Double-lumen tubes and auto-PEEP during one-lung ventilation

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Abstract

Background: Double-lumen tubes (DLT) are routinely used to enable one-lung-ventilation (OLV) during thoracic anaesthesia. The flow-dependent resistance of the DLT’s bronchial limb may be high as a result of its narrow inner diameter and length, and thus potentially contribute to an unintended increase in positive end-expiratory pressure (auto-PEEP). We therefore studied the impact of adult sized DLTs on the dynamic auto-PEEP during OLV.

Methods: In this prospective clinical study, dynamic auto-PEEP was determined in 72 patients undergoing thoracic surgery, with right- and left-sided DLTs of various sizes. During OLV, air trapping was provoked by increasing inspiration to expiration ratio from 1:2 to 2:1 (five steps). Based on measured flow rate, airway pressure (Paw) and bronchial pressure (Pbronch), the pressure gradient across the DLT (∆P_{DLT}) and the total auto-PEEP in the respiratory system (i.e. the lungs, the DLT and the ventilator circuit) were determined. Subsequently the DLT’s share in total auto-PEEP was calculated.

Results: ∆P_{DLT} was 2.3 (0.7) cm H2O over the entire breathing cycle. At the shortest expiratory time the mean total auto-PEEP was 2.9 (1.5) cm H2O (range 0–5.9 cm H2O). The DLT caused 27 to 31% of the total auto-PEEP. Size and side of the DLT’s bronchial limb did not impact auto-PEEP significantly.

Conclusions: Although the DLT contributes to the overall auto-PEEP, its contribution is small and independent of size and side of the DLT’s bronchial limb. The choice of DLT does not influence the risk of auto-PEEP during OLV to a clinically relevant extent.

Clinical trial registration: DRKS00005648.

Key words: airway management; airway resistance; intrinsic peep; one-lung ventilation

Expiratory flow-dependent resistance during mechanical ventilation can lead to auto-PEEP and to progressive dynamic hyperinflation of the lungs.1,2 Auto-PEEP develops when tidal volume cannot be evacuated during the allocated expiratory time. Three factors, sometimes in combination, predispose to auto-PEEP generation (1) respiratory mechanics of the patient (i.e. patients with chronic obstructive airways disease may more readily develop auto-PEEP), (2) ventilator settings with inappropriately short expiratory times and (3) the added resistance of the artificial airways, comprising ventilator tubing, heat and moisture exchanger and, during one-lung ventilation (OLV), the double-lumen tube (DLT).3–5 While the influence of the patients’ respiratory mechanics has already been the subject of multiple clinical trials,6,7 the role of the ventilator settings and the DLTs’ flow-dependent resistance has not been examined systematically. The DLT is the device of choice for establishing OLV during thoracic surgical procedures.8 For
Editor’s key points

• The contribution of double lumen endobronchial tubes (DLT) on resistance to expiration during one-lung ventilation (OLV) is unknown.
• This clinical study evaluated the effect of DLT size and changing ventilation on gas flow rate and airway pressures.
• There was a consistent increase in airway pressure across the DLT, relatively unaffected by DLT size.
• These data suggest that using a DLT during OLV increases positive end-expiratory pressure (auto-PEEP) to a moderate extent.

that purpose the DLT combines a shorter tracheal and a longer bronchial limb for either right- or left-sided bronchial placement, respectively to the bronchial anatomy, by differing in curvature and existence of a ‘Murphy-eye’ for ventilation of the right upper lobe. Although a previous study has shown low resistance of the DLT during two-lung ventilation, during OLV particularly the expiratory flow-dependent resistance of the DLT’s bronchial lumen may increase the pressure gradient across the DLT, thus contributing to auto-PEEP.

This prospective clinical study investigates to which extent the pressure gradient across the DLT (ΔP<sub>DLT</sub>) contributes to auto-PEEP during OLV, depending on the DLT’s size and side of bronchial limb. Therefore expiratory time was consecutively shortened during OLV, expecting increased probability of auto-PEEP.

