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Original Contribution

Regional lung ventilation during supraglottic and subglottic jet ventilation: A randomized cross-over trial

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HIGHLIGHTS

- In a cross-over trial, we compared supraglottic and subglottic jet ventilation during open-airway laryngeal surgery.
- Jet ventilation did not significantly shift the overall center of ventilation as determined by EIT.
- Supraglottic jet ventilation worsened ventilation in dorsal lung regions compared to subglottic jet ventilation by 4 %.
- Oxygenation was substantially better with subglottic than supraglottic jet ventilation.
- Either type of jet ventilation appears suitable for open-airway laryngeal surgery.

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ABSTRACT

Objective: Test the hypothesis that the center of ventilation, a measure of ventro-dorsal atelectasis, is posterior during supraglottic ventilation indicating better dependent-lung ventilation. Secondarily, we tested the hypothesis that supraglottic ventilation improves oxygenation and carbon dioxide elimination.
Background: Supraglottic and subglottic jet ventilation are both used during laryngotracheal surgery. Supraglottic jet ventilation may better prevent atelectasis and provide superior ventilation.
Design: Randomized, cross-over trial.
Setting: Operating rooms.
Patients: Patients having elective micro-laryngotracheal surgery.
Interventions: Patients were sequentially ventilated for 5 min with one randomly selected type of jet ventilation before being switched to the alternative method.
Measurements: Regional ventilation distribution was estimated using electrical impedance tomography, with arterial oxygenation and carbon dioxide partial pressures being simultaneously evaluated.
Results: Thirty patients completed the study. There were no statistically significant or clinically meaningful differences in the center of ventilation with supraglottic and subglottic ventilation. However, ventilation with the supraglottic approach was about 4 % higher in the ventromedial lung region and about 4 % lower in the dorsal

Abbreviations: AU, Arbitrary Unit;; ASA, American Society of Anesthesiologists; EIT, Electrical Impedance Tomography; ENT, Ear, nose, and throat; NIRS, Near-infrared spectroscopy; PaO_2/FiO_2, Ratio of arterial oxygen partial pressure to fraction of inspired oxygen; PEEP, Positive end expiratory pressure; tcCO2, transcutaneous CO_2.

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lung. Surprisingly, arterial blood oxygenation was considerably worse with supraglottic (173 [156, 199] mmHg) than subglottic ventilation (293 [244, 340] mmHg). Arterial carbon dioxide partial pressure was near 40 mmHg with each approach, although slightly lower with supraglottic jet ventilation.

Conclusion: The center of ventilation distribution, a measure of atelectasis, was similar with supraglottic and subglottic jet ventilation. Subglottic jet ventilation improved the dorsal-dependent lung region and provided superior arterial oxygenation. Both techniques effectively eliminated carbon dioxide, with the supraglottic approach demonstrating slightly superior efficacy.

1. Introduction

Changing from spontaneous to controlled mechanical ventilation promotes dorsal atelectasis and ventilation/perfusion mismatch. Atelectasis is most common in dependent areas of the lung, occurs in 90 % of anesthetized patients within minutes of anesthetic induction, and affects 20–50 % of basal lung tissue. [1] Positive end-expiratory pressure (PEEP) is the best way to prevent and treat atelectasis. PEEP, which is normally easy to apply, can be challenging during laryngotracheal surgery because the airway often needs to remain open to provide good surgical visualization. Jet ventilation is often used because it works well in unsealed airways.

There are two general approaches to jet ventilation, both of which depend on the jet stream entraining surrounding air which admixes with the jet gases. The first approach is to use a supraglottic jet laryngoscope equipped with two nozzles, one of which provides a low-frequency (10–20 min^{-1}) jet stream that sustains tidal volume by providing airway pressure and a second that provides a high-frequency (600–1500 min^{-1}) jet stream that generates PEEP. The two jet streams are superimposed during the inspiratory and expiratory phases, thus enabling ventilation at distinct pressures. [2–5] A third cannula at the tip monitors airway pressure. The second approach to jet ventilation uses a single thin catheter that is inserted subglottically via a translaryngeal approach. The system delivers continuous high-frequency ventilation, albeit at a lower frequency of 120–150 min^{-1} (Fig. 1).

Jet ventilation is challenging because tidal volume and minute ventilation cannot be monitored due to the open-lung approach. Air entrainment, which is the fundamental operating principle of jet ventilation, occurs to a varying extent depending on the route of jet ventilation administration, anatomical factors and jet alignment with the airway. [6] Furthermore, standard intraoperative monitoring does not evaluate changes in regional lung ventilation. Use of electrical impedance tomography (EIT) provides a visual and quantitative representation of ventilated lung areas. [7–11] The principle of lung EIT relies on small alternating electrical currents that traverse the thorax and voltage measurements using electrodes on the skin surface generating cross-sectional images representing impedance change in a nominal slice of the thorax. The EIT variable "center of ventilation" characterizes the shift in ventilation on the anterior-to-posterior axis of the chest. [12] It is a radiation-free imaging method that provide real-time estimates of ventilation distribution.

PEEP during open-airway ventilation is thought to be largely maintained by the high-frequency component of jet ventilation, suggesting that higher continuous frequencies during supraglottic ventilation might produce less atelectasis than subglottic ventilation. [13] A further advantage of supraglottic ventilation is that the low-frequency component, resembling conventional ventilation, presumably helps eliminate carbon dioxide and may similarly improve oxygenation. We therefore tested the primary hypothesis that the center of ventilation, a measure of posterior-ventral atelectasis, is posterior (better) during supraglottic ventilation. [9] Secondarily, we tested the hypothesis that supraglottic ventilation improves oxygenation and carbon dioxide elimination.

