belt, which carries 16 electrodes, was placed around the thorax in the 4–5th intercostal space (VenTom-100, MidasMED Biomedical technology, Suzhou, China). EIT images were continuously recorded at 20 Hz and stored. Caution was taken to confirm that the electrode measurement planes were the same for each measurement time point.

The ventilation management followed the internal surgical guideline using assist-control mode (volume controlled with tidal volume of 10 ml kg^{-1} predicted body weight, peak airway pressure alarm 30 cmH_2O, respiratory rate 12 min^{-1}, and an adequate positive end-expiratory pressure around 5–6 cmH_2O). Recruitment manoeuvres were performed after the surgery (sustained inflation, lasted ~30 s and peak pressure ~40 cmH_2O). Spontaneous breathing trial started after the effect of general anesthesia subsided and breathing muscles recovered. The weaning protocol was the same for both left- and right-side lung parenchymal resections regarding the types and length of spontaneous breathing trial, ready-to-wean criteria, etc At T2, patients were under oxygen therapy with either Aerosol Mask (fractional inspired oxygen FiO_2 0.4) or nasal cannula (3 l min^{-1}).

2.2. Data collection and outcome measurements

EIT data were analyzed offline with customized software using MATLAB R2023a (The MathWorks Inc., Natick, MA). Functional EIT image of mean tidal variation was constructed for a 5 min period of measurement for each time point (Zhao *et al* 2018). Considering the influence of surgery types, ventilation distributions in left and right lungs were calculated to reflect the body position during the surgery. As a parameter, left lung to global ratio was calculated as follows:

$$F_{\mathrm{l}} = \frac{\sum_l \boldsymbol{Z}_l}{\sum_{i=1}^{1024} \boldsymbol{Z}_i} \cdot 100\%,\ l \in \text{left lung}, \tag{1}$$

where F_{l} denoted the fraction of left lung ventilation to the global one; Z was the relative ventilation distribution during tidal breathing.

Another EIT-based parameter to assess spatial ventilation distribution was the global inhomogeneity (GI) index (Zhao *et al* 2009), which was calculated according to the following formula:

$$\mathrm{GI} = \frac{\sum_{x,y\in \mathrm{lung}} |DZ_{xy} - \mathrm{Median}(DZ_{\mathrm{lung}})|}{\sum_{x,y\in \mathrm{lung}} DZ_{xy}}, \tag{2}$$

where DZ denotes the value of the differential impedance in the tidal variation images; DZ_{xy} is the pixel in the identified lung area; DZ_{lung} are all pixels in the lung area under observation.

Two parameters for assessing the temporal ventilation distribution were calculated.

Pendelluft amplitude was proposed previously (Sang *et al* 2020). For each pixel, the impedance difference at the global time points (end-inspiration and end-expiration) was subtracted by the regional tidal variation of the corresponding pixel:

$$A_i = \frac{1}{N}\sum_{n=1}^{N} (V_{R\_i,n} - V_{G\_i,n})/TV \times 100\% \quad i \in \text{lung}, \tag{5}$$

where TV represents the global tidal variation; V_{R_i} is the regional variation of pixel i during tidal breathing; N is the number of breaths within analyzed period; V_{G_i} is the global variation. To minimize the influence of noises in the calculation, we set the $A_i = 0$ if $A_i < 0.05\%$ of TV

Regional ventilation delay RVD is calculated as the time required for 40% increase of pixel impedance compared to the inspiration time of global impedance curve (Muders *et al* 2012):

$$\mathrm{RVD}_{xy} = \frac{t_{xy,40\%}}{T_{\mathrm{inspiration,global}}} \cdot 100\%,$$

$\mathrm{RVD}_{\mathrm{SD}}$ is the standard deviation of RVD_{xy}.

2.3. Statistical analysis

The analysis was performed using MATLAB R2023a. Sample size calculation was not applicable in the observational study, as there was no expected ventilation distribution prior to the study. Primary analysis was to compare the spatial and temporal ventilation distributions for the same position before and after surgery respectively at different time points. The Lilliefors test was used for normality testing. For normally distributed data, results were expressed as mean ± standard deviation. Paired t-test was used to compare the measurement before and after the surgery. For abnormally distributed data, results were expressed with median (interquartile range) and compared with Mann–Whitney U test. A statistically significant difference was determined at $p < 0.05$. The significance level was corrected for multiple comparisons using Holm's sequential Bonferroni method.

