Comparison of superimposed high-frequency jet ventilation with conventional jet ventilation for laryngeal surgery

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Background. New ventilators have simplified the use of supraglottic superimposed high-frequency jet ventilation (SHFJV SG), but it has not been systematically compared with other modes of jet ventilation (JV) in humans. We sought to investigate whether SHFJV SG would provide more effective ventilation compared with single-frequency JV techniques.

Methods. A total of 16 patients undergoing minor laryngeal surgery under general anaesthesia were included. In each patient, four different JV techniques were applied in random order for 10-min periods: SHFJV SG, supraglottic normal frequency (NFJV SG), supraglottic high frequency (HFJV SG), and infraglottic high-frequency jet ventilation (HFJV IG).

Results. Chest wall volumes were normalized to NFJV SG end-expiratory level. The increase in end-expiratory chest wall volume (EEVCW) was 239 (196) ml during SHFJV SG (P<0.05 compared with NFJV SG). EEVCW was 148 (145) and 44 (106) ml during HFJV SG and HFJV IG, respectively (P<0.05 compared with SHFJV SG). Tidal volume (VT) was 269 (149) ml during SHFJV SG, 229 (169) ml (P=1.00 compared with SHFJV SG), 145 (50) ml (P<0.05), and 110 (33) ml (P<0.01) during NFJV SG, HFJV SG, and HFJV IG, respectively.

Intratracheal pressures corresponded well to changes in both EEVCW and VT. All JV modes resulted in adequate oxygenation. However, PaCO2 was lowest during HFJV SG [4.3 (1.3) kPa; P<0.01 compared with SHFJV SG].

Conclusion. SHFJV SG was associated with increased EEVCW and VT compared with the other investigated JV modes. All four modes provided adequate ventilation and oxygenation, and thus can be used for uncomplicated laryngeal surgery in healthy patients with limited airway obstruction.

Keywords: high frequency jet ventilation; laryngoscopic surgery; plethysmography; pulmonary gas exchange

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Editor’s key points

- Four modes of high-frequency jet ventilation (HFJV) useful for laryngeal microsurgery were systematically compared.
- Use of supraglottic superimposed HFJV produced the largest end-expiratory chest wall volume and tidal volume.
- All four modes of HFJV provided adequate ventilation and oxygenation.

Jet ventilation (JV) was introduced more than 40 yr ago,1 and high-frequency jet ventilation (HFJV)2 is today routinely used for airway surgery (e.g. laryngoscopic or bronchoscopic procedures).3 4 It can be beneficial for thoracic surgery5 – 8 and during procedures requiring minimal respiratory excursion (e.g. radiofrequency ablation of small tumours in the lung or liver).9 – 11 However, for laryngoscopy, single-frequency HFJV might not provide adequate carbon dioxide elimination and oxygenation in patients with severe airway stenosis or other complicating respiratory diseases.

To address this problem, the combination of HFJV with a low-frequency jet component (superimposed high-frequency jet ventilation, SHFJV) has been proposed12 and has proved to be a safe and effective mode of ventilation during airway surgery.13 Studies on SHFJV imply that it provides more effective ventilation than single-frequency JV, but because of a lack of studies directly comparing SHFJV with other modes of JV, this hypothesis needs to be confirmed.

When evaluating different HFJV techniques, tidal volume and minute ventilation are difficult to assess because HFJV is applied in open systems. Air entrainment occurs to a varying extent depending on the route of JV administration,14 anatomical factors and jet alignment with the airway. Thus a standard pneumotachograph does not provide accurate values. Likewise, assessing changes in end-expiratory volume is impossible with conventional inert gas methods. Optoelectronic plethysmography (OEP) has been developed for non-invasive measurements of chest...

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wall volume changes\textsuperscript{15} and provides high enough temporal and spatial resolution to make it suitable for studying JV. OEP has been tested and validated in a variety of conditions\textsuperscript{16–19} and chest wall volume changes assessed by OEP correlate well with changes in lung volume.\textsuperscript{17 20}

In the present study, we sought to compare four modes of JV with settings that have been used clinically at our hospital. Our aim was to assess whether supraglottic SHFJV provides more effective ventilation than other supraglottic and infraglottic JV techniques.