Fig. 1. Images of a jet-laryngoscope (left side) and jet-catheter (right side) (Carl Reiner GmbH, Vienna, Austria).

2. Material and methods

Our randomized cross-over trial was approved by the local ethics committee at the Medical University Vienna, Vienna, Austria (1298/2019). The study was registered on ClinicalTrials.gov by Marita Windpassinger on June 4, 2019 (NCT03973294). Participating patients provided written consent.

2.1. Patients

We recruited patients aged 18–99 years who were classified American Society of Anesthesiologists (ASA) physical status I-III and were scheduled for elective laryngotracheal surgery with jet ventilation. We excluded patients with acute bleeding in or near the larynx and/or trachea, infectious lung disease, thoracic wall deformities, body mass index >30 kg/m^2, implantable electronic devices, or who were expected to need postoperative mechanical ventilation.

2.2. Protocol

Anesthesia was induced and maintained with propofol (2–5 mg kg^{-1}) and remifentanil (0.1–0.3 μg kg^{-1} min^{-1}); rocuronium (0.6 mg kg^{-1}) was given to induce paralysis. Mask ventilation with volume-controlled ventilation was then initiated with a tidal volume of 6 ml kg^{-1}, positive end-expiratory pressure (PEEP) 5 cmH_2O, FiO_2 0.8, and a respiratory rate of 12 min^{-1} and maintained for 2 min.

We used a cross-over design. Thus, each patient was sequentially ventilated for 5 min with one randomly selected type of jet ventilation before being switched to the alternative method. Randomization 1:1 to initial supraglottic or subglottic ventilation was assigned based on computer-generated codes with random permuted blocks and was provided to investigators through a secure web-based system (Research Electronic Data Capture, REDCap; Vanderbilt University). Allocation was thus concealed until just before treatment. Both treatments and all trial-related measurements were completed before surgery started.

In patients initially assigned to supraglottic ventilation, a jet laryngoscope was introduced by the ear, nose, and throat (ENT) surgeon, and the device was connected to the jet ventilator (Twin Stream jet ventilator, C. Reiner GmbH, Vienna, Austria). Ventilation was initiated at 12 min^{-1} for the lower frequency with an I/E ratio of 1 and a superimposed high-frequency jet ventilation of 600 min^{-1} at an FiO_2 of 0.8. The driving pressure was defined by the body weight (range 1–2.1 bar, provided by the manufacturer).

In patients initially assigned subglottic ventilation, tracheal intubation was performed with a laser-resistant LaserJet catheter with a 3.8-mm external diameter (Carl Reiner GmbH Vienna, Austria) by an anesthesiologist. The tip was positioned 4 cm below the vocal cords. The device was connected to the jet ventilator which was set to a frequency of 120 min^{-1}, I/E ratio of 0.67, and FiO_2 of 0.8. The driving pressure was defined by the body weight (range 1–2.1 bar).

After five minutes with the initially designated type of jet ventilation, patients were mask-ventilated for at least 2 min and then switched to the alternate type of jet ventilation (Fig. 2). Jet ventilation was discontinued if SpO_2 was <90 % or barotrauma seemed immanent, with conventional mechanical ventilation via a tracheal tube being used for rescue.

2.3. Measurements

We inserted an arterial catheter for arterial blood gas analyses and hemodynamic monitoring. Additionally, we connected near-infrared spectroscopy (NIRS) leads (Foresight Elite, Casmed, CT, USA) for cerebral oxygen monitoring and transcutaneous carbon dioxide monitoring ($tcCO_2$) (SenTec Digital Monitoring System - SDMS, SenTec AG, Therwil, CH).

We used electrical impedance tomography (EIT) to generate real-time 50-Hz images of regional lung ventilation which estimates ventilator adequacy in various lung regions (Fig. 3). A 32-electrode EIT monitoring belt (SwissTom BB^2 EIT belt, Sentec, Landquart, Switzerland) was positioned around the thorax per the manufacturer's instructions and connected to a portable EIT monitor (SwissTom BB^2, Sentec, Landquart, Switzerland). An alternating current (3 mA at 200 kHz) was passed between each pair of electrodes. The resulting surface potentials were measured across the remaining electrode pairs. All 32 electrode pairs were sequentially used as the injecting electrodes with the resulting surface potential being measured at each of the remaining electrodes. EIT data were processed and analyzed offline using Ibex (SwissTom, Sentec, Landquart, CH). Lung contours were estimated from population CT-derived thorax and lung contours adjusted for sex, weight, and height.

Specifically, we evaluated the center-of-ventilation, which characterizes the overall impedance mid-point as a percentage of anteroposterior extension (0 % most dorsal, 100 % most ventral). [14] A center-of-ventilation of 50 % indicates a perfect vertical balance of ventilation. [8,14] The normal range of mid-point impedance location remains poorly characterized, but changes might help guide ventilation strategy. [15] A ventral shift may indicate dorsal atelectasis formation whereas a dorsal shift suggests improved ventilation in dependent lungs. For example, there is a 9 % ventral shift in the center of ventilation during conversion from spontaneous breathing to controlled ventilation. [1,11] We therefore considered an absolute ventral shift of 5 % to be potentially clinically meaningful.

We split each EIT image into regions of interest (ROI), represented as four horizontal layers of equal thickness in our supine patients, with layer 1 (ROI 1) being the most ventral and layer 4 (ROI 4) being the most dorsal. Impedance changes over a respiratory cycle were summed over each region of interest and divided by the total to provide the fraction attributable to each region. [16,17] Tidal impedance variation, the index of alveolar recruitment, as defined by the difference between end-inspiratory and end-expiratory lung impedance, comparable to the tidal volume inhaled in one breath during spontaneous breathing. [18] The primary focus of EIT assessment is how impedance values change over time, rather than on their absolute measurements. [19] Arbitrary units (AU) are thus used for tissue impedance variation, denoting relative changes of the electrical impedance.