3. Results

It was impossible to maintain the same EIT measurement plane after surgery in 6 patients. Therefore, 34 patients were included to the final analysis. Fifteen patients had the right-lung resection (left lateral) and 19 patients had the left-lung resection (right lateral). Typical functional EIT images are shown in figures 1 and 2. After surgery (T2), ventilation at the operative sides were worse compared to T1 (figures 1(A) and 2(A)). RVD was more heterogeneous (figures 1(B) and 2(B)).

The spatial and temporal ventilation distribution before and after surgery were summarized in table 1. The GI index was significantly worse after surgery at the supine position ($p < 0.01$). For right-side resection, ventilation distributed at the right lung was significantly worse at T2 compared to T1 at both supine and left lateral positions ($p < 0.001$). For left-side resection, similar effects could be observed but statistically insignificant. On the other hand, $\mathrm{RVD}_{\mathrm{SD}}$ was worse at T2 compared to T1 at left lateral position ($p = 0.002$). The

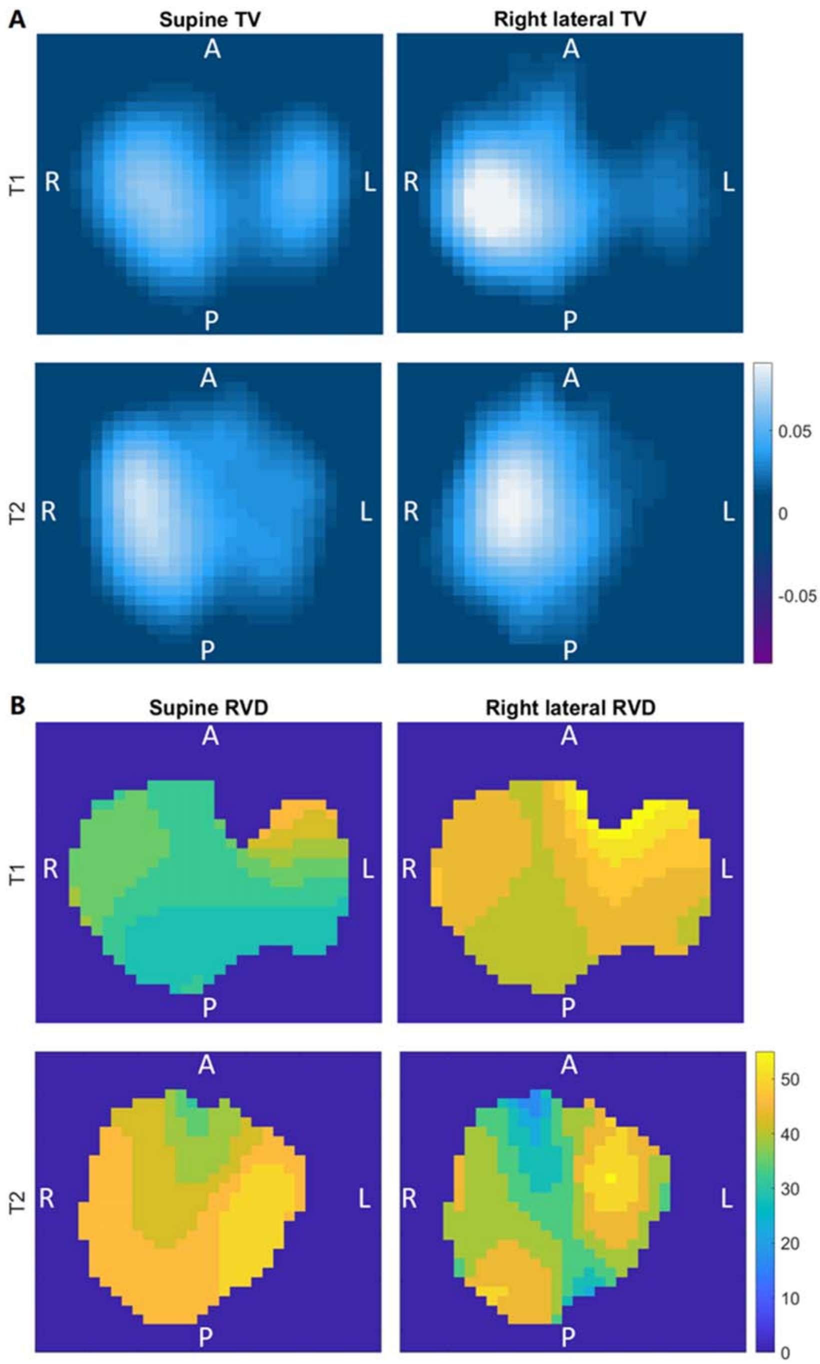

Figure 1. Tidal variation (TV) and regional ventilation delay (RVD) maps of a 33 year old female subject with left lung resection in supine and right lateral position before (T1) and after (T2) surgery. A: TV maps. Highly ventilated regions are highlighted in white or light blue. B: RVD maps. The color bar denotes the time of pixels impedance curve increasing to 40% of maximum inspiratory amplitude. The time is presented as percentage to global inspiration time. Detail calculations of these functional EIT images please refer to the Method section. R for right,L for left,A for anterior,P for posterior.

other EIT-based parameters showed no significant differences between two time points. No significant differences were observed between supine and lateral positions for the same time points respectively. No significant differences were observed between male and female patients in the evaluated EIT-based parameters.

The differences in EIT-based parameters between T1 and T2 in the left and right lateral positions were compared in figure 3. Patients who underwent right-side resection and were examined in the left lateral position had significantly worse ventilation in the left lung (figure 3 left top). Although patients with left-side resection showed worse ventilation in the right lung in the right lateral position compared to the distribution before surgery, the decrease in ventilation in the right lung was insignificant. RVD_{SD} deteriorated in both groups but for patients with right-side resection, the variation was much larger among patients and therefore ΔRVD_{SD} was insignificant (figure 3 right bottom). The variation of ventilation distribution was large. Two cases are plotted in