\textbf{Methods}

\textbf{Patient characteristics}

After approval by the local ethics committee and written informed consent, 16 patients undergoing minor laryngotracheal surgery were included in this prospective study from November 2008 until June 2009. Inclusion criteria were age $>18$ yr, ASA (American Society of Anesthesiologists) classification I–II, and BMI $<35$ kg m$^{-2}$. Patients with respiratory diseases such as asthma and chronic obstructive pulmonary disease or with symptomatic airway stenosis were excluded.

To ensure patient safety, the study protocol included discontinuing JV if $S_{pO_2}$ or $S_{aO_2} < 90\%$, $P_{aCO_2} > 8$ kPa or if signs of air trapping and lung hyperinflation were observed, with conventional ventilation as a rescue therapy.

In all patients, the study protocol was performed before the start of surgery.

\textbf{Anaesthesia induction and ventilation}

After PO premedication with midazolam 0.1 mg kg$^{-1}$ and paracetamol 30 mg kg$^{-1}$, i.v. anaesthesia was started and maintained using propofol (TCI, Schnider model, Ce 2.5–4.0 $\mu$g ml$^{-1}$) and remifentanil (TCI, Minto model, Ce 4.0–8.0 ng ml$^{-1}$). Neur muscular block was achieved using rocuronium bromide with an induction dose of 0.6 mg kg$^{-1}$ i.v. and repeated maintenance doses of 0.2 mg kg$^{-1}$ when train-of-four (TOF) stimulation (TOF-Watch\textsuperscript{\textregistered}, Organon-Teknika, The Netherlands) resulted in more than two twitches.

For supraglottic ventilation and subsequent surgery, a Carl Reiner Jet-Laryngoscope\textsuperscript{\textregistered} (Carl Reiner GmbH, Vienna, Austria) was placed by an experienced laryngeal surgeon. A Twinstream\textsuperscript{\textregistered} jet ventilator (Carl Reiner GmbH) was used for all supraglottic JV. Weight-adjusted emission pressure settings provided by the manufacturer were used and, when necessary, increased to improve oxygenation. A HumiCare\textsuperscript{\textregistered} 200 breathing gas humidifier (Gründler Medical GmbH, Freudenstadt, Germany) was used during all supraglottic JV.

For infraglottic JV, the trachea was also intubated with a LaserJet\textsuperscript{\textregistered} catheter (Acutronic Medical Systems AG, Hirzel, Switzerland); the tip was positioned 4 cm below the vocal cords, verified fibreoptically. The catheter has a JV lumen with an inner diameter of 1.8 mm, a lumen for pressure measurement with an internal diameter of 0.8 mm and the external diameter of the catheter is 3.2 mm. Infraglottic high-frequency jet ventilation (HFJV\textsubscript{IG}) during the study was delivered with an AMS1000\textsuperscript{\textregistered} jet ventilator (Acutronic Medical Systems AG). Ventilation frequency for HFJV\textsubscript{IG} was 150 min$^{-1}$ with an I/E ratio of 0.43. The driving pressure (range 1.5–2.5 bar) was set by the anaesthesiologist in charge by evaluating chest movements, and adjusted to achieve normocapnoea ($P_{aCO_2} = 5–6$ kPa).

A catheter for blood gas analyses and haemodynamic monitoring was inserted into the right radial artery. ECG, heart rate, arterial blood pressure, and $S_{pO_2}$ were continuously monitored.