Silent spaces were defined by regions of the lungs where the impedance varied <10 %, corresponding to areas in which air content changes minimally during tidal ventilation. Silent spaces therefore potentially represent collapsed or over-distended regions. [11] Silent spaces were separately evaluated in dependent and non-dependent lung regions, separated by the center of ventilation.

EIT has been validated for assessment of ventilation distribution and regional respiratory mechanics across various pulmonary conditions including acute respiratory distress syndrome (ARDS), chronic obstructive pulmonary disease (COPD), and cystic fibrosis. EIT has also been instrumental in exploring different ventilation strategies, including high-frequency oscillatory ventilation and high-frequency jet

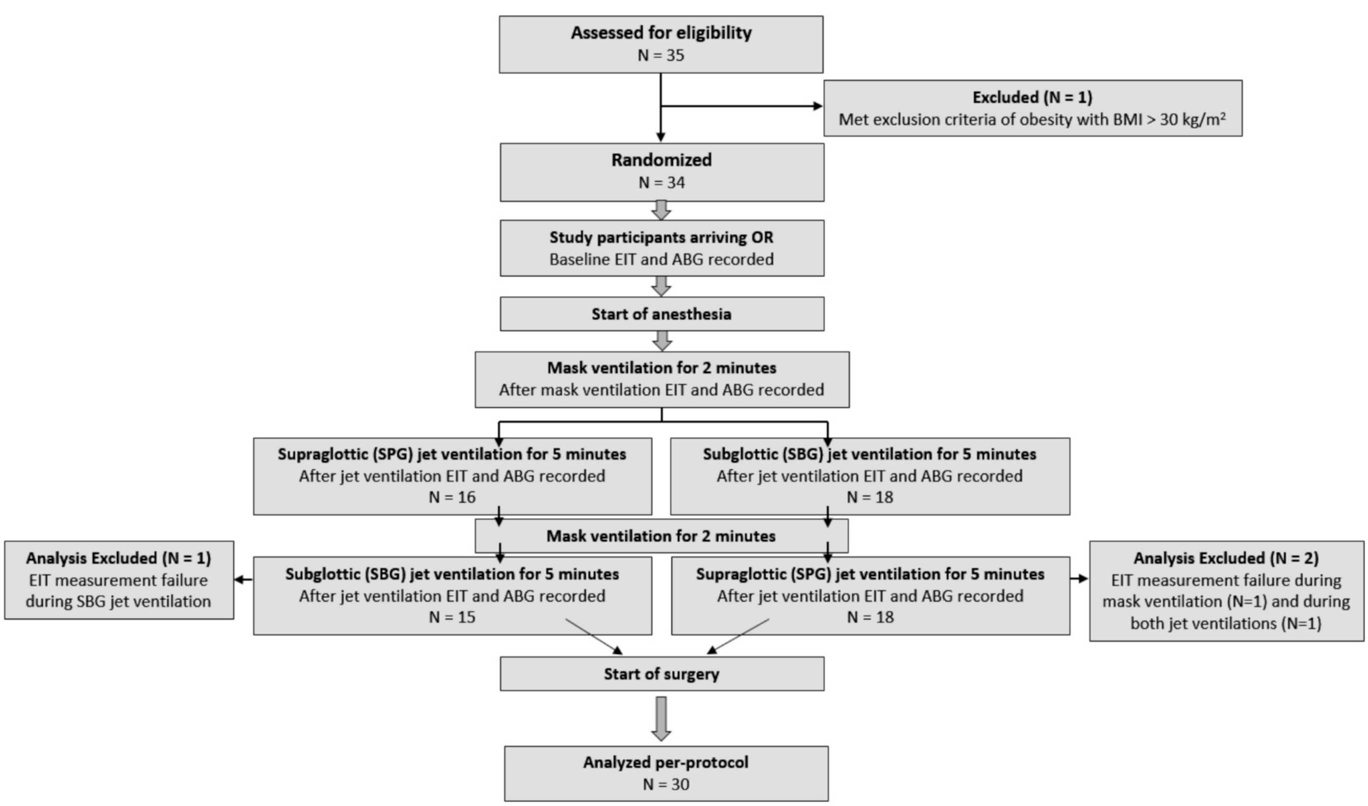

Fig. 2. Flowchart and study design of the crossover trial comparing supraglottic jet ventilation and subglottic jet ventilation.