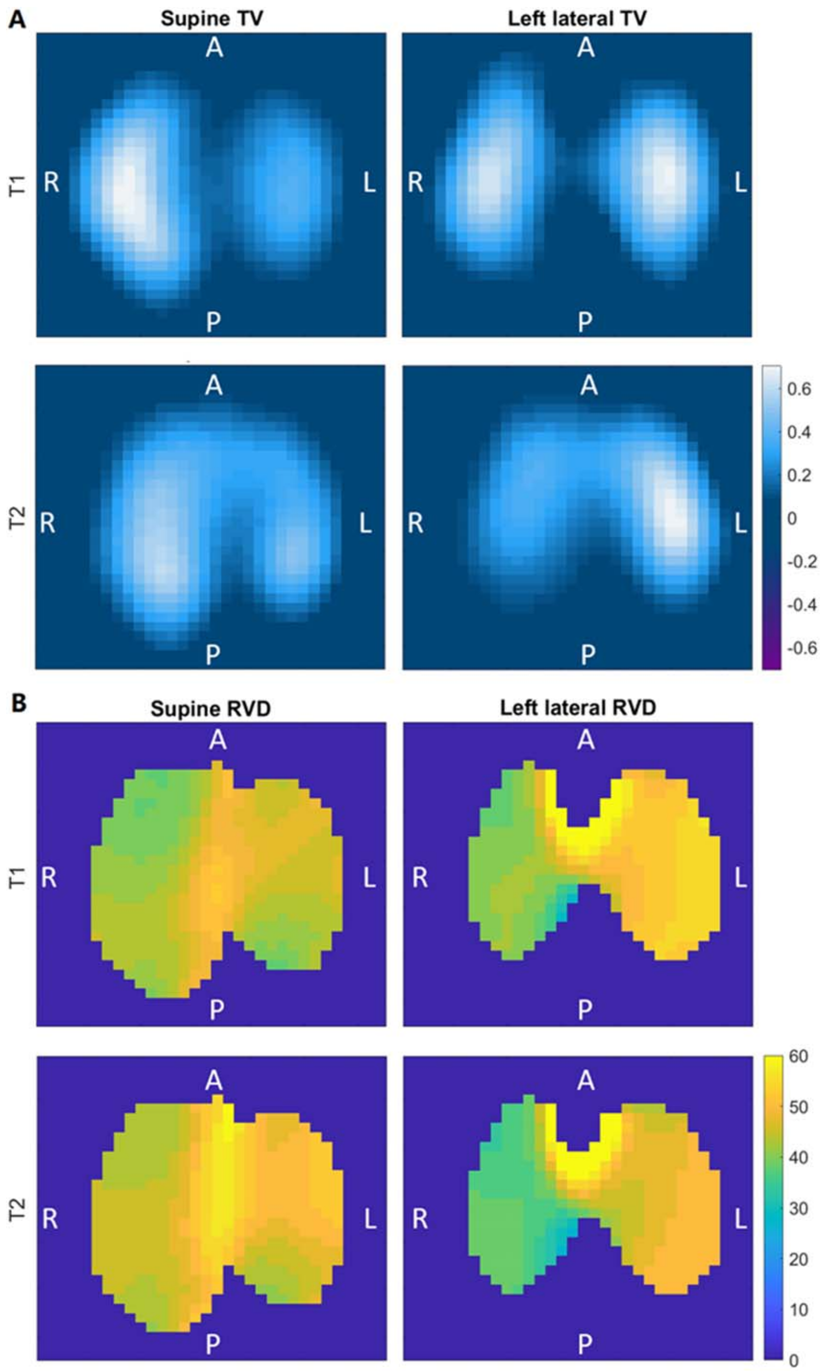

Figure 2. Tidal variation (TV) and regional ventilation delay (RVD) maps of a 35 year old male subject with right lung resection in supine and left lateral position before (T1) and after (T2) surgery. A: TV maps. Highly ventilated regions are highlighted in white or light blue. B: RVD maps. The color bar denotes the time of pixels impedance curve increasing to 40% of maximum inspiratory amplitude. The time is presented as percentage to global inspiration time. Detail calculations of these functional EIT images please refer to the Method section. R for right,L for left,A for anterior,P for posterior.

figure 4 showing that even for the surgery on the same side, ventilation recovery was different depending on the individual status.

4. Discussion

In the present study, we found that the surgery side influenced the ventilation distribution. When the resection was on the right lung, the right lung ventilation ratio was significantly worse. When the resection was on the left lung, the ventilation delay was significantly increased.

EIT is a bedside imaging tool that recently gain more attention in setting ventilator parameters in ICU (Becher *et al* 2021, He *et al* 2021, Hsu *et al* 2021) as well as perioperatively to protect the lung (Liu *et al* 2019,

