Electrical impedance tomography to confirm correct placement of double-lumen tube: a feasibility study

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Background. Double-lumen tubes (DLTs) are frequently used to establish one-lung ventilation (OLV). Their correct placement is crucial. We hypothesized that electrical impedance tomography (EIT) reliably displays distribution of ventilation between left and right lung and may thus be used to verify correct DLT placement online.

Methods. Regional ventilation was studied by EIT in 40 patients requiring insertion of left-sided DLTs for OLV during thoracic surgery. EIT was recorded during two-lung ventilation before induction of anaesthesia and after DLT placement, and during OLV in the supine and subsequently in the lateral position. EIT measurements were made before and after verification of correct DLT placement by fibreoptic bronchoscopy (FOB).

Results. EIT accurately displayed distribution of ventilation between left and right lung online. All cases (n=5) of initially misplaced DLTs in the contralateral right main bronchus were detected by EIT. However, EIT did not allow prediction of FOB-detected endobronchial cuff misplacement requiring DLT repositioning. Furthermore, after DLT repositioning, distribution of ventilation, as assessed by EIT, did not change significantly (all P>0.5).

Conclusions. This study demonstrates that EIT enables accurate display of left and right lung ventilation and, thus, non-invasive online recognition of misplacement of left-sided DLTs in the contralateral main bronchus. However, as distribution of ventilation did not correlate with endobronchial cuff placement, EIT cannot replace FOB in the routine control of DLT position.

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Double-lumen tubes (DLTs) are frequently used to establish selective one-lung ventilation (OLV) to facilitate thoracic surgery. Their correct placement is crucial for effective OLV. If placement of the DLT is checked only by clinical signs (i.e. observation of chest movement and auscultation), intraoperative problems with either deflation of the non-dependent lung or ventilation of the dependent lung have been observed in up to 25% of cases. Routine control of DLT positioning by fibreoptic bronchoscopy (FOB) is, therefore, recommended after initial intubation and after any subsequent change in patient position. Alternative techniques that have been proposed to verify the correct position of the DLT include chest X-ray, selective end-tidal CO2 monitoring, analysis of pressure–volume or flow–volume loops, intraoperative palpation of the DLT by the surgeon, and acoustic monitoring. However, to date, FOB remains the method of choice.

Electrical impedance tomography (EIT) is a relatively new non-invasive monitoring method that generates cross-sectional images of the chest organs based on the analysis of transthoracic electrical conductivity. EIT can be used for assessment of regional lung ventilation. Functional imaging transforms the intra-tidal changes in electrical impedance into a colour-coded image reflecting the time course of regional ventilation. This way, EIT allows visualization and quantification of regional lung ventilation at the bedside.

†The first two authors contributed equally to this work.
In the context of DLT placement, the ability of EIT to provide non-invasively online information on the regional distribution of ventilation is a highly attractive feature of this technique. As the incidence of misplacement of left-sided DLTs into the contralateral right main bronchus is as high as 7–24%, a means of detecting such gross misplacement immediately, reliably, and non-invasively after the initial DLT placement would be of great clinical benefit. EIT may serve such purpose. Accordingly, the aim of this study was to evaluate the feasibility of using EIT as a means of assessing regional lung ventilation (i) during two-lung ventilation immediately after the initial placement of the DLT and (ii) during subsequent OLV. We hypothesized that EIT identifies effective left and right lung ventilation and would thus be helpful in verifying correct placement of DLTs. As EIT assesses distribution of ventilation, we additionally hypothesized that it should not be able to detect wrong position of the endobronchial cuff requiring correction of DLT placement as diagnosed by FOB. Since FOB represents the gold standard for verification of DLT placement, and since we intended to examine the impact of FOB-indicated corrections in DLT placement, and since we intended to examine the impact of FOB-indicated corrections in DLT placement, we compared distribution of ventilation before FOB control and after FOB confirmed correct position of endobronchial cuff placement.

Methods

We studied 40 consecutive patients requiring intubation with a DLT and subsequent OLV for thoracic surgical procedures. Exclusion criteria included age <18 yr, pregnancy and lactation period, and any contraindication to the use of EIT (pacemaker, automatic implantable cardioverter defibrillator, and implantable pumps). The study was approved by the local ethics committee. Written informed consent was obtained from all patients before the study.