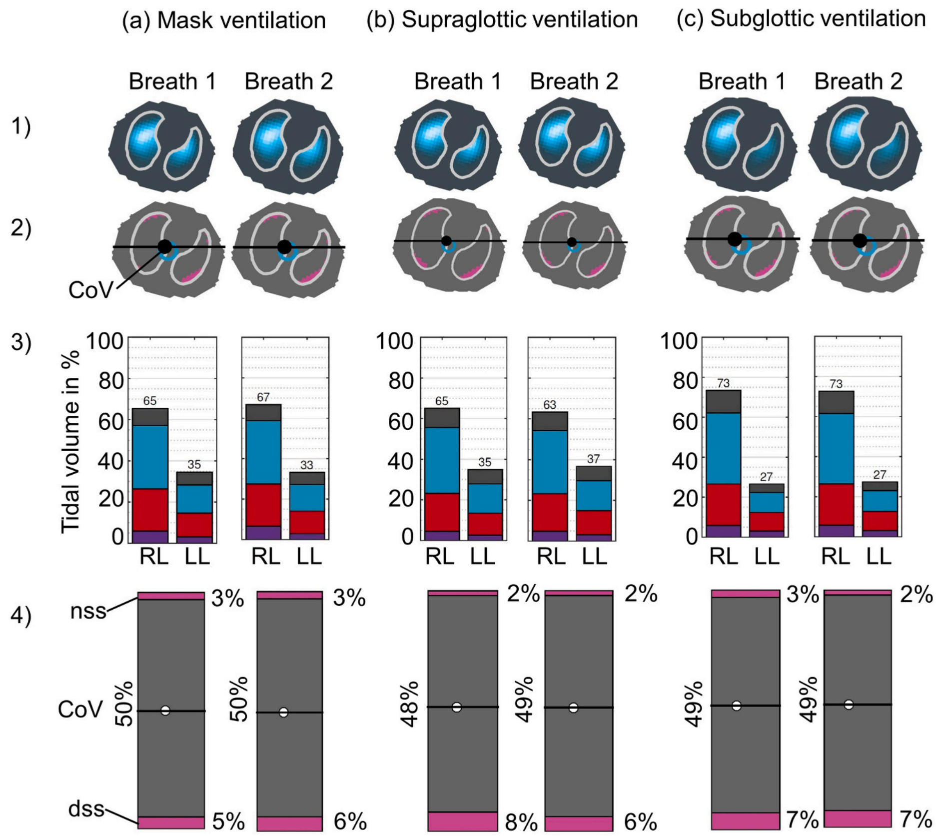

Fig. 3. Sample of a single patient's electrical impedance tomography (EIT) recordings.

ventilation. [17,20–30] Regional ventilation distribution, an important lung function metric, traditionally relies on intermittent CT scans, but EIT offers a continuous bedside alternative. [12,31–34]

Preliminary data from 5 patients indicated that relevant EIT variables reached steady state within 2 min. EIT was therefore assessed 2 min after mask ventilation and 5 min after each jet ventilation method started. At the time of each EIT measurement, we simultaneously determined arterial PaO_2, $PaCO_2$, PaO_2/FiO_2 ratio and cerebral oxygenation via NIRS.

2.4. Statistical analysis

Our primary analysis was per-protocol. Patients were excluded from the analysis if they did not have mask, supraglottic jet ventilation, and subglottic jet ventilation.

Based on a paired *t*-test analysis with a standard deviation of 6.7 % and no correlation across repeated measurements, we estimated that a sample size of 30 would provide 80 % power at an alpha of 0.05 to detect a 5 % difference in center of ventilation. [11] Consequently, we planned to enroll 30 patients.

Demographic and morphometric characteristics were summarized as means and standard deviations (SD) or median and interquartile range (IQR) for continuous variables, and frequencies and percentages for categorical variables. Paired *t*-tests were used to compare jet ventilation and mask ventilation on all the primary and secondary outcomes including ventro-dorsal center of ventilation shift, region of interest 1–4 tidal impedance variation, non-dependent silent spaces, and dependent silent spaces. Comparisons between supraglottic and subglottic jet ventilation were performed using repeated-measure linear regression models, adjusted for mask ventilation measurements. Because the distributions of tidal impedance variation and dependent and non-dependent silent spaces were not normally distributed, logarithm transforms were performed before analysis, and geometric mean ratios were estimated.

We compared the arterial PaO_2, $PaCO_2$, PaO_2/FiO_2 ratio, and NIRS using paired *t* or Wilcoxon signed rank tests, based on distribution, across different time points including baseline, the end of mask ventilation, and the end of each jet ventilation. Spearman correlation was used to assess the correlation of the changes between jet ventilation and mask ventilation on the primary outcome center of ventilation vs. PaO_2, $PaCO_2$, and PaO_2/FiO_2 ratio.

Analyses were based on an overall significance threshold of 0.05. We used SAS statistical software (version 9.4, Cary, NC).

3. Results

We enrolled 35 patients of whom 5 were subsequently excluded: 1 did not meet enrollment criteria, 3 had failed EIT assessments, and 1 proved unsuitable for subglottic jet ventilation (Fig. 2). The mean age was 48 years (SD 15 yrs), body mass index was 26 kg m^{-2} (SD 3 kg m^{-2}), and 67 % were designed ASA status I. None of the patients had pre-existing lung conditions or used inhaled medications. Fourteen patients were randomized to initial supraglottic jet ventilation and 16 to initial subglottic ventilation.

There were no statistically significant or clinically meaningful shifts in ventro-dorsal center of ventilation between supraglottic jet ventilation and mask ventilation (mean difference − 0.3, 95 %CI [−1.6, 1.0] %, $p = 0.64$), between subglottic and mask ventilation (mean difference 0.6, 95 %CI [−2.3, 3.5] %, $p = 0.66$), or between supraglottic and subglottic jet ventilation after adjustment of mask ventilation measurement (mean difference − 0.9, 95 %CI [−3.9, 2.0] %, $p = 0.53$, Fig. 4).