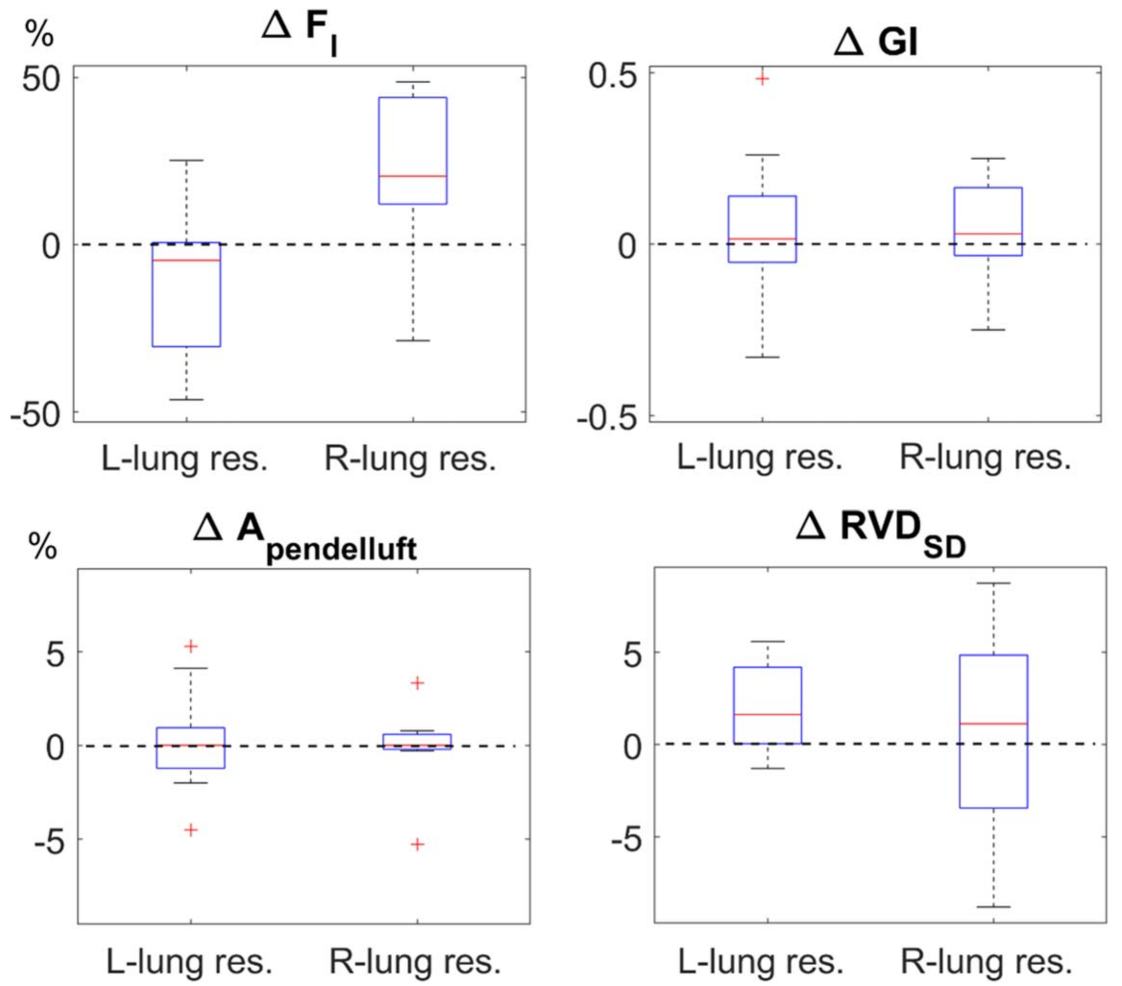

Figure 3. The change of EIT-based parameters after operation in surgical lateral positions. F_l, fraction of tidal ventilation in the left lung to global. GI, the global inhomogeneity index. $A_{pendelluft}$, pendelluft amplitude. RVD_{SD}, standard deviation of regional ventilation delay. The boxes mark the quartiles while the whiskers extend from the box out to the most extreme data value within 1.59 the interquartile range of the sample. Red pluses highlight the outliers. The black dashed lines denote the zero line—no change compared to the values prior to the operation. L-lung dis., left lung resection; R-lung dis., right lung resection.

Table 1. EIT-based parameters comparing the spatial and temporal ventilation distribution before and after surgery.

		F_l (%)	GI	$A_{pendelluft}$ (%)	RVD_{SD}