After establishing standard monitoring, a thoracic epidural catheter was placed before induction of anaesthesia in all patients undergoing thoracotomy. In patients undergoing thorascopic procedures, an intercostal nerve block was performed after induction of anaesthesia. After preoxygenation, anaesthesia was induced with alfentanil (20 μg kg⁻¹) (thorascopic procedures) or sufentanil (0.25 μg kg⁻¹) (thoracotomy) and target-controlled infusion (TCI) of propofol at 4 μg ml⁻¹. Cisatracurium (0.1 mg kg⁻¹) was used for muscle relaxation. After face mask ventilation with 100% oxygen until muscle relaxation, the trachea was intubated with a left-sided DLT (Broncho-Cath, left-sided; Mallinckrodt, Athlone, Ireland) of appropriate size (35, 37, or 39 French)³ 20 After passing the vocal cords, the DLT was rotated by 90° towards the left and advanced until a slight resistance was encountered, at which time the tracheal cuff was inflated. After tracheal intubation, both lungs were mechanically ventilated (Cicero EM, Dräger Medical, Lübeck, Germany) with a tidal volume of 10 ml kg⁻¹ body weight and a ventilatory frequency of 12 min⁻¹. During OLV, the tidal volume was reduced to 5 ml kg⁻¹ body weight and the inspired oxygen concentration was increased to 100%. The bronchial cuff was inflated immediately before OLV and deflated while the patient was placed in the lateral position for surgery. Anaesthesia was maintained by TCI of propofol (3 μg ml⁻¹)¹⁹ and additional doses of alfentanil or sufentanil as required.

EIT was started in the spontaneously breathing patients before induction of anaesthesia and continued until the start of surgery. Distribution of ventilation was assessed visually and quantitatively in the spontaneously breathing patients before induction of anaesthesia. In the anaesthetized patients, distribution of ventilation was assessed visually and quantitatively during two-lung ventilation after endotracheal placement of the DLT, and during left and right OLV in the supine and lateral positions after positioning of the patient for surgery. In all cases, EIT was performed before and after FOB control of DLT position (Fig. 1). DLT placement was corrected if indicated by respective FOB findings along recent recommendations.⁴ Throughout the procedure, the anaesthetists were blinded.
Confirmation of DLT placement

to the EIT findings, and the EIT investigators were blinded to the FOB findings. Clinical decisions were based solely on clinical judgement and FOB findings.

For EIT, before induction of anaesthesia, an EIT electrode belt containing an array of 16 electrodes was placed around the thorax at the fifth intercostal space and connected to the EIT monitor for online visualization (EIT Evaluation KIT II, Dräger Medical). EIT data were generated by application of electrical alternating currents with an amplitude of 5 mA and a frequency of 50 kHz. Voltage differences between neighbouring electrode pairs were measured in a sequential rotating process displaying the ventilation-induced impedance changes during the scan.13 14 16 17 After signal processing, the resulting EIT image represents a transversal thoracic slice of 5–10 cm thickness.16 17 The processed EIT data were recorded at a rate of 20 images per second and stored for off-line analysis. As electrocautery interferes with data acquisition of the prototype EIT device used in this study, EIT could not be assessed during surgery, and the EIT electrode belt was removed immediately before surgery.

For analysis of regional distribution of ventilation, the total EIT image was symmetrically subdivided into four quadrants that were defined as regions of interest (ROI)13 (DraegerEIT Data Review software, Draeger Medical), with ROI 1, ventral right; ROI 2, dorsal right; ROI 3, ventral left; and ROI 4, dorsal left field of the total image. All EIT images and impedance curves of the ROIs were available online on the EIT monitor during the measurements.

For further off-line analysis, the impedance–time curves of these ROIs were exported as ASCII-files. For each ROI, the intra-tidal impedance changes (ΔZ) between maximal expiration and maximal inspiration were averaged for three consecutive breaths during spontaneous breathing, after tracheal intubation, and during left and right OLV.21 The relative change in impedance during OLV was calculated by the following formulae:

Left OLV = \[ \frac{\sum \Delta Z_{ROI3} + \sum \Delta Z_{ROI4}}{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI2} + \sum \Delta Z_{ROI3} + \sum \Delta Z_{ROI4}} \times 100\% \]

(1)

Right OLV = \[ \frac{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI2}}{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI2} + \sum \Delta Z_{ROI3} + \sum \Delta Z_{ROI4}} \times 100\% \]

(2)

The relative change in impedance of ventral-to-dorsal distribution of ventilation during either spontaneous breathing or two-lung ventilation after tracheal intubation was calculated by the following equations:

Ventral ventilation = \[ \frac{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI3}}{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI2} + \sum \Delta Z_{ROI3} + \sum \Delta Z_{ROI4}} \times 100\% \]

(3)