Regions of interest 1–4 showed no significant change in supraglottic jet ventilation compared to mask ventilation. In contrast, subglottic jet ventilation reduced ventilation in region 2 and increased ventilation in region 4, with both changes being approximately 4 % compared to both

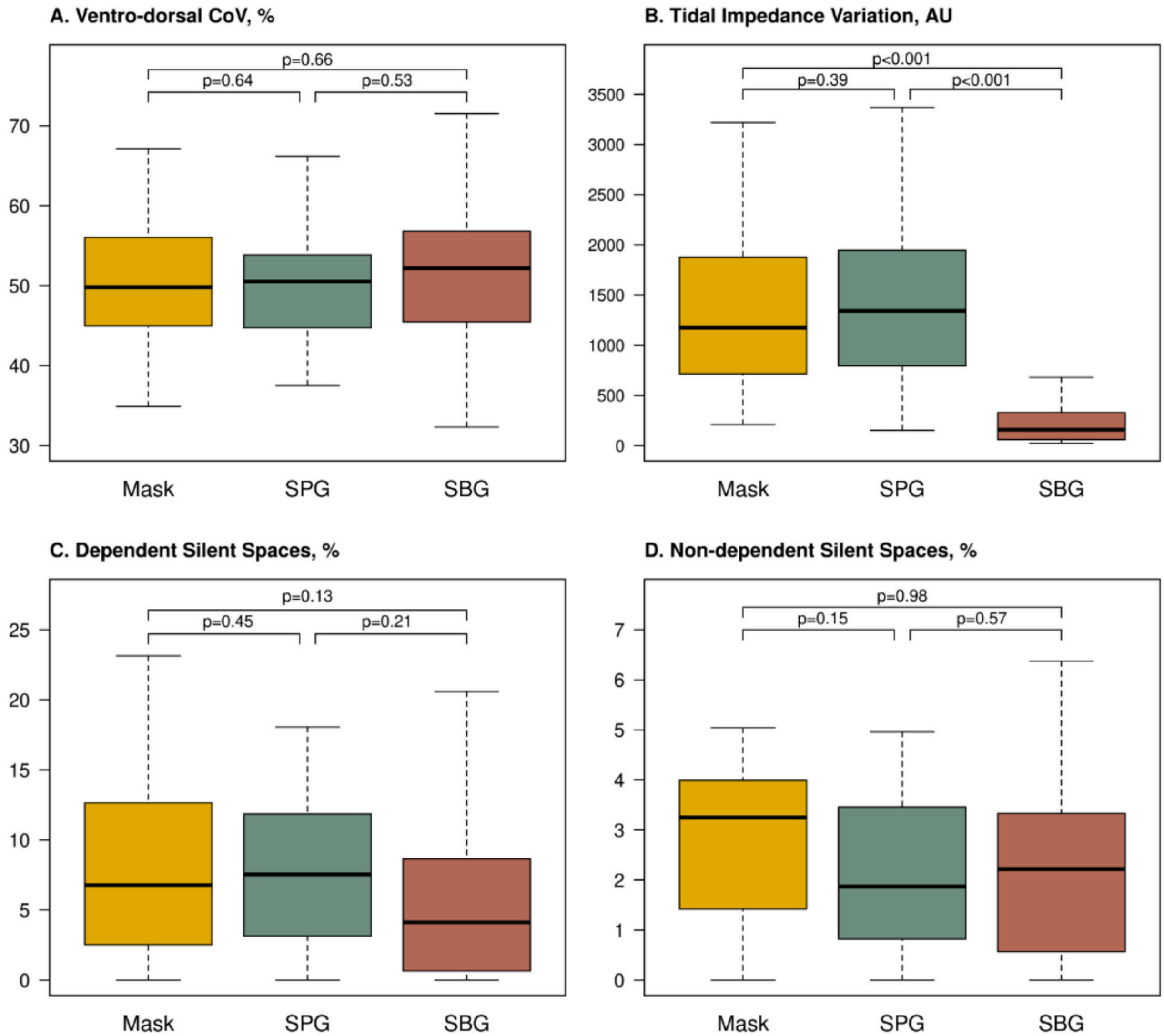

Fig. 4. Boxplot graphics illustrating the distribution of ventro-dorsal center of ventilation shift, tidal impedance variation, and silent spaces including dependent and non-dependent silent spaces during mask ventilation, supraglottic, and subglottic jet ventilation.

mask and supraglottic jet ventilation as illustrated in Fig. 5. Tidal impedance variation did not differ significantly with supraglottic versus mask ventilation (mean difference 135 arbitrary units, 95 %CI [−183, 453], $p = 0.39$). However, there was a significantly lower tidal impedance variation with subglottic jet ventilation than with mask ventilation (geometric mean ratio 0.13, 95 %CI [0.10, 0.16], $p < 0.001$). Tidal impedance variation was significantly higher with supraglottic than subglottic jet ventilation, with a geometric mean ratio of 7.9 (95 %CI [6.1, 10.3], $p < 0.001$), after adjustment of mask ventilation measurement (Fig. 4). Among supraglottic, subglottic, and mask ventilation, there was no significant difference in dependent or non-dependent silent space volumes.

Overall, our results suggest that there was a significant difference in region of interest 2, region of interest 4, and tidal impedance variation between subglottic and mask ventilation, and between the two modes of jet ventilation (Fig. 4, Fig. 5, Table 1).

Baseline NIRS and blood gas measures were similar in patients assigned to each treatment sequence. Oxygenation variables (SpO_2, PaO_2, PaO_2/FiO_2 ratio) and NIRS were higher during subglottic jet ventilation than during supraglottic jet ventilation. Specifically, PaO_2 was approximately 120 mmHg greater with subglottic than supraglottic ventilation ($p < 0.001$). $PaCO_2$ was significantly lower with supraglottic (38 ± 7 mmHg) than subglottic (41 ± 6 mmHg) jet ventilation ($p = 0.013$; Table 2). Furthermore, there were no significant correlations between the center of ventilation and PaO_2, $PaCO_2$, or PaO_2/FiO_2 in the changes from mask ventilation to supraglottic and subglottic jet ventilation.

4. Discussion

There were no substantive shifts in ventilation distribution across the entire lung cross-section with either jet ventilation technique as assessed by ventro-dorsal center-of-ventilation. However, the subglottic approach favored dorsal regions, presumably because dependent ventilation was better maintained. Dependent silent-space ventilation was also reduced with subglottic ventilation, although not significantly. Together, these findings suggest that the subglottic approach may provoke slightly less atelectasis.