\textbf{Volume measurement}

Chest wall volume was measured with OEP. An OEP System\textsuperscript{\textregistered} (BTS Bioengineering, Milan, Italy) consisting of six infrared cameras was used to assess the position and movement of 52 adhesive reflective markers that were attached to the chest wall (Fig. 1a). Commercial software (OEP Capture\textsuperscript{\textregistered}, BTS Bioengineering) was used to reconstruct the position of each marker in a three-dimensional coordinate system for each time point (Fig. 1b). The volume enclosed by the surface formed by triangles between the markers represents the chest wall volume, which is recorded with accuracy and high time resolution as described in previous studies.\textsuperscript{15} Tidal volume was calculated as the difference between end-inspiratory and end-expiratory chest wall volume. The percentage contribution of pulmonary rib cage (RC\textsubscript{p}), abdominal
rib cage (RCₐ), and abdomen (AB) to tidal volume was analysed. To calculate minute ventilation, tidal volume was multiplied with the jet frequency that contributed to bulk air movements, excluding the superimposed frequency.

Pressure measurements
A 200-mm-long air-filled 16 G Secalon™ Seldy catheter (BD Medical Surgical Systems, Stockholm, Sweden) was inserted into the trachea to measure intratracheal pressure. Correct position 1 cm above the carina was verified endoscopically. An analogue pressure transducer (RCEM250DU, Sensorteknics GmbH, Puchheim, Germany) was used to acquire airway pressure readings that were recorded continuously and synchronized with the volume measurements by the OEP Capture® software.

Experimental protocol
After titration of HFJVIG-driving pressure to achieve normoventilation, the experimental protocol was started. Four different modes of JV were applied in each patient for 10-min periods in a computer-generated randomized order (Excel, Microsoft, Redmond, WA, USA) (Fig. 2): (i) SHFJVSG at 12+600 min⁻¹ with I/E=1.0 and working pressures of 0.7–1.7 bar for the low-frequency component and 0.6–1.1 bar for the high-frequency component, (ii) supraglottic normal frequency JV (NFJVSG) at 12 min⁻¹ with I/E=1.0 and working pressures of 0.7–1.7 bar, (iii) SHFJVSG at 150 min⁻¹ at I/E=1.0 and at working pressure 0.6–1.1 bar, and (iv) HFJVIG at 150 min⁻¹ with I/E=0.43 and driving pressures from 1.5 to 2.5 bar.

After 5 and 10 min of ventilation in each mode, arterial blood gas samples were obtained, ventilation was paused and intratracheal suction was performed for 5 s with low pressure using a 16 G catheter in order to normalize lung volume history. This effect of the manoeuvre was verified by OEP analysis.

Volume and pressure definitions
OEP measures total chest wall volume rather than lung volume. Therefore, apnoeic chest wall volume contains lung volume at apnoeic functional residual capacity (FRC). Accordingly, we chose to normalize end-expiratory chest wall volume to apnoeic FRC so that tidal volume changes and increases in FRC could be deduced. At a frequency of 12 min⁻¹ and an I/E ratio of 1.0, the duration of the expiratory pause was 2.5 s. Chest wall volume recruitment at such a low frequency in an open system was regarded as negligible and thus end-expiratory chest wall volume (EEVₑcw) was assumed to be at apnoeic FRC in the NFJVSG mode. Therefore, chest wall volume was normalized to NFJVSG end-expiratory chest wall volume (Fig. 2). Hence, for all measured volumes, EEVₑcw during NFJVSG has been subtracted.

Pressure transducers were calibrated and offset was corrected for using a MATLAB® (The MathWorks, Natick, MA, USA) programme developed at Politecnico di Milano, Italy. For each patient, means for chest wall volumes and corresponding intratracheal pressure were extracted from the raw data material using at least five consecutive steady-state breaths.

Positive end-expiratory pressure (PEEP) was defined as the mean pressure registered via the intratracheal catheter at end-expiration during five consecutive breaths.

Time constants and estimated steady-state recruitment
Transition from apnoea to the next ventilation mode increases EEVₑcw breath by breath until steady state. Time constants for the transients were calculated by fitting a single exponential function to the points formed by the

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Fig 2 Schematic overview of the experimental protocol illustrated by chest wall volume variations from a representative subject. SHFJVSG (supraglottic superimposed jet ventilation 12+600 min⁻¹), NFJVSG (supraglottic jet ventilation at 12 min⁻¹), HFJVSG (supraglottic jet ventilation at 150 min⁻¹) and HFJVIG (infroglottic jet ventilation at 150 min⁻¹) were applied in sequence after randomization. Asterisks mark apnoea with intratracheal suctioning.
EEV CW of each breath. Only 9 out of 15 subjects provided end-expiratory chest wall volumes that could be fitted by a single exponential function with an \( r^2 \) of >0.8.