Dorsal ventilation = \[ \frac{\sum \Delta Z_{ROI2} + \sum \Delta Z_{ROI4}}{\sum \Delta Z_{ROI1} + \sum \Delta Z_{ROI2} + \sum \Delta Z_{ROI3} + \sum \Delta Z_{ROI4}} \times 100\% \]

(4)

Statistical analysis

The number of patients required for statistical analysis was calculated by an a priori power analysis. On the basis of an assumed proportion of 90% or higher for accuracy of EIT in comparison with FOB for correct identification of OLV, 36 patients were required.22 To compensate for possible dropouts, 40 patients were enrolled. Data are presented as median and inter-quartile range (IQR) unless otherwise indicated. Data were analysed by Friedman’s test, followed by Wilcoxon’s signed-rank test if indicated (MATLAB® 7.2 statistic toolbox, The MathWorks Inc., Natick, MA, USA). P<0.05 was chosen as the level of significance.

Results

Forty patients (28 male, 12 female; mean age 66 yr, range 23–80 yr; mean body weight 75 kg (SD 13 kg); ASA I–III) were enrolled in this study. Twenty-nine patients underwent thoracotomy (mostly for resection of pulmonary tumours), the remaining 11 patients underwent video-assisted thorascopic procedures. In all but one of the 40 patients, EIT could be carried out without any difficulty at all observation points. In one patient, EIT recording was discontinued inadvertently during lateral positioning.

With replacement of spontaneous breathing by controlled ventilation during induction of anaesthesia, EIT demonstrated a ventil shift in the distribution of ventilation (Fig. 2A and B; Table 1). After verification of correct DLT placement by FOB, distribution of ventilation to the left and right lung during left and right OLV, respectively, was unequivocally demonstrated by EIT (Fig. 2C and D).

The distribution of ventilation between the left and right lung did not differ between the awake state and after induction of anaesthesia and endotracheal intubation (P=0.31) (Fig. 3). In contrast, the distribution of left and right lung ventilation differed significantly (P<0.01) between the initial two-lung ventilation and subsequent left and right OLV, and between left and right OLV in the supine and lateral positions, respectively (Fig. 3).

FOB yielded three types of findings (pooled data for supine and lateral positions): (i) incorrect positioning of
the bronchial tip of the DLT in the contralateral right main bronchus \((n=5)\), (ii) correct placement of the tip of the DLT in the left main bronchus, but need for adjustment in endobronchial cuff positioning \((n=39)\), and (iii) correct placement of the DLT requiring no further repositioning \((n=35)\). Throughout all subsequent surgical procedures, there was never any need for repeat bronchoscopy or repositioning of the DLT.

**Fig 2** Representative EIT images recorded in one patient: during spontaneous breathing (A), after endotracheal intubation (B), during left OLV (C) and right OLV (D) in the supine position, and during left OLV (E) and right OLV (F) in the lateral position. EIT images during OLV were obtained after ensuring optimal placement of the DLT by FOB. During left and right OLV, the percentage of ventilation distributed to the respective lung is listed in brackets. Numbers 1–4 indicate ROIs as defined in the text.

**Table 1** Ventral-to-dorsal distribution of ventilation during spontaneous breathing and after tracheal intubation. Values are medians (inter-quartile range).

<table>
<thead>
<tr>
<th>Ventral (%)</th>
<th>Spontaneous breathing</th>
<th>After tracheal intubation</th>
<th>P-value</th>
</tr>
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<tbody>
<tr>
<td>50 (45–60)</td>
<td>72 (61–76)</td>
<td>&lt;0.0001</td>
<td></td>
</tr>
<tr>
<td>Dorsal (%)</td>
<td>50 (40–55)</td>
<td>28 (24–39)</td>
<td>&lt;0.0001</td>
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</tbody>
</table>
After FOB-guided correction of initially malpositioned DLTs in the contralateral right main bronchus (Fig. 4) or of dislocation of the bronchial cuff into the trachea after placement of the patient into the lateral position (Fig. 5), EIT demonstrated correct regional distribution of ventilation during subsequent left and right OLV (Figs 4 and 5; Table 2). EIT findings indicated malpositioning of DLTs in the right main bronchus in all five cases.

In contrast, after FOB-guided correction of wrongly placed endobronchial cuffs (requiring 0.5–1 cm advancements or 0.5–3 cm withdrawals of the DLT), EIT did not indicate any change in the distribution of ventilation during left and right OLV compared with EIT findings before correction of DLT position (Table 2). As expected, no change in the distribution of ventilation was observed if the tube position remained unchanged (Table 2).

