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Redistribution of pulmonary ventilation after lung surgery detected with electrical impedance tomography

Martin Lehmann[1] | Beatrice Oehler[2] | Jonas Zuber[3] | Uwe Malzahn[4] | Thorsten Walles[5] | Ralf M. Muellenbach[6] | Norbert Roewer[1] | Markus Kredel[1]

[1]Department of Anaesthesia and Critical Care, University Hospital of Würzburg, Würzburg, Germany
[2]Wolfson Centre for Age-Related Diseases, King's College London, London, UK
[3]Department of Anesthesia, General Intensive Care and Pain Management, Medical University of Vienna, Vienna, Austria
[4]Clinical Trials Center Würzburg, University Hospital of Würzburg, Würzburg, Germany
[5]Department of Thoracic Surgery, Magdeburg University Medicine, Magdeburg, Germany
[6]Department of Anesthesiology, Critical Care Medicine, Emergency Medicine and Pain Therapy, ECMO Center, Campus Kassel of the University of Southampton, Kassel, Germany

Correspondence
Markus Kredel, Department of Anaesthesia and Critical Care, University Hospital of Würzburg, Oberdürrbacher Strasse 6, 97080 Würzburg, Germany.
Email: Kredel_M@ukw.de

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Background: Regional ventilation of the lung can be visualized by pulmonary electrical impedance tomography (EIT). The aim of this study was to examine the post-operative redistribution of regional ventilation after lung surgery dependent on the side of surgery and its association with forced vital capacity.

Methods: In this prospective, observational cohort study 13 patients undergoing right and 13 patients undergoing left-sided open or video-thoracoscopic procedures have been investigated. Pre-operative measurements with EIT and spirometry were compared with data obtained 3 days post-operation. The center of ventilation (COV) within a 32 × 32 pixel matrix was calculated from EIT data. The transverse axis coordinate of COV, COVx (left/right), was modified to COVx′ (ipsilateral/contralateral). Thus, COVx′ shows a negative change if ventilation shifts contralateral independent of the side of surgery. This enabled testing with two-way ANOVA for repeated measurements (side, time).

Results: The perioperative shift of COVx′ was dependent on the side of surgery (P = .007). Ventilation shifted away from the side of surgery after the right-sided surgery (COVx′-1.97 pixel matrix points, P < .001), but not after the left-sided surgery (COVx′-0.61, P = .425). The forced vital capacity (%predicted) decreased from 94 (83-109)% (median [quartiles]; [left-sided]) and 89 (80-97)% (right-sided surgery) to 61 (59-66)% and 62 (40-72)% (P < .05), respectively. The perioperative changes in forced vital capacity (%predicted) were weakly associated with the shift of COVx′.

Conclusion: Only after right-sided lung surgery, EIT showed reduced ventilation on the side of surgery while vital capacity was markedly reduced in both groups.

1 | INTRODUCTION

Patients undergoing intrathoracic procedures have the highest risk of developing post-operative pulmonary complications (PPCs)[1-3] that increase hospital stay and mortality.[4] After lobectomy, post-operative lung function tests, like forced vital capacity, are reduced for months.[5,6] In patients with sublobar resections, pulmonary function is diminished only for a few days post-surgery.[6,7]

Pulmonary electrical impedance tomography (EIT) is a bedside application that indicates changes of the regional distribution of lung ventilation.[8] Thus, the differential ventilation of the left and the right lung in ventilated patients can be discriminated.[9-11] In several studies, EIT was applied in patients who breath spontaneously after surgery.[12-14] Furthermore, results obtained in awake patients with lung cancer by EIT are in accordance with the ventilation scintigraphy estimating a left-right division of ventilation.[15,16] Being radiation-free and having a higher time resolution makes EIT a favorable method. Since forced vital capacity is expected to be reduced after lung surgery,[5,6] pulmonary EIT might show a reduced ventilation on the side of surgery. Because of the anatomic asymmetry of the lungs and the heart, the left lung receives less ventilation and the impedance change during breathing is lower on this side.[17] Thus, an effect of lung surgery on the distribution of ventilation might be dependent on the side of surgery.

The primary aim of this study was to investigate if an ipsi- or contralateral redistribution of the regional ventilation to the side of lung surgery is present according to pulmonary EIT in spontaneously breathing patients. The secondary aim was whether this redistribution is dependent on the side of surgery. We hypothesized that the ventilation always shifts from the side of surgery to the healthy side. The data were correlated with forced vital capacity.

Editorial Comment

Regional ventilation in the lung can be redistributed after lung resection surgery. In this study, electrical impedence tomography was used to assess regional ventilation after lung surgery. This imaging modality identified some post-operative ventilation reductions and particularly for one side.