We hypothesized that the DLT’s contribution to auto-PEEP during OLV depends on the internal diameter and the side of the DLT’s bronchial limb, and the expiratory time.

Methods

This prospective clinical study was performed in the Department of Anesthesiology and Intensive Care Medicine, University Medical Center Freiburg. Patients were enrolled from January to October 2014. The study was approved by the institutional review board (Research Ethics Committee) at the University Medical Center Freiburg and registered at the German Clinical Trials Register (DRKS 00005648) before enrolment of the first patient. Written informed consent was obtained from every patient included in this study. Inclusion criteria were age between 18 and 75 yr, ASA physical status I-III, and lung resection via open thoracotomy or thorascopic procedure. Exclusion criteria were additional chest wall resection, emergency surgery, pregnancy, obesity (BMI>50 kg m<sup>-2</sup>), terminal illness and any type of implanted automatic device (i.e. pacemaker). All patients received preoperative lung function testing.

Anaesthesia

After establishing standard monitoring, patients received regional anaesthesia (epidural anaesthesia, paravertebral block, intercostal block) if not contraindicated. Subsequently, anaesthesia was induced with sufentanil (0.4–0.6 µg kg<sup>-1</sup>) and target-controlled infusion (TCI, Propofol 1% MCT Injectomat TIVA Agilia, Fresenius-Kabi GmbH, Bad Homburg, Germany) of propofol at plasma concentration of 2–4 µg ml<sup>-1</sup>. Cisatracurium 0.1 mg kg<sup>-1</sup> (Nimbex®, GlaxoSmithKline, Munich, Germany) was administered to facilitate tracheal intubation. Anaesthesia was maintained with propofol TCI at plasma concentrations of 2–4 µg ml<sup>-1</sup> and additional bolus doses of sufentanil 0.1–0.2 µg ml<sup>-1</sup>. The depth of anaesthesia was monitored by the bispectral index of the EEG (BIS, BISw A-2000 monitor, average time=30 s; Aspect Medical Systems, Newton, MA, USA) and the BIS value was kept between 40 and 60.

Double-lumen tubes selection

Patients were prospectively screened for tracheal intubation with a DLT of the Robertsaw type (Broncho-Cath<sup>TM</sup>, Mallinckrodt, Dublin, Ireland) with right- or left-sided bronchial limb and 35, 37 or 39 Fr outer diameter (OD). At least 12 patients were recruited to each of 6 resultant study groups (DLT’s side and OD). Left-sided DLTs were chosen for right-sided surgery, respectively right-sided DLT for left-sided surgery to ensure OLV across the bronchial limb. The appropriate size of the DLT was chosen by the attending anaesthetist, based on measurement of the inner bronchial diameter derived from either CT scan or chest X-ray, following clinical routine. The correct position of the DLT was verified by flexible fibre optic bronchoscopy after tracheal intubation and after patient positioning for surgery.

Intraoperative ventilator settings

During two-lung ventilation, the lungs were ventilated in the pressure-controlled mode (Zeus, Dräger, Luebeck, Germany) at tidal volumes of 6–8 ml kg<sup>-1</sup> and an inspired oxygen fraction (F<sub>O2</sub>) of 0.6. Respiratory rates were set to maintain end-tidal carbon dioxide partial pressure between 4.9 and 5.7 kPa. External PEEP was set individually for each patient at the discretion of the anaesthetist and was kept at a constant level in the period of measurements. During OLV, peak inspiratory pressure was adjusted to achieve tidal volumes at 6 ml kg<sup>-1</sup> and F<sub>O2</sub> was increased to 0.6–1.0. Respiratory rates were set to maintain end-tidal carbon dioxide concentration between 4.6 and 5.9 kPa with a maximum of 12 bpm using a routine inspiration to expiration (I:E) ratio of 1:2. The DLT’s tracheal- and bronchial-cuff pressures were kept within a range of 20 to 25 cm H<sub>2</sub>O. To enable OLV the tracheal limb of the DLT was disconnected from the ventilator and kept open to atmosphere (Fig. 1).