Right lung resection (supine; $n = 15$)	T1	44.47 ± 11.69	0.55 ± 0.05	0 (1.07)	7.73 ± 2.24
	T2	70.41 ± 17.71	0.70 ± 0.17	0 (0.57)	7.15 ± 3.27
	P	<0.001 **	<0.01 *	0.44	0.51
Right lung resection (left lateral; $n = 15$)	T1	47.56 ± 18.58	0.64 ± 0.12	0 (0.28)	8.43 ± 4.18
	T2	70.12 ± 18.19	0.68 ± 0.11	0 (3.30)	8.92 ± 4.20
	P	<0.001 **	0.32	0.65	0.72
Left lung resection (supine; $n = 19$)	T1	41.19 ± 12.73	0.51 ± 0.06	0 (1.82)	7.24 ± 2.87
	T2	35.11 ± 29.26	0.61 ± 0.14	0.38 (5.39)	7.07 ± 2.72
	P	0.33	<0.01 *	0.58	0.85
Left lung resection (right lateral; $n = 19$)	T1	35.19 ± 17.68	0.65 ± 0.16	0 (1.84)	6.55 ± 2.28
	T2	24.34 ± 14.68	0.66 ± 0.14	0.29 (2.57)	8.45 ± 2.68
	P	0.11	0.24	0.89	0.002 **

F_l, fraction of tidal ventilation in the left lung to global. GI, the global inhomogeneity index. $A_{pendelluft}$, pendelluft amplitude. RVD_{SD}, standard deviation of regional ventilation delay. T1, before, and T2, after surgery.