The advantages of the supraglottic approach are unrestricted surgical visibility, free instrumental access, a larger entrainment effect, and the absence of laser tube ignition risk. A further benefit is that exhaled gas pushes blood and secretion towards the upper respiratory tract, thus reducing aspiration risk. [35] Subglottic jet ventilation reduces vocal cord movement but at the cost of restricted surgical visibility. [36] Subglottic jet ventilation requires specialized jet catheters made from materials such as polytetrafluoroethylene (PTFE), which offer the

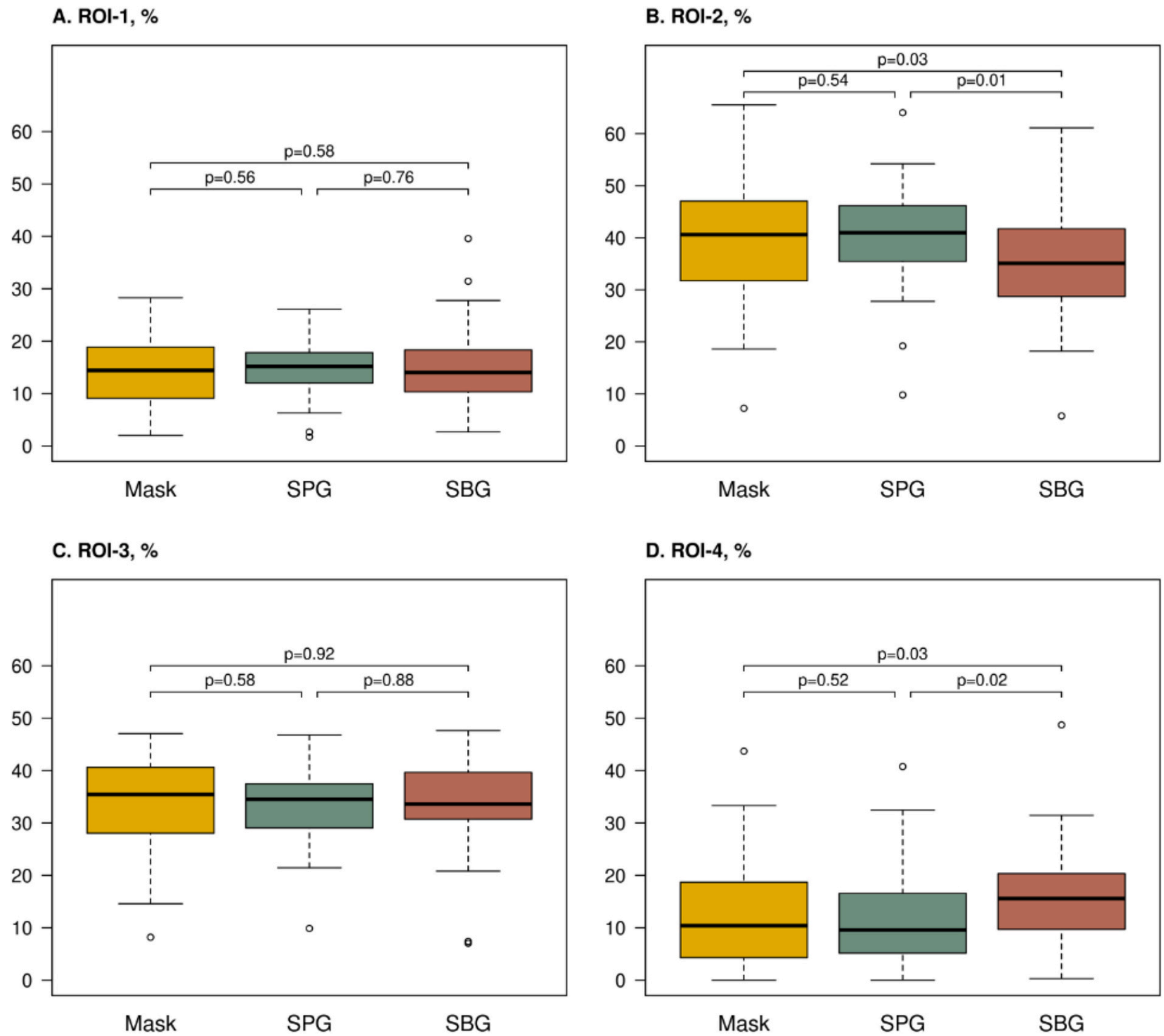

Fig. 5. Boxplot graphics illustrating the regions of interest 1–4 during mask ventilation, supraglottic, and subglottic jet ventilation.

advantage of being safe for laser microsurgery. [37–39] Jet tidal volumes are small (1–3 ml kg^{-1}), even less than dead-space, thus non-conventional mechanisms are involved in the gas exchange. [40] Among them is bulk convection which continuously entrains fresh gas as oxygen is absorbed at the alveoli. Pendelluft mixing involves gas exchange between lung units with different compliance levels, Taylor dispersion creates a central jet of oxygenated gas diffusing into peripheral bronchi. A further mechanism is coaxial flow during which there is inspiratory flow at the center of the air column combined with peripheral expiratory flow.