**Statistical analysis**

With a power of 0.8 and a \( P \)-value of <0.05, a sample size of at least 11 patients (ANOVA, four groups) would be needed to detect a difference in \( P_{aCO_2} \) of 1.5 kPa with a standard deviation of 1.0 kPa.\(^2\) Because of a lack of data on lung volume changes during SHFJV in healthy humans, we were not able to define expected differences in EEV CW and \( V_T \) between the modes and therefore, a sample size could not be calculated for these variables. Finally, we included 16 patients to compensate for potential dropouts and to increase the likelihood of significant findings for the lung volume measurements.

**Results**

The study consisted of 16 subjects (9 females, 7 males). One subject had to be excluded from the study because of signs of hyperinflation. Patient characteristics are summarized in Table 1 and all measurement results can be found in Table 2.

After the end of the study protocol, intratracheal catheters were removed and surgery could be carried out as planned without complications intraoperatively or after operation. All measurements were completed before the start of surgery.

One subject with subglottic stenosis was excluded from the study because of repeatedly exceeding the airway pressure limit (30 mbar) during HFJV IG. This was accompanied by a clinically observed expansion of the chest wall. Subsequent analysis of the obtained data revealed that only within seconds of HFJV IG, the subject had accumulated \( \approx 450 \) ml of air and would have reached a steady-state EEV CW of 672 ml after 40–50 s. Unfortunately, because of technical problems with the pressure transducer, it was not possible to acquire intratracheal pressure readings at the time.

### Table 1 Patient characteristics data. Values are mean (range) for age, or mean (SD)

<table>
<thead>
<tr>
<th></th>
<th>Male</th>
<th>Female</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>7</td>
<td>9</td>
<td>16</td>
</tr>
<tr>
<td>Age (years)</td>
<td>55.9 (41–72)</td>
<td>45.1 (33–68)</td>
<td>49.8 (33–72)</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>94.3 (10.1)</td>
<td>69.4 (17.3)</td>
<td>81.0 (22.4)</td>
</tr>
<tr>
<td>Length (cm)</td>
<td>183 (11)</td>
<td>162 (7)</td>
<td>171 (13)</td>
</tr>
<tr>
<td>ASA I</td>
<td>3</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>ASA II</td>
<td>4</td>
<td>5</td>
<td>9</td>
</tr>
<tr>
<td>Supraglottic neoplasia</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Vocal cord polype</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Vocal cord scar</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Vocal cord neoplasia</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Laryngeal papilloma</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Web of the larynx</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Subglottic stenosis</td>
<td>0</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Tracheal stenosis</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

### Table 2 The effect of jet ventilation mode on end-expiratory chest wall volume (EEV CW), tidal volume (\( V_T \)), PEEP, pressure over PEEP, minute ventilation, gas exchange, and haemodynamics. Data are expressed as mean (SD). \( P \)-values are global values between all groups