In order to increase the probability of auto-PEEP during OLV expiratory time was consecutively shortened by setting I:E ratio from 1:2 to 1:1.5, 1:1, 1.5:1 and 2:1. In between, the expiratory time was set back to baseline for 1 min, to avoid carry-over effects.

Intraoperative, flow and airway pressure measurements

Airway pressure (P<sub>aw</sub>) and flow rate (V') were measured by means of a pneumotachograph (Fleisch Type 1, Dr. Fenyes & Gut, Hechingen, Germany). Tidal volume (V<sub>T</sub>) was numerically integrated from V'.

In order to measure the bronchial pressure (P<sub>bronch</sub>), a sterile plastic catheter with an OD of 1.1 mm and a length of 90 cm (Epidural Catheter 16 G with three lateral eyes, Portex, Smith medical, Keene, USA) was placed inside the DLT’s bronchial limb. Insertion of the bronchial pressure catheter (BPC) into the DLT’s bronchial lumen was realized with a specially manufactured connector (Fig. 1. BOX). Insertion depth of the BPC was determined beforehand in the sterile setup. The pressure gradient across the DLT’s bronchial lumen (ΔP<sub>DLT</sub>) was calculated in terms of the root means square difference (RMSD) over the entire breathing cycle. Respiratory and haemodynamic variables were measured for at least 15 consecutive breaths, after five min of equilibration time at each I:E ratio.
signal, thereby affecting the synchrony of $P_{aw}$ and $P_{bronch}$ signals to a relevant extent. Therefore, the response time of the BPC was quantified. A balloon was attached to the distal end of the artificial bronchus and was then inflated maintaining a constant pressure. Afterwards the balloon was burst by a flame and the response time of the BPC was determined by the time the pressure takes to reduce to 90% of the initial value. The response time of the signal measured via the BPC was 45 (4) ms (data not shown).

**Determination of auto-PEEP**

End-expiratory measurements were performed within the last 50 ms before onset of the following inspiration. The end-expiratory pressure was measured via the BPC in the ventilated bronchus and at the $P_{aw}$ measuring site.

For calculation of the total auto-PEEP ($P_{aw}$total) the contribution of three pressure components were assumed:

1. auto-PEEPbiol: the pressure gradient across patients’ biological airways (from bronchus downwards the airways)
2. auto-PEEPDLT: the pressure gradient across the DLT (connector to bronchial tip) and
3. auto-PEEPcircuit: pressure gradient across the expiratory limb of the respiratory circuit (ventilator to connector of DLT).

Ad (1) auto-PEEPbiol cannot be directly measured and was therefore calculated as the absolute value of the product of (measured) end-expiratory flow rate ($V_{ee}$) and resistance. Assuming that the respiratory system reflects a resistance-compliance model, resistance ($R_{total}$) and compliance ($C_{total}$) of the biological airways were calculated by multiple linear regression analysis of the equation of motion, based on $P_{bronch}$, $V$, $V_{t}$ and PEEP, measured over the entire breathing cycle:

$$P_{bronch} = R_{total} \cdot V_t + \frac{1}{C_{total}} \cdot V_t + PEEP$$

Thereby $P_{bronch}$ equals the sum of the pressure gradient across the resistance of the biological airways ($P_{bronch} = R_{total} \cdot V_t$) and the pressure in the alveoli, which comprises of the volume dependent compliance component ($C_{total} \cdot V_t$) and the external PEEP. Calculation of the resistance was based on measured $P_{bronch}$ instead of $P_{aw}$ excluding the DLT’s non-linear flow-dependent resistance. With this, equal inspiratory and expiratory resistance of the biological airways was assumed.

Ad (2) auto-PEEPDLT was calculated as the absolute difference between end-expiratory measured $P_{bronch}$ and $P_{aw}$ (i.e. end-expiratory $\Delta P_{DLT}$).