Proximal airway obstruction combined with short expiratory times predispose air trapping and barotrauma with subglottic ventilation if the injected air cannot escape through the proximal airway which may be partially obstructed by the catheter itself. [41,42] Furthermore, in severe obstructive or restrictive lung diseases, multiple mechanisms involved in gas exchange can be disrupted. For instance obstructed airways can limit inflow of fresh gas, reducing effective ventilation in bulk convection or differences in lung unit compliance can impede Pendelluft gas exchange across regions. [43]

Applying large tidal volumes can provoke pulmonary complications such as ventilator-induced lung injury, highlighting the importance of using lung-protective strategies. [44] Conversely, low tidal volumes facilitate alveolar collapse, atelectasis, and pulmonary shunting. [45] Jet ventilation uses tiny tidal volumes that are delivered as pulsed air-oxygen mixture at high pressure in an open airway system. Using only high frequency jet ventilation at rates >300 min^{-1} impairs oxygenation and reduces carbon dioxide elimination because tidal volumes are inadequate. It is therefore common to combine high-frequency ventilation with a slower physiological frequency. [46] Furthermore, Venturi air entrainment during jet ventilation leads to larger effective tidal volumes than delivered supraglottic volumes. Thereby, FiO_2 in the trachea is 15–25 % lower than the FiO_2 set on the jet ventilator. [47] Specifically, ventilator gas mixes with environmental air at an FIO_2 of 0.21 between the laryngoscope and the trachea with environmental air comprising 50 %–60 % of the total tidal volume. [3]

Our results suggest that there was substantial entrainment of environmental air with supraglottic ventilation, as indicated by tidal impedance variation. Specifically, there was a shift in ventilation towards more ventromedial lung regions (region of interest 2). Bialka and colleagues similarly observed over-inflation of non-dependent lung areas rather than meaningful redistribution of ventilation towards dependent lung areas with higher tidal volumes during supraglottic jet ventilation. [17] In contrast, tracheal FIO_2 matches ventilator FIO_2 during subglottic jet ventilation, indicating low environmental air entrainment and consequent lower tidal volumes. [3] As might therefore be expected, arterial oxygenation was substantially better — by more than 100 mmHg — with subglottic than supraglottic jet ventilation.

The average PaO_2 of nearly 300 mmHg at an FiO_2 of 80 % suggests

Table 1
EIT measures observed for each ventilation technique, including mask ventilation, subglottic and supraglottic jet ventilation. (N = 30).

Variable	Descriptive statistics MASK	Descriptive statistics Supraglottic	Descriptive statistics Subglottic	Mean difference (95 %CI) Supraglottic - MASK	p-value	Mean difference (95 %CI) Subglottic - MASK	p-value	Mean difference (95 %CI) Supraglottic - subglottic	p-value
COV ventro-dorsal (%; 0–100)[a]	51 ± 8	51 ± 7	52 ± 9	−0.3 (−1.6, 1.0)	0.64	0.6 (−2.2, 3.5)	0.66	−0.9 (−3.9, 2.0)	0.53
Tidal impedance variation (AU)[b]	1175 [713, 1876]	1343 [793, 1946]	158 [60, 329]	1.0 (0.8, 1.3)	0.69	0.13 (0.10, 0.16)	<0.001	7.9 (6.1, 10.3)	<0.001
Dependent Silent Spaces (%)[b]	7 [3,13]	8 [3,12]	4 [1, 9]	1.0 (0.6, 1.6)	0.97	0.6 (0.4, 1.0)	0.05	1.6 (0.9, 2.6)	0.09
Non-Dependent Silent Spaces (%)[b]	3 [1, 4]	2 [1, 4]	2 [1,3]	0.9 (0.6, 1.6)	0.81	0.9 (0.5, 1.5)	0.57	1.1 (0.6, 1.9)	0.76
region of interest 1 (%)[a]	14 ± 7	15 ± 6	15 ± 8	0.4 (−0.9, 1.6)	0.56	0.8 (−2.2, 3.8)	0.58	−0.4 (−3.5, 2.6)	0.76
region of interest 2 (%)[a]	40 ± 12	40 ± 11	36 ± 11	0.5 (−1.1, 2.0)	0.54	−4.2 (−7.8, −0.5)	0.03	4.6 (1.0, 8.3)	0.01
region of interest 3 (%)[a]	34 ± 9	33 ± 8	33 ± 10	−0.4 (−1.9, 1.1)	0.58	−0.2 (−3.5, 3.2)	0.92	−0.26 (−3.6, 3.1)	0.88
region of interest 4 (%)[a]	12 ± 10	12 ± 9	16 ± 10	−0.4 (−1.8, 0.9)	0.52	3.5 (0.3, 6.7)	0.03	−3.9 (−7.2, −0.6)	0.02

CI = confidence interval; COV = center of ventilation.

[a] Data reported as mean ± standard deviation. Mean difference and 95 % confidence interval was estimated by repeated-measure linear regression models between supraglottic and mask ventilation, and between subglottic and mask ventilation. The estimates comparing supraglottic and subglottic jet ventilation was adjusted on the measurements in mask ventilation.

[b] Data reported as median [interquartile range]. Geometric mean ratio and 95 % confidence interval was estimated by repeated-measure linear regression models after logarithm transformation of the outcome, comparing between supraglottic and mask ventilation, and between subglottic and mask ventilation. The estimates comparing supraglottic and subglottic jet ventilation was adjusted on the measurements in mask ventilation.

Table 2
Intraoperative measures of oxygenation, carbon dioxide partial pressure, and cerebral oxygenation across ventilation techniques (N = 30).