**Discussion**

The main findings of this clinical feasibility study can be summarized as follows: (i) EIT reliably identified left
and right OLV, both in the supine and in the lateral positions; (ii) EIT allowed reliable detection of initial misplacement of DLTs in the contralateral main bronchus; and (iii) EIT did not allow detection of wrongly positioned endobronchial cuffs, which required correction of DLT placement, as diagnosed by FOB. At the same time, our findings indicate that by virtue of providing online information on the distribution of ventilation, EIT might be an additional tool to auscultation for assessment of DLT placement and verification of
correct DLT positioning. Furthermore, it could be useful to monitor OLV during closed chest conditions, mainly if it is prolonged (e.g. during OLV in intensive care).

The clinically most relevant finding of this preliminary feasibility study is that EIT allows reliable online diagnosis of grossly malpositioned DLT immediately after endotracheal intubation. This is of considerable clinical relevance because the incidence of initially misplaced left-sided DLTs into the right main bronchus varies between 7% and 24%. Our 12.5% incidence (5 of 40 patients) of initially misplaced DLTs is in agreement with those previous findings. EIT correctly identified appropriate regional distribution of ventilation after correction of the DLT position under FOB control.

Gross abnormality in regional distribution of ventilation during OLV also frequently develops due to displacement of the bronchial cuff, as may occur during patient positioning. If not recognized, such displacement results in an increased incidence of hypoxaemic episodes during OLV. Thus, detection and correction of DLT displacement after patient positioning are crucial. The example presented in Figure 5 shows that EIT allows immediate online detection of such displacement.

Rapid and reliable identification of correct distribution of ventilation after endotracheal intubation is not only important in the context of DLT placement and OLV, but equally so in routine anaesthetic practice. Inadvertent endobronchial intubation is one of the most common complications of endotracheal intubation during induction of anaesthesia. As auscultation of bilateral breath sounds does not exclude endobronchial intubation (particularly in children), new techniques for the confirmation of correct endotracheal tube position have been suggested. The findings of our study suggest that EIT may also be useful in the early diagnosis of inadvertent endobronchial intubation in adults and children during induction of anaesthesia.

Correct placement of the endobronchial cuff of the DLT is as crucial for effective OLV as is correct placement of the tip of the tube. In our study, the incidence of wrongly positioned endobronchial cuffs as diagnosed by FOB was 49% (39 of 79 fibreoptic controls in the supine and lateral positions). The incidence may be as high as 78%. These numbers emphasize the magnitude of the potential problem and the importance for reliable detection and correction of endobronchial cuff misplacement. The large overlaps in the distribution of ventilation during OLV between cases of entirely correctly placed DLTs and those with misplaced endobronchial cuffs, and between cases before and after FOB-guided correction of DLT misplacement (Table 2), clearly indicate that EIT is unable to provide assurance of optimal DLT placement according to previous findings. Thus, EIT cannot replace FOB in this context, and FOB will continue to be the method of choice in verifying the correct position of DLTs.

In addition to the qualitative assessment of OLV, EIT provided quantitative online information on the effect of anaesthesia and body position on the distribution of ventilation. Definition of individual ROI allowed documentation of a ventral shift in the distribution of ventilation after induction of anaesthesia and mechanical ventilation (Table 1). These results are in agreement with the previous studies which used the same methodology.

The EIT prototype device used in this study allows online assessment of the distribution of ventilation via a monitor. By using modern EIT belts instead of multiple single electrodes, we could demonstrate that EIT monitoring can reliably be performed in the lateral position. The capability for rapid attachment and removal of the EIT device makes it suitable for clinical purposes. However, as electrocautery interferes with EIT signal acquisition of the EIT prototype used in this study, it cannot presently be used during surgery. Further development of the device will have to focus on the elimination of the interference.

As we used EIT in the presence of left-sided DLTs only, our findings are strictly applicable only to circumstances in which such DLTs are being used. However, identification of incorrect distribution of ventilation by EIT should equally be possible during the use of right-sided DLTs. Nevertheless, assessment of EIT monitoring during the use of right-sided DLTs might require additional definitions of ROI to account for the regional ventilation of the right upper lobe.

In conclusion, we have shown that EIT can provide an accurate online display of left and right OLV. These findings suggest that EIT can be clinically useful in the immediate recognition of DLT misplacement in the contralateral main bronchus and in the quantitative assessment of OLV. We have also shown that EIT is not suitable to detect incorrectly positioned endobronchial cuffs and can, thus, not replace fibreoptic bronchoscopic control of DLT placement.

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