Ad (3) auto-PEEPcircuit was calculated as the absolute difference between end-expiratory $P_{aw}$ measured at the actual I:E ratio and end-expiratory $P_{aw}$ measured in the same individual at an I:E-ratio of 1:2, where we assumed that auto-PEEP would be zero.

Then, auto-PEEPtotal was calculated as the sum of auto-PEEPbiol, auto-PEEPDLT and auto-PEEPcircuit.

**Statistical analysis**

The number of patients required for the statistical analysis to identify a clinically relevant effect of the DLT on the primary end-point auto-PEEP was calculated by an a priori power analysis of repeated measures ANOVA regarding six groups (DLT sizes) and five repeated measurements (expiratory times). Based on our own data from a series of ex-vivo measurements, with DLT size and expiratory time comparable with the clinical study protocol (unpublished data), a uniformly distributed range of auto-PEEP between 0.03 and 0.5 cm H2O and a standard deviation of...
0.8 cm H₂O was assumed for the clinical measurements. The resulting standardized effect size was calculated as 0.45. To achieve a study power of 80% at an alpha error probability of 0.05, a total sample size of 72 patients was required. Data are presented as mean (SD) if not indicated otherwise. One-way ANOVA was used to compare differences in preoperative pulmonary function variables between DLT-related study groups (Table 1) and to compare time of expiration, intraoperative ventilation and

Table 1 Patients’ characteristics. Data are given as mean (sn) or absolute number of patients. DLT, double-lumen endobronchial tube; ASA, ASA physical status; VC, vital capacity; FEV₁, forced expired volume in 1 s; FVC, forced vital capacity; PaO₂, arterial oxygen partial pressure; PaCO₂, arterial carbon dioxide partial pressure; *percent of predicted value (referred to age and height); VATS: video-assisted thoracoscopic surgery; n.s., not significant (P>0.05)

<table>
<thead>
<tr>
<th>DLT group</th>
<th>35 Fr (n=24)</th>
<th>37 Fr (n=24)</th>
<th>39 Fr (n=24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sex (female/male)</td>
<td>22/2</td>
<td>1/23</td>
<td>0/24</td>
</tr>
<tr>
<td>Age (yr)</td>
<td>65 (39–82)</td>
<td>69 (34–86)</td>
<td>63 (47–87)</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>162 (7)</td>
<td>172 (5)</td>
<td>181 (6)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>67 (11)</td>
<td>78 (14)</td>
<td>86 (12)</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>25.5 (6.6)</td>
<td>26.6 (7.2)</td>
<td>26.1 (9.7)</td>
</tr>
<tr>
<td>ASA (I/II/III)</td>
<td>0/14/10</td>
<td>0/3/21</td>
<td>0/6/18</td>
</tr>
<tr>
<td>Smoking (yes/no)</td>
<td>9/15</td>
<td>14/10</td>
<td>9/15</td>
</tr>
</tbody>
</table>

Preoperative pulmonary function

- VC (% predicted) 95 (21) 92 (20) 91 (14) n.s.
- FEV₁ (% predicted) 90 (20) 81 (24) 83 (24) n.s.
- FEV₁/FVC (% predicted) 93 (12) 86 (15) 96 (1.3) n.s.
- PaO₂ (kPa) 9.9 (1.1) 8.9 (1.5) 9.6 (1.3) n.s.
- PaCO₂ (kPa) 4.9 (0.4) 4.8 (1.1) 4.8 (0.3) n.s.