<table>
<thead>
<tr>
<th></th>
<th>SHFJV</th>
<th>NFJV</th>
<th>HFJV IG</th>
<th>HFJV IG</th>
<th>( P )-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>EEV CW (ml)</td>
<td>239 (196)</td>
<td>0</td>
<td>148 (145)</td>
<td>44 (106)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>( V_T ) (ml)</td>
<td>269 (149)</td>
<td>229 (169)</td>
<td>145 (50)</td>
<td>110 (33)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Pulmonary rib cage (%)</td>
<td>28 (10)</td>
<td>30 (10)</td>
<td>26 (10)</td>
<td>26 (12)</td>
<td>0.66</td>
</tr>
<tr>
<td>Abdominal rib cage (%)</td>
<td>10 (5)</td>
<td>9 (5)</td>
<td>7 (6)</td>
<td>8 (6)</td>
<td>0.62</td>
</tr>
<tr>
<td>Abdomen (%)</td>
<td>62 (12)</td>
<td>61 (12)</td>
<td>67 (15)</td>
<td>66 (17)</td>
<td>0.60</td>
</tr>
<tr>
<td>PEEP (cm H_2O)</td>
<td>3.1 (2.2)</td>
<td>0</td>
<td>2.1 (2.3)</td>
<td>1.1 (1.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Pressure over PEEP (cm H_2O)</td>
<td>10.4 (2.4)</td>
<td>7.5 (2.6)</td>
<td>7.4 (2.8)</td>
<td>6.2 (3.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Minute ventilation (litre min(^{-1}))</td>
<td>3.2 (1.8)</td>
<td>2.8 (2.0)</td>
<td>21.7 (7.6)</td>
<td>16.6 (4.9)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>( P_{aO_2} ) (kPa)</td>
<td>13.6 (7.6)</td>
<td>12.9 (5.9)</td>
<td>13.4 (6.4)</td>
<td>13.2 (4.6)</td>
<td>0.91</td>
</tr>
<tr>
<td>( P_{aCO_2} ) (kPa)</td>
<td>5.6 (1.1)</td>
<td>5.9 (1.2)</td>
<td>4.3 (1.3)</td>
<td>5.2 (1.3)</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Heart rate (min(^{-1}))</td>
<td>73 (18)</td>
<td>72 (16)</td>
<td>73 (14)</td>
<td>72 (16)</td>
<td>0.66</td>
</tr>
<tr>
<td>Systolic blood pressure (mm Hg)</td>
<td>108 (15)</td>
<td>109 (16)</td>
<td>109 (15)</td>
<td>113 (20)</td>
<td>0.18</td>
</tr>
<tr>
<td>Diastolic blood pressure (mm Hg)</td>
<td>61 (7)</td>
<td>61 (8)</td>
<td>61 (8)</td>
<td>61 (8)</td>
<td>0.96</td>
</tr>
</tbody>
</table>
End-expiratory chest wall volume and PEEP

The highest normalized end-expiratory chest wall volume (EEVCW) of 239 (196) ml was observed during SHFJVSG. NFJVSG was chosen as reference and EEVCW was therefore zero \((P < 0.05)\) compared with SHFJVSG). During HFJVSG normalized EEVCW was 148 (145) ml \((P > 0.05)\) and during HFJVIG 44 (106) ml \((P < 0.05)\). Further, the difference between NFJVSG and HFJVSG was statistically significant \((P < 0.05, \text{Fig. 3}A)\).

When superimposing a high frequency of 600 min\(^{-1}\) onto NFJVSG, a subsequent increase of EEVCW was observed that reached a steady state of 330 (240) ml with a time constant of 20.1 (6.6) s \((n=9)\). In practice, this means that steady state will be reached after \(\approx 100\) s.

The corresponding end-expiratory pressures were also highest during SHFJVSG and reached 3.1 (2.2) cm H\(_2\)O. Despite great inter-patient variabilities, there were statistically significant differences between the modes. Compared with SHFJVSG, NFJVSG had a PEEP of 0 \((P < 0.01)\), PEEP during HFJVSG was 2.1 (2.3) cm H\(_2\)O \((P = 0.15)\) and during HFJVIG was 1.1 (1.3) cm H\(_2\)O \((P < 0.01, \text{Fig. 3A})\).

Tidal volumes, pressure over PEEP, and minute ventilation

Tidal volume was affected by the mode of ventilation. It was greatest during SHFJVSG at 269 (149) ml, followed by NFJVSG at 229 (169) ml \((P = 1.00)\) compared with SHFJVSG, HFJVSG at 145 (50) ml \((P < 0.01)\), and HFJVIG at 110 (33) ml \((P < 0.01)\). There was a significant difference between NFJVSG and HFJVIG \((P < 0.01)\).