2 | METHODS

This monocentric, prospective, observational cohort study examined perioperative redistribution of ventilation in patients with lung surgery. The medical ethics committee of the University Hospital of Würzburg, Germany approved the study protocol (58/16-ge). All patients provided written informed consent before inclusion. The study protocol was registered in advance at ClinicalTrials.gov: NCT02779595.

2.1 | Patients

Adult patients undergoing open thoracic surgery or video-thoracoscopic procedures were recruited and followed up between June 2016 and June 2017 at the University Hospital of Würzburg. Although the type of anesthesia, airway management, and intraoperative ventilation were not part of the study protocol, procedures were recorded. In accordance with the standard operating procedures, general anesthesia was induced with fentanyl, propofol, and rocuronium and maintained with an opioid (remifentanil or fentanyl) and an anesthetic (propofol or sevoflurane) completed with or without an additional epidural regional anesthesia with ropivacaine 0.375%. A double lumen tube or a single lumen tube in combination with a bronchus blocker enabled separate ventilation of both lungs. Pressure controlled ventilation was performed. For post-operative analgesia NSAIDs like metamizole, paracetamol or ibuprofen and opioids such as oxycodone or piritramide, and/or patient controlled epidural or intercostal analgesia were used. For epidural analgesia, a combination of ropivacaine 0.2% and sufentanil 5 µg/mL was used whereas intercostal analgesia was achieved with ropivacaine 0.2% alone.

Exclusion criteria were emergency procedures, re-surgery of hospitalized patients, pre-operative pneumothorax, relevant pre-operative pleural effusion, pleural empyema, planned pneumonectomy, expected post-operative mechanical ventilation, expected hospital stay less than 3 days, pregnancy, and contraindications for the application of EIT (eg, pacemaker). Post hoc, patients were excluded if pneumonectomy was performed or the patients were ventilated longer than 3 post-operative days. If re-surgery was performed, patients were only included to follow-up PPCs.

2.2 | Study procedures

EIT, spirometry, and pulse oximetry were executed one day before surgery and on the post-operative days 3, 5, and 7 as long as patients were not discharged from hospital. The respiratory rate was recorded by EIT; dyspnea was determined by a questionnaire. Respiratory infection, respiratory failure, pleural effusion, atelectasis, pneumothorax, bronchospasm, or aspiration pneumonitis that define PPCs[2] were followed up by examining clinically indicated thoracic x-ray or CT, patient visit, and chart review. Pain scores were measured by Numeric Rating Scale (0-10).

2.3 | Measurements

The pulse oximeter served to measure peripheral oxygen saturation non-invasively before performing spirometry (combined spirometer and pulse oximeter, Spirodoc®, Medical International Research).

For EIT, a silicon belt with 16 equidistantly integrated electrodes was applied around the patients' thorax at the height of their third intercostal space determined in the medioclavicular line with a reference electrode on the abdomen. If necessary, wound dressings were removed and were replaced afterward. The patient was in supine position with a 30° elevated upper body and arms resting beside. After a resting period of 2 minutes, the EIT system (Pulmovista 500®, Dräger Medical AG) recorded 2 minutes of spontaneous breathing. Then spirometry was performed while EIT recording was continued. The best value of three attempts regarding FVC and FEV1 was used. Percentages of predicted values were calculated according to Knudson ($FVC\%_{predicted}$ and $FEV1\%_{predicted}$).

2.4 | Processing of EIT data

The EIT system recorded changes in pulmonary electrical bioimpedance. Data were analyzed with special software (Dräger EIT Data Analysis Tool 6.1, Dräger Medical AG). A low-pass filter (30 bpm) excluded cardiac and perfusion-related impedance changes. The software transformed EIT data into images of an ellipsoid shape that were reconstructed into a 32 × 32 pixel matrix. The EIT image matrix represented the impedance change relative to a baseline set at the expiration of tidal breathing at rest. To analyze breathing at rest, the impedance changes from baseline to inspiration were averaged over 1 minute of normal breathing (analysis at rest, minute image of breathing with tidal volumes at rest). For analyzing forced breathing, the impedance change from baseline to maximal inspiration before forced expiration during spirometry was selected (analysis at forced breathing, tidal image of one breath with inspiratory capacity). The matrix data of relative intensity change (.ASC File) were processed with Microsoft Excel. This 32 × 32 matrix defined x = 1 (right) to 32 (left) and y = 1 (dorsal) to 32 (ventral). Within this matrix, the center of ventilation (COV) with a horizontal (COVx) and sagittal (COVy) coordinate represented the center of gravity if each point of the matrix would represent a mass. The calculation of COVx and COVy is described in our previous work.[18]

To allow the summation of EIT images independent of absolute impedance and breathing effort, each matrix of the tidal images was normalized to the same global impedance change. Thus, the sum of all 32 × 32 intensity changes was the same for every EIT image. The averaged normalized matrices for each time point visualized the pulmonary ventilation for a whole group by a colored contour line graph (Origin Pro 9.1 G, OriginLab Corporation).