Type of surgery

- VATS 13 13 11
- Open surgery 11 11 13
- Side of surgery (right/left) 12/12 12/12 12/12

Table 2 Ventilation and haemodynamic variables during one-lung ventilation. Data are given as mean (sn). All measurements were performed during OLV and opened pleura, in the lateral position. †P<0.05 (‡P<0.001) compared with baseline (inspiration to expiration ratio=1:2); ‡P<0.05 vs Pmean at I:E=1.5:2; Vt, tidal volume; Paw, peak airway pressure; Pmean, mean airway pressure; ΔPDLT, root mean square difference (RMSD) between Paw and bronchial airway pressure (Pbronch); External PEEP, positive end-expiratory pressure set at the ventilator; Paw-ee, end-expiratory airway pressure measured proximal to the DLT; Pbronch-ee, end-expiratory bronchial pressure measured in the ventilated bronchus; V₀e-peak, peak expiratory flow; V₀e, mean end-expiratory flow within the last 50 ms of expiration; Rbiol, resistance of the biological airways; Cbiol, compliance of the biological airways; CO₂, end-expiratory carbon dioxide partial pressure; SpO₂, peripheral oxygen saturation; HR, heart rate; BPsys, systolic blood pressure; BPdia, diastolic blood pressure; MAP, mean arterial pressure

<table>
<thead>
<tr>
<th>Inspiration : Expiration ratio</th>
<th>1 : 2</th>
<th>1 : 1.5</th>
<th>1 : 1</th>
<th>1.5 : 2</th>
<th>2 : 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expiratory time (s)</td>
<td>3.9 (0.3)</td>
<td>3.5 (0.3)†</td>
<td>3.0 (0.2)†</td>
<td>2.4 (0.2)†</td>
<td>2.0 (0.2)†</td>
</tr>
<tr>
<td>Vt, (ml)</td>
<td>523 (107)</td>
<td>559 (116)</td>
<td>579 (135)</td>
<td>577 (141)</td>
<td>558 (136)</td>
</tr>
<tr>
<td>Paw (cm H₂O)</td>
<td>20.7 (3.3)</td>
<td>20.8 (3.4)‡</td>
<td>21.0 (3.3)</td>
<td>21.1 (3.3)</td>
<td>21.1 (3.3)</td>
</tr>
<tr>
<td>Pmean (cm H₂O)</td>
<td>11.5 (1.5)†</td>
<td>12.4 (1.7)‡</td>
<td>13.7 (1.9)‡</td>
<td>15.2 (2.2)‡</td>
<td>16.0 (2.3)‡</td>
</tr>
<tr>
<td>ΔPDLT (cm H₂O)</td>
<td>2.3 (0.7)</td>
<td>2.4 (0.7)</td>
<td>2.5 (0.8)</td>
<td>2.4 (0.7)</td>
<td>2.4 (0.7)</td>
</tr>
<tr>
<td>External PEEP (cm H₂O)</td>
<td>7.0 (1)</td>
<td>7.0 (1)</td>
<td>7.0 (1)</td>
<td>7.0 (1)</td>
<td>7.0 (1)</td>
</tr>
<tr>
<td>Paw-ee (cm H₂O)</td>
<td>7.0 (1.1)</td>
<td>7.1 (1.1)</td>
<td>7.2 (1.1)</td>
<td>7.4 (1.1)</td>
<td>7.6 (1.1)‡</td>
</tr>
<tr>
<td>Pbronch-ee (cm H₂O)</td>
<td>7.2 (1.1)</td>
<td>7.3 (1.1)</td>
<td>7.3 (1.2)</td>
<td>8.0 (1.2)‡</td>
<td>8.4 (1.3)‡</td>
</tr>
<tr>
<td>Vₑ-peak, (ml/sec⁻¹)</td>
<td>−509 (103)</td>
<td>−534 (104)</td>
<td>−552 (99)</td>
<td>−563 (98)†</td>
<td>−576 (98)†</td>
</tr>
<tr>
<td>Vₑ, (ml/sec)</td>
<td>−29 (19)</td>
<td>−43 (24)†</td>
<td>−69 (32)</td>
<td>−109 (47)†</td>
<td>−145 (54)†</td>
</tr>
<tr>
<td>Rbiol, (cm H₂O litre⁻¹ s⁻¹)</td>
<td>11.3 (7.8)</td>
<td>11.1 (8.0)</td>
<td>11.0 (8.1)</td>
<td>10.5 (8.5)</td>
<td>9.9 (8.8)</td>
</tr>
<tr>
<td>Cbiol, (ml/cm H₂O)</td>
<td>51.6 (17.9)</td>
<td>53.4 (18.9)</td>
<td>53.5 (17.1)</td>
<td>52.2 (15.7)</td>
<td>51.5 (5.0)</td>
</tr>
<tr>
<td>CO₂ (mm Hg)</td>
<td>38 (4)</td>
<td>39 (4)</td>
<td>38 (4)</td>
<td>39 (5)</td>
<td>39 (5)</td>
</tr>
<tr>
<td>SpO₂ (%)</td>
<td>98 (2)</td>
<td>98 (3)</td>
<td>97 (3)</td>
<td>97 (3)</td>
<td>97 (3)</td>
</tr>
</tbody>
</table>