Likewise, pressure over PEEP during SHFJVSG was 10.4 (2.4) cm H\(_2\)O, during NFJVSG was 7.5 (2.6) cm H\(_2\)O \((P < 0.01)\) compared with SHFJVSG, during HFJVSG was 7.4 (2.8) cm H\(_2\)O \((P < 0.01)\), and during HFJVIG was 6.2 (3.3) cm H\(_2\)O \((P < 0.01)\) (Fig. 3B).

For calculation of minute ventilation for SHFJVSG, only the low-frequency component was used. The high frequency of 600 min\(^{-1}\) resulted in inconsistent tidal volumes of <10 ml that were considered negligible in terms of their contribution to bulk alveolar ventilation. Minute ventilation during SHFJVSG was 3.2 (1.8) litre min\(^{-1}\). Comparing the other modes with SHFJVSG, NFJV SG minute ventilation was 2.1 (2.0) litre min\(^{-1}\) \((P = 1.00)\); during HFJVSG, it was 21.7 (7.6) litre min\(^{-1}\) \((P < 0.01)\); and during HFJVIG, it was 16.6 (4.9) litre min\(^{-1}\) \((P < 0.01)\). There was also a statistically significant

![Fig 3](https://academic.oup.com/bja/article-abstract/108/4/690/257386)
difference between supraglottic and HFJVIG (P<0.01) and between both HFJV modes and NFJVSG (P<0.01, Fig. 4).

Oxygenation, gas exchange, and haemodynamics

All four modes resulted in adequate oxygenation and carbon dioxide elimination. Comparing arterial $P_aO_2$ of SHFJVSG with the other modes, there was no difference in statistical significance. Despite great variability, there were however differences in carbon dioxide elimination. Comparing $P_aCO_2$ of SHFJVSG [5.6 (1.1) kPa] with the other modes, during NFJVSG it was 5.9 (1.2) kPa (P=1.00), during HFJVSG it was 4.3 (1.3) kPa (P<0.01), and during HFJVIG it was 5.2 (1.3) kPa (P=1.00, Fig. 4). Linear regression revealed a significant influence of minute ventilation on $P_aCO_2$ (P<0.01, $r^2=0.35$). All blood gas data are summarized in Table 2. 

$FIO_2$ in the trachea ranged between 0.3 and 0.5.

No significant differences in haemodynamic values were found between ventilation modes.

Discussion

This is the first study to compare lung volume and airway pressure changes and also gas exchange during SHFJVSG with other modes of JV using clinically relevant settings. Our hypothesis was that SHFJV should be a more effective mode of ventilation that increases oxygenation and carbon dioxide elimination compared with single frequency JVs.

Tidal volume and end-expiratory chest wall volume were highest during SHFJVSG, but there was no significant improvement in gas exchange. All of the investigated modes resulted in adequate oxygenation. However, carbon dioxide elimination tended to be more efficient during both HFJV modes as a result of higher minute ventilation compared with SHFJVSG and NFJVSG. SHFJVSG has previously been compared with two different types of infraglottic JV and was found to be most effective.22 Another study comparing SHFJVSG with single-frequency infraglottic JV, using either the low- or high-frequency component of SHFJVSG, found that single-frequency JV was less effective than SHFJVSG.21 This is not surprising for a frequency of 600 min$^{-1}$, as it is known that single-frequency HFJV at rates >300 min$^{-1}$ leads to impaired oxygenation23 and reduced carbon dioxide elimination24 as a consequence of the low tidal volumes at these rates. The use of physiological frequencies for jet ventilation (NFJV) is commonly applied in a supraglottic manner and has been described as safe and effective.25 Routine NFJVIG in open systems has been reported26 27 and can be effective at higher working pressures than in Bacher and co-workers’ study.27

At rates of 100–200 min$^{-1}$, as used in the present study, infraglottic JV has an optimum where it provides sufficient gas exchange with relatively low airway pressures.4 28 This was confirmed by the present study and can be explained by minute ventilation. During HFJV, four to seven times higher minute ventilation was observed, compared with both modes involving a low-frequency component. Consequently, carbon dioxide was eliminated more effectively during HFJV.