Variable	Mask (2 min after start)	Supraglottic (5 min after start)	Subglottic (5 min after start)
SpO_2, %	99 [99, 100] [2]	99 [98, 99] [1,3]	99 [99, 100] [2]
PaO_2, mmHg	317[293, 349] [2]	173 [156, 199] [1,3]	293[244, 340] [2]
$PaCO_2$, mmHg	44 ± 5 [2,3]	38 ± 7 [1,3]	41 ± 6 [1,2]
PaO_2/FiO_2	396 [366, 436] [2]	228 [195, 250] [1,3]	366 [305, 425] [2]
NIRS	77 ± 6 [2]	73 ± 6 [1,3]	77 ± 7 [2]

Statistics presented as Mean ± SD or Median [P25, P75].
Comparisons: 1- significant difference (p < 0.05) from mask (2 min after start)
2-significant difference (*p* < 0.05) from supraglottic (5 min after start)
3- significant difference (p < 0.05) from subglottic (5 min after start)
Paired t-tests were used to compare the means and Wilcoxon rank sum tests were used to compare medians

that lower concentrations can be used safely, possibly reducing the risk of oxidative lung injury. In this respect, our results contrast with Bacher and colleagues who reported that arterial oxygenation is better maintained with supraglottic jet ventilation, attributing improved oxygenation to the large tidal volume consequent to entrainment. [2,3] The superior PaO_2 observed under mask ventilation may be attributed to the higher FiO_2 since there was no air entrainment. Stable tidal impedance variation despite varying PaO_2 may be explained by the fact that EIT measures relative ventilation distribution but does not directly capture gas exchange dynamics. Thus, better oxygenation could result from improved oxygen delivery, even if ventilation distribution remains stable. The trend towards lower $PaCO_2$ with jet ventilation may be due to the continuous backstream of gas, that enhances CO_2 elimination.

As expected, tidal impedance varied far more with supraglottic ventilation which combined a 12 breath/min cycle with superimposed high-frequency jet ventilation. A consequence was that $PaCO_2$, and presumably CO_2 elimination, was better with supraglottic than subglottic ventilation. However, the difference was small and possibly not clinically important. A previous study similarly reported that superimposed high-frequency ventilation increases end-expiratory chest wall volume compared to single-frequency modes. [48] The observed superiority of left lung ventilation with face mask ventilation compared to subglottic ventilation may be related to the position and direction of the jet catheter tip inside the trachea (Fig. 3).

Computerized tomography (CT) is considered the reference for diagnosing lung atelectasis, consolidation or pathological alterations. However, it provides only momentary diagnostic information. [1,49] Chest ultrasound is a safe, dynamic, and radiation-free alternative for diagnosing and managing lung atelectasis. [50,51] However, continuous ultrasound assessments are not normally practical, can miss consolidation in central areas, and skilled operators are needed to obtain sensitive and accurate results. We selected EIT because it provides noninvasive real-time dynamic tidal images of gas distribution, coupled with quantitative estimates including center of ventilation, region of interest, and silent spaces. Although the application of EIT is prone to interference, it represents the only viable alternative for continuous monitoring of ventilation during surgery.

Our cross-over design was both a strength and a limitation. By eliminating among-subject variation, we were powered to identify small differences consequent to the ventilation approach. The short observation period — all before surgery started — meant that patients were metabolically and hemodynamically stable during the trial. On the other hand, we made assumptions (based on pilot data) that the 5-min observation periods and the 2-min washout period between treatments were sufficient. Furthermore, we did not have time to recalibrate the EIT between ventilation modes. However, similar baseline conditions for each treatment, independent of order, suggest that the timing was suitable. We did not monitor muscle relaxation, but reasonably assume that all patients were fully paralyzed during the short trial period. We did not monitor processed EEG because the electrodes would interfere with cerebral oxygenation measurements, but again it seems unlikely that hypnotic depth would much change over the short duration of our trial.

Tidal volume assessment during conventional mechanical ventilation reflects the volume of the entire lung. In contrast, tidal impedance variation is based on volume within the EIT sensitivity region in a single cross-sectional plane. It therefore reflects lung function within a region rather than whole-lung morphologic and anatomic structure as would be obtained from a CT scan. And finally, we note though that the normal range of EIT values remains poorly documented, much less what changes and absolute deviations are clinically meaningful. Existing recommendations focus on assessing trend patterns rather than specific values which is the approach we adopted with our cross-over protocol. All our patients had normal lungs. Results may well differ in patients with pre-existing pulmonary pathology.

5. Conclusions

Based on non-significant differences in the center of ventilation, we conclude that jet ventilation does not cause major alterations in ventilation distribution in patients without preexisting lung injury. Other EIT measurements such as region of interest, tidal impedance variation, and silent spaces may prove more useful. Conventional arterial blood gas analyses indicate that subglottic and supraglottic jet ventilation techniques both provide adequate oxygenation and carbon dioxide elimination, although carbon dioxide elimination was better with the supraglottic approach while oxygenation was better with the subglottic approach. Either appears suitable for elective micro-laryngotracheal surgery.

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CRediT authorship contribution statement

Marita Windpassinger: Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Michal Prusak:** Writing – review & editing, Project administration, Methodology, Investigation, Data curation, Conceptualization. **Jana Gemeiner:** Writing – review & editing, Investigation, Data curation. **Maximilian Edlinger-Stanger:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Imme Roesner:** Writing – review & editing, Investigation. **Doris-Maria Denk-Linnert:** Writing – review & editing, Investigation. **Olga Plattner:** Writing – review & editing, Supervision, Project administration, Methodology, Investigation, Conceptualization. **Ahmed Khattab:** Writing – review & editing, Visualization, Software, Investigation, Formal analysis, Data curation. **Eugenijus Kaniusas:** Writing – review & editing, Software, Methodology, Formal analysis, Data curation. **Lu Wang:** Writing – review & editing, Visualization, Validation, Formal analysis, Data curation. **Daniel I. Sessler:** Writing – review & editing, Visualization, Methodology, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data from our trial will be available on a collaborative basis from the corresponding author upon reasonable request.

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