Haemodynamic variables

- HR (min⁻¹) 67 (15) 67 (15) 68 (15) 69 (17) 67 (17)
- BPsys (mm Hg) 111 (19) 107 (19) 107 (18) 107 (17) 108 (17)
- BPdia (mm Hg) 57 (11) 54 (11) 54 (11) 55 (11) 55 (10)
- MAP (mm Hg) 76 (15) 73 (16) 73 (17) 73 (14) 74 (14)
haemodynamic data between different I:E ratios (Table 2). Comparison between the exposure variables (i.e. DLT’s size, DLT’s side of bronchial limb and expiratory time) was performed by two-way ANOVA followed by Holm Sidak post hoc test (Fig. 4). Two-way ANOVA followed by Holm Sidak post hoc test was calculated for comparison of the outcome variable auto-PEEPtotal and auto-PEEPDLT. To identify dependencies between end-expiratory flow and total auto-PEEP at a specific I:E ratio, Spearman’s rank correlation coefficients (rs) were calculated. To discard the null hypothesis a P-value was chosen <0.05.

Results

Patient characteristics

Of 94 patients assessed for eligibility, 72 patients were included in the data analysis for this study. Eleven patients were excluded after having obtained written informed consent because of cancelling (n=1) or modified date (n=5) of surgery, selection of a different size of the DLT (n=2), sickness of staff (n=2) or malfunctioning of the measurement device (n=1). Of the 83 patients enrolled in the study, valid data for analysis were available for 72 patients [49 male, 23 female, mean age 66 yr (34–87 yr)] (Fig. 2). Among patients not considered in the data analysis, four were excluded because of violation of the study protocol (intermediate two lung ventilation (n=3) and removal of the BPC for endobronchial suctioning (n=1)), four patients were excluded because of electronic artifacts and three patients because of zero line drift in the measurement signals. Patient characteristics are shown in Table 1. Pre-operative pulmonary function tests were comparable among the study groups. No pulmonary or haemodynamic adverse effect was observed during the study.

Intraoperative ventilator settings and measurements

During OLV, setting I:E ratio from 1:2 to 2:1 led to a mean expiratory time between 3.9 (0.3) s and 2.0 (0.2) s respectively.

A representative example of intraoperative pressure, flow and volume measurements in a single patient is demonstrated for each applied I:E ratio in Fig. 3. Intraoperative ventilation and haemodynamic measurement data of all patients are given in Table 2. Paw and Vt did not differ significantly between different I:E ratios, whereas Pmean increased with decreasing expiratory times.

ΔPDLT was 2.3 (0.7) cm H2O over the entire breathing cycle (range 1.1–4.8 cm H2O) at I:E baseline and remained constant with shortened expiratory time. ΔPDLT did not differ between DLT of different OD and right- or left-sided DLT of the corresponding OD (all P>0.07).