2.5 | Statistical analysis

COVx (left/right), measured at forced breathing, was calculated to compare the pre-operative values with those of the post-operative day 3. To enable the application of two-way ANOVA with one between- and one within-subject factor for the effects of time and side, COVx′ (ipsilateral/contralateral) was defined as primary outcome variable by inverting the sign of the vector of the perioperative change of COVx for right-sided surgery. Following formulae were used:

Surgery left side post-operatively and surgery both sides, pre-operatively:

$$\mathrm{COVx}' = \mathrm{COVx}.$$

Surgery right side post-operatively:

$$\mathrm{COVx}' = 2 \times \mathrm{COVx}_{\mathrm{pre-operative}} - \mathrm{COVx}_{\mathrm{post-operative}}$$

Consequently, COVx′ increases if COV shifts ipsilateral and decreases if COV shifts contralateral to the side of surgery. Taking into account the asymmetries of a thorax and its organs, the same number of patients with comparable left- and right-sided surgery was included.

For COVx′ on the pre-operative and post-operative day 3, the requirements for a two-way ANOVA with one between- and one within-subject factor were fulfilled. Since several of the remaining variables did not satisfy requirements for parametric statistics, nonparametric methods were used. The corresponding summary statistics show the median for location and quartiles (25th-75th percentile) for the spread. The Mann-Whitney U-test was used to compare between both groups whereas for intragroup comparisons with three or more time points, Friedman tests were performed. Dunn's method was used for post hoc pair-wise comparisons. The association between changes in COVx′ and $\mathrm{FVC\%}_{\mathrm{predicted}}$ was tested using Spearman's rank correlation. *P*-values < .05 for two-sided testing were considered to be statistically significant. Sigmaplot for Windows Version 11.0. (Systat Software Inc) was used for statistical calculations.

2.6 | Sample size calculation

The sample size calculation was based on the Geisser-Greenhouse F test for the within-subject factor in a two-way ANOVA. Based on previous data, a change in COVx′ from pre-operative to the post-operative day 3 of 1 unit in the 32 × 32 EIT matrix was considered to be clinically relevant. The standard deviations of pre-operative and post-operative COVx′ were expected to be 1.5 units. Assuming a linear correlation coefficient of 0.5 between pre-operative and post-operative COVx′, this corresponds to about the same standard deviation of 1.5 units for their difference. For the described assumptions, 13 patients in each of both groups were necessary to detect a mean difference of 1 between pre- and post-operative COVx′ measurements to achieve a significant deviation from the null hypothesis of equal means at α-level of .05 with a power of .90 (within-subject factor). Furthermore, the sample size is sufficient to detect a mean difference of 1.5 for patients undergoing right- and left-sided surgery with a power of .80 (between-subject factor). The power to detect an effect of the interaction term twice as much as that of the within-subject factor would be > .99.

3 | RESULTS

Pre-operative measurement and examinations on the post-operative day 3 were executed in 31 patients. However, five patients withdraw their consent. Thus, 13 patients with lung surgery on the left or right side, respectively, were recruited. Baseline characteristics (Table 1), characteristics of surgery, anesthesia, and the ARISCAT risk score for post-operative pulmonary complications[2] (Table 2) were comparable in all patients. In comparison to baseline, $\mathrm{FVC\%}_{\mathrm{predicted}}$ and $\mathrm{FEV1\%}_{\mathrm{predicted}}$ were reduced at least on the post-operative day 3 (Table 3). Seven patients were discharged from the hospital between days 3 and 5, eight patients between days 5 and 7.

The pre-operative ventilation in the right and left half of the EIT summation images during forced breathing were equally distributed, the right side ventilation markedly decreased in patients with right side surgery on the post-operative day 3 (Figure 1). COV shifted away from the side of surgery in patients after right-sided surgery (Figure 2A,B). Accordingly, COVx′ indicated a contralateral shift of the COV in those patients (Figure 2C).