Bito *et al* 2022). Although the EIT applications for patients receiving various surgery have been summarized in a review (Spinelli *et al* 2019), in most of the published studies, EIT was used in a similar setting only preoperatively to assess the distribution before surgery (Serrano *et al* 2002, 2004) or adjusting ventilation support (Wang *et al* 2018, Girrbach *et al* 2022). In one previous study, Zhao *et al* compared ventilation distribution between minimal

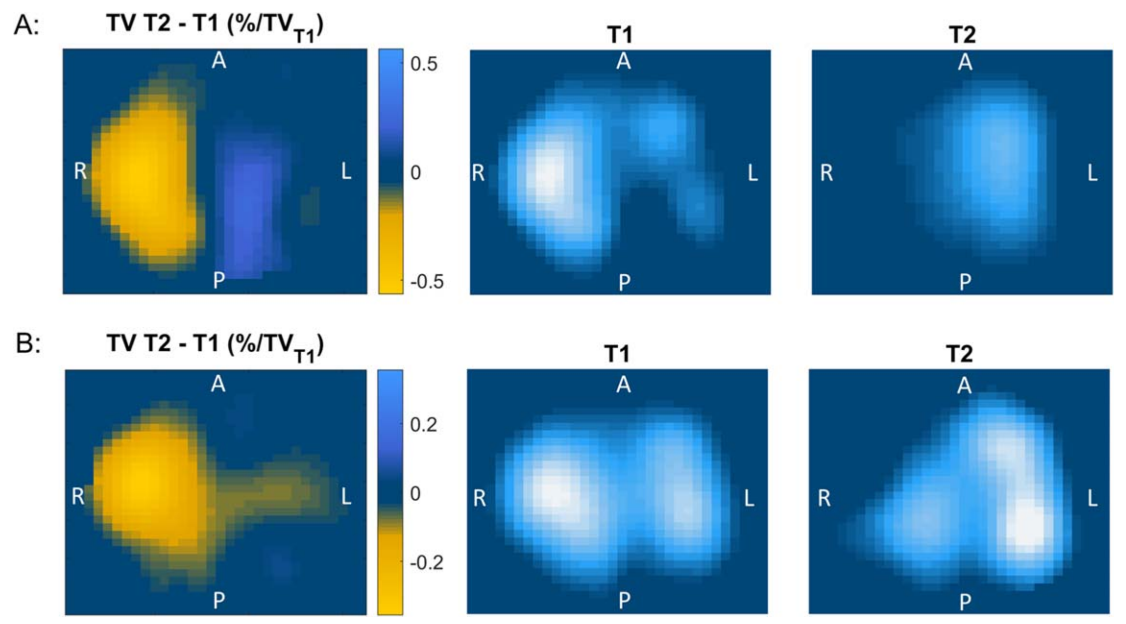

Figure 4. Two patients with partial right lung resection. A: pleural effusion in the right lung preventing fast recovery. Air mainly distributed to the left lung, which was poorly ventilated prior to the surgery. B: better recovery in the right-dorsal lung region, limiting the redistribution to the left lung. R for right,L for left,A for anterior,P for posterior.

invasive thoracotomy and traditional full sternotomy (Zhao *et al* 2021). They showed that bedside monitoring of ventilation distribution and patients' recovery were essential because the recovery of the respiratory system after surgery was very heterogeneous among individuals. In the present study, we assessed the ventilation changes at supine and operative lateral positions after 2 d of surgery. We confirmed that the effect of surgery was detectable by EIT. When the lung is partially resected, less ventilation would be expected in the corresponding regions. After surgery, not only a part of the lung tissue is gone, but there are also wounds in the lung (with small bleeding, small atelectasis, maybe small pleural effusion) and wounds on the chest. It would be painful for the patients to breath spontaneously. But as we observed in table 1 and figure 3, the variation among different subjects was quite large: some patients recovered fast and did not show large difference in ventilation distribution compared to that before surgery; some even showed improvement 2 d after surgery. Since we did not collect the data about the lung disease stages, we suspected that these patients were either diagnosed relatively late or the disease progressed to certain severe stages, so that the ventilation distribution at the affected side before surgery was not satisfactory, which allowed a room of improvement.

Another finding in the current study was that the right lung ventilation ratio was significantly worse in the patients with partial right lung resection. Such worsening was statistically insignificant in the patients with partial left lung resection. Since the right lung is larger than the left lung, theoretical speaking, the influence on lung function is larger for right lung resection compared to left lung resection. We did not collect the information about the size of the resection. Therefore, we were unable to confirm whether there was a systematic difference in lung resection size between left and right partial lung resection. The recovery of the surgery side depended on the types and severity of postoperative pulmonary complications, which affected the ventilation in the contralateral chest side as well (figure 4). Nevertheless, a clear trend of worsening was observed in patients with left lung resection as well (figure 3, left top). Significant level might be reached with increasing the sample size due to the large inter-subject variation.