Dynamic auto-PEEP and DLT related auto-PEEP

Auto-PEEPtotal and auto-PEEPDLT increased with decreasing expiratory time (all P<0.05), in all DLT groups (Fig. 4). At the shortest expiratory time and irrespective of the DLT’s bronchial limb,
Fig 3 Pressure, flow and volume curves of one representative breath at each applied inspiratory to expiratory ratio (I:E) measured in a male patient (77 kg, 177 cm) intubated with a left sided double-lumen tube (DLT) of 37 French outer diameter, during pressure controlled one-lung ventilation. Pressure-time curves are demonstrated for both airway pressure ($P_{aw}$; green line) and bronchial pressure ($P_{bronch}$; blue line), superimposed by each other. Please note the following: (1) $P_{aw}$ and $P_{bronch}$ differ by the pressure gradient across the DLT ($\Delta P_{DLT}$); (2) Shortening of the expiratory time results in a more pronounced increase in end-expiratory $P_{bronch}$ as compared with the increase in end-expiratory $P_{aw}$; (3) tidal volume increases as inspiratory time increases until the expiratory time is too short to allow complete expiration. Resulting increased end-expiratory pressure reduces the expiratory driving pressure and thus reduces tidal volume again; (4) grey markers at the end of each breathing cycle indicate the time intervals (50 ms) within the end-expiratory measurements were performed. The levels of auto-PEEP$_{circuit}$ and auto-PEEP$_{DLT}$ can be estimated within these time intervals from the pressure differences between $P_{aw}$ and PEEP (5 cm H$_2$O) and $P_{bronch}$ and $P_{aw}$ respectively.
auto-PEEP_{total} was 2.9 (1.5) cm H2O, 2.8 (1.4) cm H2O and 2.4 (1.3) cm H2O in DLTs of 35 Fr., 37 Fr. and 39 Fr. OD, respectively (Fig. 4). Corresponding to the variables mentioned above, auto-PEEP_{DLT} was 0.8 (0.4) cm H2O, 1.0 (0.6) cm H2O and 0.7 (0.5) cm H2O in DLTs of 35 Fr., 37 Fr. and 39 Fr. OD, respectively. Both, auto-PEEP_{total} and auto-PEEP_{DLT} neither depended on the DLT’s OD (P>0.23; P>0.14) nor on the DLT’s side of bronchial limb (P>0.33; P>0.82).

The contribution of auto-PEEP_{DLT} to auto-PEEP_{total} was between 27% (I:E ratio=1:2) and 31% (I:E ratio=2:1). Auto-PEEP_{total} correlated to absolute V_{aw} at all expiratory times (all rs>0.66; all P<0.001).

Discussion

This study partially confirms the hypothesis that during OLV the pressure gradient across the DLT contributes to auto-PEEP depending on the DLT’s size, side of bronchial limb and the expiratory time. The detailed results can be summarized as follows: during OLV (1) P_{aw} and P_{branch} differ by a pressure gradient across the DLT (i.e. ΔP_{DLT}) (2) total auto-PEEP increased with shortened expiratory time (3) the DLT’s contribution to total auto-PEEP was up to 31%, but (4) the DLT’s size and side of bronchial limb did not contribute to auto-PEEP significantly.

Our results demonstrate that during pressure controlled OLV, ΔP_{DLT} leads to a noticeable difference between P_{aw} and P_{branch} both during inspiration and expiration (Fig. 3). Roze and colleagues have already shown that P_{aw} can significantly overestimate P_{branch} by the end of inspiration. Conversely, during expiration, P_{branch} will be higher than P_{aw} and if expiratory time does not allow expiratory flow to reach zero, this leads to an unintended increase of end-expiratory pressure (i.e. auto-PEEP). Clinical implications of auto-PEEP are well described. At higher levels, auto-PEEP in the ventilated lung will redistribute the pulmonary blood flow to the side of the non-ventilated lung, thus increasing pulmonary shunt and compromising central venous system. Therefore high levels of auto-PEEP should be avoided.