TABLE 1 Baseline characteristics of patients with left- and right-sided lung surgery

Localization of procedure	Left (n = 13)	Right (n = 13)	*P*
Age (years)	67 (60-76)	61 (54-73)	.412
Male gender	7 (54%)	10 (77%)	.411
Body mass index	25 (24-28)	27 (24-32)	.720
ASA grade			
I	0 (0%)	0 (0%)	
II	7 (54%)	5 (38%)	
III	5 (38%)	8 (62%)	
IV	1 (8%)	0 (0%)	
Underlying condition			
Asthma	1 (8%)	1 (8%)	
COPD	4 (31%)	4 (31%)	
Cancer	9 (69%)	7 (54%)	
Hypertension	8 (62%)	5 (38%)	
Coronary disease	0 (0%)	1 (8%)	
Smoking (pack years)	20 (0-30)	27 (15-40)	.278
Respiratory symptoms	5 (38%)	7 (54%)	.695
Pulmonary infection last month	1 (8%)	2 (15%)	1.000
Pre-operative hospital stay (days)	1 (1-1)	1 (1-1)	.550
Peripheral oxygen saturation (%)	97 (94-98)	96 (96-98)	.716
Hemoglobin (g/dL)	14 (13-15)	13 (11-14)	.426

Note: The number of cases are given in the first row for left and right side procedures. Data are shown as median (interquartile range) or number (percentage). Differences between groups are tested by Mann-Whitney U-test; dichotomous variables are tested with the Fisher exact test. *P* values are not adjusted for multiple testing.

Abbreviation: ASA, American Society of Anesthesiologists.

TABLE 2 Characteristics of operation, anesthesia, intraoperative ventilation, and ARISCAT risk score in patients with left- and right-sided lung surgery

Localization of procedure	Left (n = 13)	Right (n = 13)	*P*
Thoracotomy (versus VATS)	6 (46%)	8 (62%)	.695
Procedure			
Wedge resection	5 (38%)	3 (23%)	
Lobectomy	6 (46%)	4 (31%)	
Bilobectomy	0 (0%)	3 (23%)	
Emphysema	1 (8%)	1 (8%)	
Thoracic wall/ pleura	1 (8%)	2 (15%)	
Anesthesia			
General	13 (100%)	13 (100%)	
Epidural	6 (46%)	6 (46%)	
Intercostal	0 (0%)	1 (8%)	
Duration of procedure (min)	145 (75-160)	140 (85-200)	.778
Duration of anesthesia (min)	245 (210-275)	220 (180-300)	.980
Maximal PEEP (mbar)	5 (5-6)	7 (5-8)	.197
Minimal FiO_2	0.8 (0.74-0.98)	0.77 (0.5-0.85)	.171
Fluid balance (liters)	1.5 (1.0-1.7)	1.5 (1.3-1.7)	.481
ARISCAT score	56 (48-64)	63 (40-64)	.855

Note: The number of cases are given in the first row for left and right sided procedures. Data are shown with median (interquartile range) or number (percentage). ARISCAT Score: risk score for post-operative pulmonary complications.[2] Differences between groups are tested by Mann-Whitney U-test; dichotomous variables are tested by the Fisher exact test. *P* values are not adjusted for multiple testing.

Abbreviations: FiO_2, inspiratory oxygen fraction; PEEP, positive end-expiratory pressure; VATS, video-assisted thoracoscopy.

3.1 | Results from primary statistical analysis

The influence of the factors side (of surgery) and time (from the pre-operative to the post-operative day 3) on COVx′ were tested with a two-way ANOVA with one within-subject factor (time) during forced breathing and one between-subject factor (side). Analysis revealed an effect of the factor time on mean COVx′ (1.29 matrix points decrease, $P < .001$). There was no statistically significant effect of the factor side (0.92 matrix points lower in right sided surgery; $P = .066$), but an interaction between side and time ($P < .007$). Therefore, subgroup analyses had to follow.

3.2 | Secondary analysis: subgroup analyses and analysis at fixed time

Post-operatively there was a statistically significant effect of side on COVx′ (1.60 matrix points lower in right sided procedures, $P = .029$). Only in right-sided surgery a statistically significant effect of time was detected (1.97 matrix points decrease, $P < .001$), but not in left-sided surgery (0.61 matrix points decrease, $P = .425$).

Pre- to post-operative changes of COVx′ and vital capacity ($FVC\%_{predicted}$) were weakly associated during forced breathing ($r = .388$; $P < .05$) and breathing at rest ($r = .489$; $P = .011$). Table 4 shows the changes of COVx′ and COVy for the whole study period. COVy did not change compared to pre-operative values. Breathing at rest showed very similar results (Table 4).

PPCs were present in 38% of patients prior to surgery and increased up to 85% within the first week after surgery (day 3:24 of 30; day 5:18 of 24; day 7:12 of 14). On day 3, pleural effusion (eight left, six right), atelectasis (one left, eight right), pneumothorax (six left, four right), respiratory insufficiency (one left, four right) and pulmonary infection (two left, two right) were the leading causes of PPCs. Differences in $FVC\%_{predicted}$, $FEV1\%_{predicted}$, or the perioperative change of COVx′ between patients with PPCs and without were not statistically significant.