The GI index was proposed to assess the spatial ventilation distribution and guide ventilator settings (Zhao *et al* 2010). Although this measure is effective, the inadequate definition of lung regions might influence the results (Yang *et al* 2021b, Heines *et al* 2022). Therefore, it is essential, the same regions were used before and after surgery for GI calculation. However, the measurement plane could not be 100% identical even we had marked the position. On lateral positions, the electrode belt might have shifted undetected, which led to insignificant worsening of GI (figure 3 right top). From the definitions of the calculated parameters, we know that F_l is a very general measure with limited spatial resolution (2-side $\times$ 1 region/side), whereas GI has a much higher resolution (usually $>$300 pixels depending on the lung regions identification). The calculation of GI is influenced by many factors and therefore the correlation between F_l and GI was poor ($R = -0.11$).

Pendelluft is a phenomenon that air redistributed among various lung regions due to heterogeneous lung mechanics (Su *et al* 2022). Pendelluft increases in patients with strong inspiration need and require higher ventilation support (Yoshida *et al* 2016). Chi *et al* found that patients with spontaneous breathing had higher overall occurrence compared with patients under controlled ventilation (Chi *et al* 2022). In the present study, the pendelluft amplitude was relatively low (table 1 and figure 3 left bottom), indicating that the support levels were sufficient. Several other pendelluft calculation methods were proposed. For example, Coppadoro *et al* calculated pendelluft within 4 regions of interest so that the spatial resolution was reduced to 4×1 (Coppadoro *et al* 2020). With such calculation one would expect a lower pendelluft volume compared to the method used in the present study.

The RVD parameter was originally proposed during a low-flow maneuver (Muders *et al* 2012). During spontaneous breathing, the inspiration time is brief, and variation can be large due to noise and various inspiratory efforts (Yang *et al* 2021a). Therefore, the EIT data of 5 min were analyzed (instead of analyzing just one breath) and the average value was used. Besides, the calculation of RVD was originally using 10% of inspiratory volume as threshold (Wrigge *et al* 2008) and in a later study the authors proposed another threshold of 40% (Muders *et al* 2012). We think that helps with the calculation, as the noise in the signal is much higher proportionally at 10% of inspiratory volume compared to 40%. In the present study, we found that the patients at left lateral position showed much larger variation compared to the group at right lateral position. We suspected that this could be related to the position of the heart, which affected the operated left lung more by compressing the lung tissue. This could increase ventilation delay in the left lung if it was not in a good condition. If the left lung recovered from the mechanical ventilation very well, the delay might be similar compared to T1. Therefore, besides the surgical side (right lung), there could be an additional factor, which introduced the high variation in RVD for patients with right-lung resection. Unfortunately, no other reference method could be utilized to confirm this speculation. Nevertheless, we could not rule out the possibility that high variation might be due to the calculation of RVD during spontaneous breathing.

The study has several limitations in addition to those discussed above. (1) Lung functions (airway flow and lung volume limitations) were not evaluated. Although the objective of the study was to assess the ventilation distribution after surgery in supine and lateral position, it would have been nice to compare the changes of lung functions with the EIT measurements. (2) only two measurement time points were initiated. Ideally, a longer follow-up period to depict the ventilation distribution change after surgery might help to better understand the influence of partial lung resection and recovery. EIT applications in respiratory rehabilitation have been proposed recently (Longhini *et al* 2020, Ma *et al* 2022, Li *et al* 2023). Further studies may include individualized rehabilitation programs to the subjects and evaluate the efficacy. (3) In this physiological study, we only revealed that the effects of the right-side resection and left-side resection were dissimilar (e.g. figure 3). As our study was not designed to explore the reasons behind the phenomenon, we were not able to provide suggestions on the clinical usefulness with such EIT findings. Further quantitative studies comparing the exact size of the resected lung tissues and ventilation defect should be considered.

5. Conclusion

Partial lung resection influences regional ventilation distribution in supine as well as lateral positions 48 h after surgery. EIT is feasible in perioperative ventilation monitoring in this patient group.

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Data availability statement

Data are available upon reasonable request addressed to the corresponding authors.

Declaration of interests

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