The present study is the first to use three-dimensional kinematic chest wall volume measurements (OEP) to study JV. There have been attempts to estimate lung volume changes previously using either semi-closed systems for direct measurement of $V_t$29 or simplified one-dimensional models to estimate lung volume changes.24 In all four modalities in this study, OEP allowed breath-by-breath measurement of chest wall volume, consisting of end-expiratory and tidal volume changes.

Increased EEV and maintenance of PEEP are effects of JV at high rates. For a given driving pressure, the $I/E$ ratio rather than ventilatory frequency increases lung volume,28 as corroborated by the present study. End-expiratory chest wall volume was highest during SHFJVSG, an effect likely to

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**Table 2**

<table>
<thead>
<tr>
<th>Mode</th>
<th>$P_aO_2$ (kPa)</th>
<th>$P_aCO_2$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SHFJV</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NFJV SG</td>
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<tr>
<td>HFJV SG</td>
<td></td>
<td></td>
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<tr>
<td>HFJV IG</td>
<td></td>
<td></td>
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</tbody>
</table>

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**Fig 4** Mean(±) values for minute ventilation (blue squares) and $P_aCO_2$ (green triangles) during SHFJVSG compared with NFJV and HFJV. Asterisks indicate significant differences compared with SHFJVSG, hashes indicate significant differences compared with NFJVSG (P<0.05), cross indicates significant difference compared with HFJV SG. Note the inverted axis scale for minute ventilation.
result from the synergism of the low- and the high-frequency jet components. Interestingly, supraglottic monofrequency JV resulted in a stronger increase in EEV_{CW} than HJV_{IG}, despite the same frequency used. This might be explained by the fact that the I/E ratio for supra- (I/E=1.00) and infra-glottic (I/E=0.43) ventilation was different, reducing air trapping with HJV_{IG} in our study. Another contributing factor could be that less entrainment might occur during HJV_{IG}, which is applied far more distally in the airway.

The excluded subject is an interesting example of how an (iatrogenically) obstructed airway can lead to air trapping when HJV_{IG} is used. In this case, the duration of expiration during HJV was too short to allow complete exhalation and air was trapped inside the lungs. This phenomenon has been shown to be accompanied by an increase in airway pressure everywhere distal to the stenosis, an effect that depends on the degree of stenosis and on driving pressure. With both jet injector and monitoring channel located at a sub-stenotic level, airway pressure curve monitoring helps prevent fatal hyperinflation caused by air trapping. Interestingly, when the JV catheter was removed, the procedure could be continued on supraglottic SHFJV without signs of air trapping.

Limitations

This study was performed to assess the effect on lung volume and gas exchange of pressures and frequencies used in our clinical practice, and was not designed to obtain equal airway pressure or alveolar ventilation. Moreover, as the study was performed before surgery, it was necessary to limit the time for each intervention. All findings of this work can therefore only reflect the first 10 min of JV with the described settings. The long-term effects of JV on lung volume and on gas exchange were thus not studied. It is however unlikely that major increases in lung volume would occur after a longer period of time as the time constants of EEV_{CW} increase indicate that steady state had been reached within the observation period. Greater differences in gas exchange between the groups could possibly have been recorded if more time had been allowed to reach equilibrium. Furthermore, gas distribution and exchange during high-frequency JV is complex, and recording the changes in chest wall configuration might underestimate the actual movement of oxygen and carbon dioxide since other mechanisms than bulk air movement might be relevant.

Conclusions

In healthy subjects with limited airway obstruction, short sessions of SHFJV were associated with increased EEV and tidal volume compared with the three other investigated JV modes. All studied modes provided adequate ventilation and oxygenation, and can thus be used for uncomplicated laryngeal surgery. Further studies comparing different JV modes in patients with significant airway stenosis, pulmonary pathology, or both are needed.

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Declaration of interest

There are no economic conflicting interests. A.A. is one of the inventors of OEP. The patents are owned by the Politecnico di Milano (Milan, Italy) and licensed to BTS Spa Company.

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