TABLE 3 Respiratory rate and results of oximetry and spirometry in patients before and up to 7 d after left- and right-sided lung surgery

Localization of procedure	Left (n = 13)	Right (n = 13)	*P*
Respiratory rate (per minute)			
Pre-operative (n = 13/13)	13 (12-16)	15 (12-17)	.604
Post-operative day 3 (n = 13/13)	16 (14-18)	14 (13-17)	.552
Post-operative day 5 (n = 9/9)	16 (13-18)	15 (12-17)	.624
Post-operative day 7 (n = 5/6)	16 (16-16)	14 (13-16)	.662
Peripheral oxygen saturation (% at room air)			
Pre-operative (n = 13/13)	97 (94-98)	96 (96-98)	.716
Post-operative day 3 (n = 13/13)	95 (91-97)	96 (89-96)	.641
Post-operative day 5 (n = 10/9)	96 (93-98)	96 (93-98)	.805
Post-operative day 7 (n = 5/6)	97 (91-97)	98 (96-99)	.329
Pain during forced breathing (NRS)			
Pre-operative (n = 13/13)	0 (0-0)	0 (0-0)	.611
Post-operative day 3 (n = 13/13)	0 (0-4)	2 (0-3)	.556
Post-operative day 5 (n = 9/8)	2 (0-2)	2 (0-3)	.960
Post-operative day 7 (n = 5/6)	0 (0-0)	0 (0-0)	.931
FVC (%predicted)			
Pre-operative (n = 13/13)	94 (83-109)	89 (80-97)	.292
Post-operative day 3 (n = 13/13)	61 (59-66)*	62 (40-72)*	.817
Post-operative day 5 (n = 9/8)	73 (64-76)	51 (41-73)*	.136
Post-operative day 7 (n = 5/6)	78 (72-81)	55 (45-81)	.247
FEV1 (%predicted)			
Pre-operative (n = 13/13)	81 (76-94)	75 (66-84)	.130
Post-operative day 3 (n = 13/13)	55 (43-65)*	53 (39-58)*	.426
Post-operative day 5 (n = 9/8)	63 (57-74)*	43 (31-63)*	.067
Post-operative day 7 (n = 5/6)	75 (61-76)	45 (38-62)	.126

Note: The total number of cases are given in the first row for left- and right-sided procedures. The number of cases available at the respective days are given in the first column for each measurement (left/right). Data are shown as median (interquartile range). Differences between groups are tested by Mann-Whitney U-test; dichotomous variables are tested by the Fisher exact test. Absolute *P* values are given. Repeated measurements are tested by Friedman ANOVA followed by Dunn's post hoc test (*$P < .05$ versus pre-operative).

Abbreviations: FEV1, forced expiratory volume in one second; FVC, forced vital capacity; NRS, numeric rating scale.

4 | DISCUSSION

In the present study, patients undergoing lung surgery were examined by pulmonary EIT and spirometry. After right-sided lung surgery, patients showed less ventilation on the side of surgery and the center of ventilation shifted to the contralateral side. Left-sided surgery caused no marked effect on the distribution of ventilation. However, $FVC\%_{predicted}$ was equally reduced in both groups. The association between perioperative changes in $FVC\%_{predicted}$ and COVx′ was weak. Taken together, the reduction of $FVC\%_{predicted}$ cannot sufficiently be explained by a diminished ventilation on the side of surgery. Moreover, ventilation did not change in sagittal direction (COVy). A global reduction of ventilation in patients after lung surgery, for example by reduced respiratory effort, might contribute to the changes in forced vital capacity.

In this prospective study, FVC and FEV1 were decreased on the post-operative day 3 and did not reach baseline values obtained before surgery within one week. Ergegovac et al also reported decreased FVC and FEV1 that recovered partially within one week in patients after lung resections. In their study, no marked differences in patients with and without respiratory and other complications were present.[19] Decreased vital capacity was found also in patients with cardiopulmonary bypass surgery. In patients with intercostal drainages, the decrease of the FVC was higher than in those with subxyphoid drainages, most likely due to different pain intensities.[20] In our study, expected changes in pulmonary function tests were found in patients serially tested after lung surgery. Pain scores were not different between the groups tested. To our knowledge, this is the first study where an imaging method is used to examine the changes in regional ventilation during the first days after lung surgery. Ventilation scintigraphy