Given the functional mechanism discussed above, we systematically shortened the expiratory time interval to induce homogenous dynamic hyperinflation. We found that total auto-PEEP increased with decreasing expiratory times but was relatively low during OLV. As described elsewhere, we used a mathematical method to calculate auto-PEEP, which does not require special manoeuvres or interrupting the ventilation. This method yields a dynamic auto-PEEP which is in contrast to the static auto-PEEP measured via end-expiratory occlusion technique. The auto-PEEP during dynamic conditions is usually lower than the auto-PEEP during static conditions, as under static conditions the characteristics of the respiratory system differ substantially from those under the dynamic conditions of ongoing mechanical ventilation. Auto-PEEP during ongoing ventilation (dynamic auto-PEEP) is discussed to reflect the lowest regional value of auto-PEEP, underestimating static auto-PEEP in the presence of relevant constant inequalities of the biological airways. In the static end-expiratory pause, viscoelastic processes, equilibration (pendelluft) and lung derecruitment take place. This explains why total auto-PEEP values in our study are substantially lower than (static) values described previously. However, as an end-expiratory hold manoeuvre is not routinely available in most modern anaesthesia ventilators, alternative methods to measure auto-PEEP may gain clinical importance.

It has to be considered that external PEEP influences the level of auto-PEEP during OLV. Addition of external PEEP usually lowers the expiratory driving pressure. However, in patients presenting with expiratory flow limitation, external PEEP will not lower the expiratory driving pressure until the level of external PEEP exceeds the level of auto-PEEP by a ratio of 50 to 75%. External PEEP was variable in our study. However, external PEEP may not affect our results, as the level of total auto-PEEP was low, the variance of external PEEP was small (7 (1) cm H2O) and calculation of dynamic auto-PEEP has shown to be reliable in the presence of expiratory flow limitation and added external PEEP.

It could be questioned whether mode of ventilation (i.e. pressure controlled ventilation, PCV) might be associated with the low level of total auto-PEEP found in our study. Pressure controlled ventilation is potentially preferred during OLV, as peak inspiratory pressure is lower and arterial oxygenation is improved compared with volume controlled ventilation (VCV). During PCV the inspiratory driving pressure define tidal volume. An increase in end-expiratory pressure, caused by incomplete tidal exhalation, will lead to a decrease in the amplitude of the inspiratory driving pressure. The resulting decrease in inspiratory tidal volume will limit level of auto-PEEP. In contrast, during VCV one could expect higher levels of auto-PEEP compared with our
results, as the regulating mechanisms of PCV are ruled out. The VCV driven tidal volume is defined irrespective of elevated end-expiratory pressure (auto-PEEP). Thus, VCV will lead to a breath-by-breath increase in end-expiratory lung volume and peak airway pressure until the peak airway pressure gain a pre-set limit value.

Of the total auto-PEEP identified approximately 30% were caused by the DLT’s flow-dependent pressure gradient. Surprisingly, the DLT’s contribution to auto-PEEP did not differ significantly among the different sized DLTs, even though previous studies have shown that a tube’s inner diameter determines flow-dependent resistance. However, in our study’s DLTs, the narrowest inner diameters of the bronchial limbs differed marginally (4.8, 5.1 and 5.3 mm for DLT 35, 37 and 39 Fr. OD) and the lengths were similar in all types.

In conclusion, approximately 30% of the auto-PEEP was because of the flow-dependent resistance of the DLT. Against our hypothesis, the DLT’s contribution to auto-PEEP was independent of the DLT’s size and side of bronchial limb. From a clinical perspective, our findings suggest that dynamic analysis of respiratory mechanics, excluding the artificial system (respiratory circuit and DLT), may be helpful in monitoring and optimizing ventilation strategy during OLV.

Authors’ contributions
Study design/planning: J.S., S.S., T.L.
Study conduct: J.S., M.O., A.G., T.L.
Data analysis: J.S., S.S.
Writing paper: J.S., M.O., A.G., S.W., S.S., T.L.
Revising paper: all authors

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