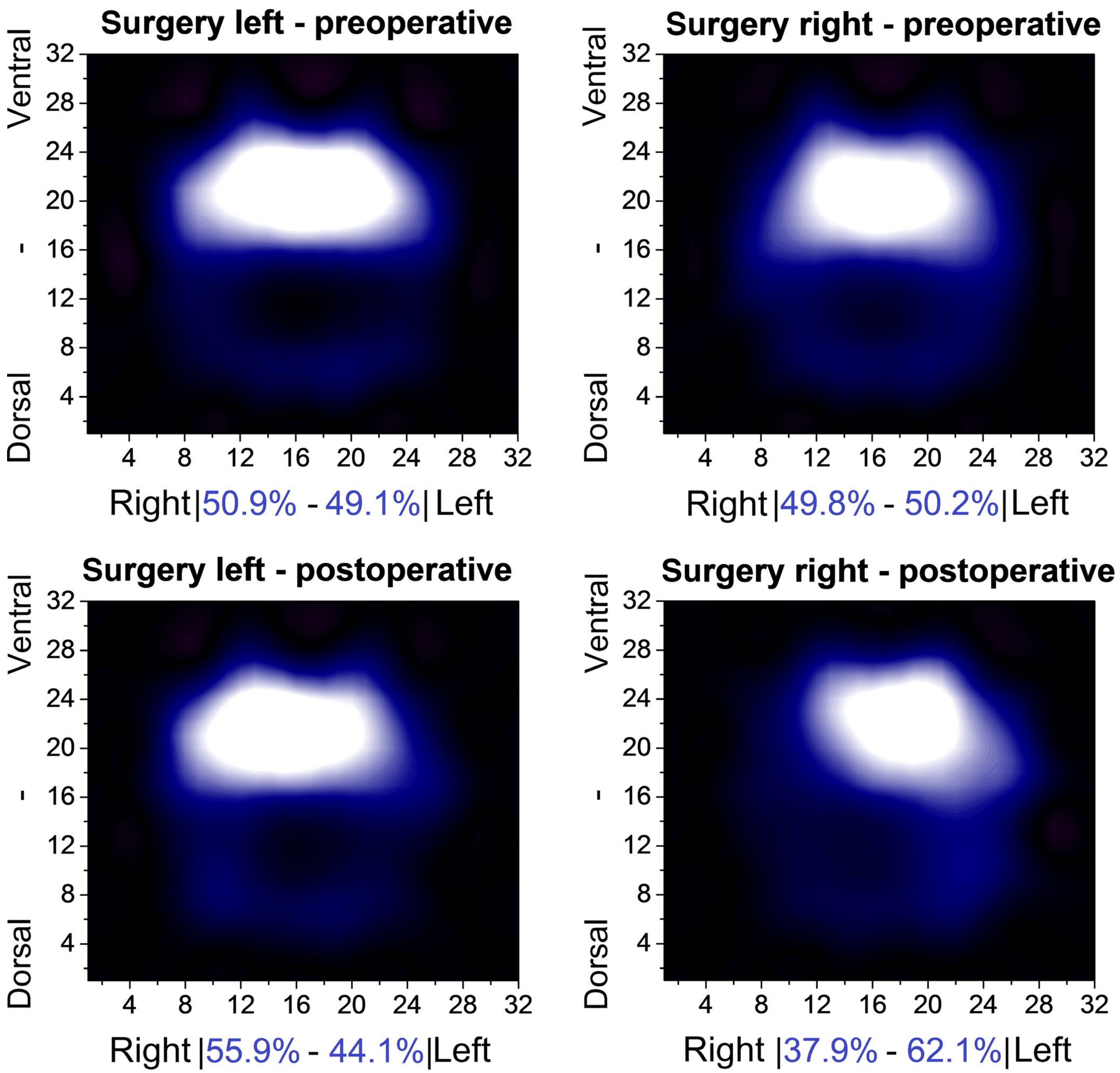

FIGURE 1 Electrical impedance tomographic images pre-operatively and 3 d post-operatively in patients with thoracic surgery on the left and right side. Summation images of 13 patients each indicating forced breathing. Bright: more ventilation. The percentages shown below the images represent the left-right distribution of ventilation on each hemithorax. Both pre-operative images (upper images) show ventilation distributed approximately equal on both, right and left, sides of the thorax. The post-operative image for surgery on the left (lower left image) shows slightly less ventilation on the left side of the thorax. The post-operative image for surgery on the right (lower right image) shows markedly less ventilation on the right side of the thorax [Colour figure can be viewed at wileyonlinelibrary.com]

was only used in one study to evaluate the late effects of lung volume reduction surgery.[21]

Reasons that may be relevant for more prominent consequences after right-sided procedures observed by EIT measurements are as follows: The anatomic asymmetry of the left and right lung measured by EIT, which is in accordance with data obtained by radionuclide-based imaging of ventilation.[15] Further, operative procedures might not be equal between both groups. Side-dependent differences in the extent of lung traumatization and -resection, effusions and pneumothoraxes have an influence on the measurements and consecutively lead to fewer impedance changes in the EIT. In our study, eight of the patients who underwent left-sided surgery had a pleural effusion post-operatively, compared to six in the other group. The incidence of pneumothorax was different too. Moreover, three patients received bilobectomy on the right side. Distribution of regional ventilation according to pulmonary EIT is depended on body posture and the intercostal level of the EIT belt.[22] In the present study, the belt was placed in the third intercostal space at the

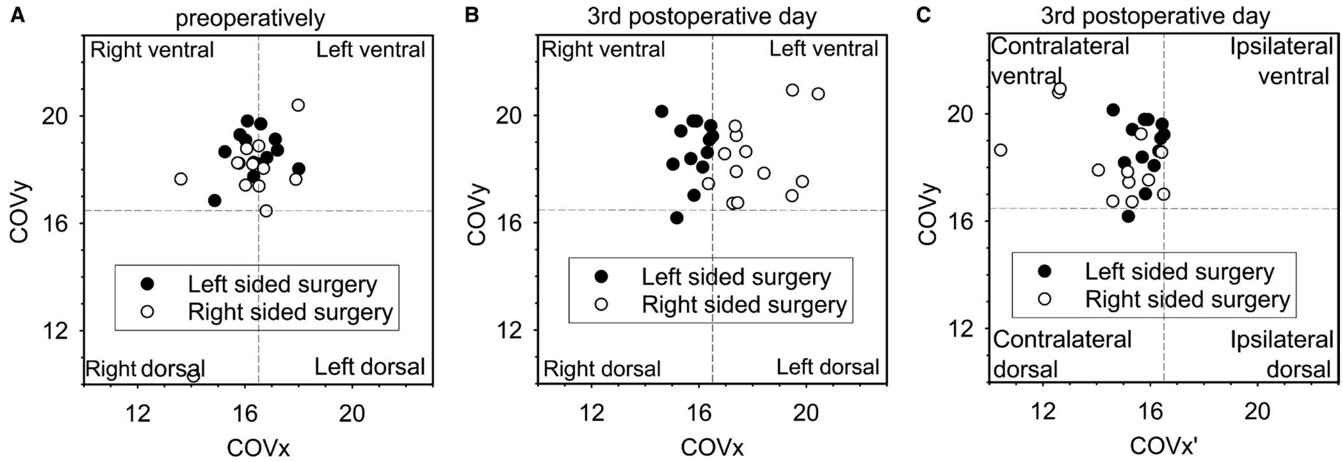

FIGURE 2 Center of ventilation (COV) calculated from electrical impedance tomographic data pre-operatively and post-operative day 3 during forced breathing while spirometry. A, Pre-operative localization of COV on the x-axis (COVx) and y-axis (COVy). B, COV shifted away from the side of surgery in most of the patients. C, Same data with inverted vector of the right sided surgery group (COVx′). Accordingly, a decrease of COVx′ indicated a contralateral shift of the COV in most of the patients. Patients with left- (filled circles) and right- (open circles) sided thoracic procedures

TABLE 4 Perioperative change of the center of ventilation in patients before and up to seven days after left- and right-sided lung surgery

Localization of procedure	Left (n = 13)	Right (n = 13)	*P*
COVx′ breathing at rest			
Pre-operative (n = 13/13)	16.0 (15.6-16.5)	16.0 (15.5-16.8)	.798
Post-operative day 3 (n = 13/13)	15.5 (15.1-16.0)	14.6 (12.8-15.4)*	.024
Post-operative day 5 (n = 9/9)	15.5 (14.6-16.2)	14.1 (12.8-14.2)*	.022
Post-operative day 7 (n = 5/6)	15.3 (14.6-15.4)	13.9 (13.1-15.3)	.329
COVy breathing at rest			
Pre-operative (n = 13/13)	18.6 (18.4-18.9)	18.1 (16.6-18.5)	.036
Post-operative day 3 (n = 13/13)	18.6 (17.2-19.1)	17.4 (16.8-18.2)	.112
Post-operative day 5 (n = 9/9)	18.7 (17.1-18.8)	17.5 (15.9-18.7)	.480
Post-operative day 7 (n = 5/6)	18.0 (17.3-18.1)	17.1 (16.1-18.4)	.662
COVx′ forced breathing			
Pre-operative (n = 13/13)	16.3 (16.0-16.8)	16.3 (15.8-16.7)	.538
Post-operative day 3 (n = 13/13)	15.8 (15.3-16.3)	15.2 (12.6-15.7)*	.036
Post-operative day 5 (n = 8/8)	15.8 (15.2-16.8)	14.2 (12.8-15.2)*	.065
Post-operative day 7 (n = 5/6)	16.0 (15.1-16.4)	14.7 (11.4-16.1)	.329
COVy forced breathing			
Pre-operative (n = 13/13)	18.7 (18.2-19.1)	18.0 (17.4-18.3)	.058
Post-operative day 3 (n = 13/13)	19.1 (18.2-19.6)	17.9 (17.5-19.2)	.330
Post-operative day 5 (n = 8/8)	18.3 (18.1-18.9)	18.7 (17.3-19.8)	.798
Post-operative day 7 (n = 5/6)	18.6 (18.1-18.6)	18.7 (18.1-19.4)	.662

Note: The number of cases are given in the first row for left- and right-sided procedures. The number of cases available at the respective days are given in the first column for each measurement (left/right). Data are shown as median (interquartile range). Differences between groups are tested by Mann-Whitney U-test. Absolute *P* values are given. Repeated measurements are tested by Friedman ANOVA post hoc Dunn's test (**P* < .05 versus pre-operative).

Abbreviation: COV, center of ventilation.

medioclavicular line. This localization was cranial of the surgical access and minimized the influence of the heart and influences evoked by the diaphragm. However, this location is more cranial than chosen for optimal correlation of the tidal impedance and tidal volume.[23]

By radiography, an elevated diaphragm and an overexpansion of the remaining lung with a mediastinal shift toward the side of a lobectomy[24] as well as atelectasis[25] can be detected. On the day 3 after surgery, the incidence of atelectasis was higher after surgery on the right lung than on the left side. These results are in line with the observations recorded by EIT.

To evaluate the regional changes of ventilation evoked by lung surgery, a separate analysis of the impedance changes on either side of the EIT appears suitable. However, in a clinical study on patients with a side-separated ventilation, impedance changes were detected at the contralateral half of the EIT image already before lung surgery.[11] Since radiologically observed shifts of the mediastinum toward the operated side are also described a side-separated evaluation of the regional ventilation is even more difficult.[24] As shown before,[17] EIT in spontaneously breathing patients at the chosen electrode plane level did not allow us to differentiate between the left and right lung. Thus, an evaluation of the contribution of each lung or a mediastinal shift is not possible. The use of the single primary outcome variable COVx′ that considers the whole EIT image, analyzed by two-way ANOVA with one between- and one within-subjects factor, enabled to test the effects of lung surgery in both groups together with their interactions. However, this simplification of the information provided by EIT might have contributed to the negative results after left-sided surgery.

Emphysematous bullae, tumor, or COPD cannot be distinguished by EIT since electrical conductivity is similarly reduced in these regions due to a reduced ventilation in all of those cases.[26] The most relevant limitation of EIT in our study is the influence of a pneumothorax. If the lung is not fully inflated because of a residual pneumothorax after extensive sublobar lung resection or lobectomy the lung is not fully attached to the thoracic wall leading to a lack of signal. By EIT, even small pneumothoraxes can be detected according to an experimental swine study and reduction of regional ventilation was confined in the upper quadrant of the affected side in ventral pneumothoraxes.[27] The changes of COVx′ and $FVC\%_{predicted}$ showed only a weak association. Besides the explanation by other influencing factors on $FVC\%_{predicted}$, the fixed linear relation between relative changes of thoracic impedance and pulmonary air volume[28] will not necessarily persist after surgery. If the operative procedure modifies the lung tissue, the magnitude of the impedance change per volume might change in the operated lung.

With EIT, the left-right side division was in good agreement with inhaled ^{81m}Kr[15] gas or ^{99}Tc gas[16,17] radionuclide scans in patients with lung cancer. In those studies, EIT was performed at two electrode planes. The use of EIT in only one plane was done to prevent interference with the surgical wound, but might have affected the results.[22] Other methods such as the hyperpolarized helium-3 gas magnetic resonance imaging of the ventilation[29] are not well-established. In comparison to those methods, EIT is radiation-free, portable, and has a high resolution in time allowing the examination of single breaths. Computed tomography might provide additional information. Nevertheless, computed tomography is no alternative to EIT, since morphology does not correlate well with the actual air flow within the lung shown by EIT.[30] Therefore, no true reference method for EIT exists, but the use of an additional imaging method might have eased the interpretation of our results.

5 | CONCLUSIONS

Pulmonary EIT and spirometry was used to investigate the postoperative redistribution of the regional ventilation of the lung in spontaneously breathing patients after left or right side lung surgery. Only in patients with surgery on the right side, a redistribution of pulmonary ventilation to contralateral side was detected by EIT. However, forced vital capacity was reduced in both groups and its change was only weakly associated with the shift of ventilation. A global reduction of ventilation in patients after lung surgery might account for some of the changes in forced vital capacity.

CONFLICT OF INTERESTS

None.

ORCID

Beatrice Oehler https://orcid.org/0000-0003-3150-2102
Thorsten Walles https://orcid.org/0000-0002-5037-054X
Markus Kredel https://orcid.org/0000-0003-2183-033X

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