Ventilation through a small-bore catheter: optimizing expiratory ventilation assistance

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Editor’s key points
- Resistance to passive gas outflow is a problem during transtracheal ventilation through small-bore catheters.
- One possible solution is to aid expiration by using negative pressure.
- In this benchtop study of a new device, minute volumes delivered through a transtracheal catheter appeared adequate.
- Further studies are required to assess whether the DE 5 may be useful in clinical practice.

Background. Emergency ventilation through a small-bore transtracheal catheter can be lifesaving in a ‘cannot intubate, cannot ventilate’ situation. Ejectors, capable of creating suction by the Bernoulli principle, have been proposed to facilitate expiration through small-bore catheters. In this bench study, we compared a novel, purpose-built ventilation ejector (DE 5) with a previously proposed, modified industrial ejector (SBP 07).

Methods. The generated insufflation pressures, suction pressures in static and dynamic situations, and also suction capacities and entrainment ratios of the SBP 07 and the DE 5 were determined. The DE 5 was also tested in a lung simulator with a simulated complete upper airway obstruction. Inspiratory and expiratory times through a transtracheal catheter were measured at various flow rates and achievable minute volumes were calculated.

Results. In a static situation, the SBP 07 showed a more negative pressure build-up compared with the DE 5. However, in a dynamic situation, the DE 5 generated a more negative pressure, resulting in a higher suction capacity. Employment of the DE 5 at a flow rate of 18 litre min⁻¹ allowed a minute volume through the transtracheal catheter of up to 8.27 litre min⁻¹ at a compliance of 100 ml cm H₂O⁻¹. The efficiency of the DE 5 depended on the flow rate of the driving gas and the compliance of the lung simulator.

Conclusion. In laboratory tests, the DE 5 is an optimized ventilation ejector suitable for applying expiratory ventilation assistance. Further research may confirm the clinical applicability as a portable emergency ventilator for use with small-bore catheters.

Keywords: airway, obstruction; equipment, ventilators; ventilation, transtracheal

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Needle cricothyroidotomy with subsequent transtracheal jet ventilation is one of the last options to restore oxygenation in a ‘cannot intubate, cannot ventilate’ (CICV) situation. One of the problems associated with jet ventilation is the difficulty in controlling expiration. Outflow of gas has to take place passively through the upper airway. In a CICV situation, one can never be sure whether an obstructed upper airway will open up or will stay blocked after initiation of high-pressure jet ventilation. Obstruction of the outflow tract, insufficient expiratory time, or both can result in air trapping with subsequent barotrauma and haemodynamic instability. Oedema, laryngospasm, and the presence of surgical instruments have all been reported to compromise the outflow of gas.

Time needed for passive backflow of gas depends on the resistance of the outflow tract (determined by its diameter and length) and on the driving force (determined by the compliance of the respiratory system which results from the elasticity of the lungs and the chest wall). If the diameter of the natural or artificial airway is restricted below a critical point (4 mm usually being considered as the cut-off point), exhalation time is prolonged exponentially. Air trapping becomes a real danger if the expiratory time in relation to the diameter and length of the outflow tract is too short. Changing the I:E ratio only provides a partial solution to the problem.

A bidirectional ventilatory system that requires only a small-bore airway catheter for both the delivery of oxygen to the lungs and the outflow of gas could completely solve the above-mentioned problems associated with jet ventilation. Application of jet flow generated suction has been proposed to facilitate expiration through large-bore and small-bore paediatric tracheal tubes. Although directly addressing the concern about using jet ventilation in the presence of airway obstruction, other ventilation concepts for adult patients applying suction to
small-bore catheters have not found their way into clinical practice.\textsuperscript{12–14}

Recently, we described a modified industrial ejector (SBP 07) using expiratory ventilation assistance (EVA) based on the Bernoulli principle.\textsuperscript{15} Although a minute volume of up to 6 litre min\textsuperscript{−1} could be achieved through a 75 mm long, 2 mm ID transtracheal catheter, this industrial ejector is not specified for ventilation but has been designed to create a maximum negative pressure to pick up and hold parts during industrial manufacturing processes. Therefore, we developed and tested in several bench studies a novel ejector-based ventilation device (DE 5) designed to provide an optimized entrainment effect for EVA.\textsuperscript{16}

The aims of this study were to compare the generated pressures, suction capacities, and entrainment ratios of the modified SBP 07 and the DE 5 and to determine the achievable minute volumes through a small-bore catheter in a simulated obstructed upper airway.

**Methods**

The modified SBP 07 (Figs 1A and 2A) has been described previously.\textsuperscript{15} The modification of the original industrial device involved both removal of the silencer and connection of a modified T-piece as a flow control unit. The DE 5 consists of a specifically designed ejector with a 0.7 mm jet needle and an identical T-piece (Figs 1A and 2A). The driving gas, coming from a calibrated, pressure-compensated oxygen flowmeter, is highly accelerated by being forced through the jet needle and creates a negative pressure downstream of this needle. This effect is based on the Bernoulli principle and results in entrainment of gas through the side port (3 in Figs 1A and 2A). By simply occluding the outlet (jet/EVA switch; 2 in Figs 1A and 2A) of the ejector, the oxygen flow can be redirected to the transtracheal catheter (connected to 5 in Figs 1A and 2A).

To control the expiratory and inspiratory flows, a T-piece (part number 84048, Qosina, Edgewood, NY, USA) with an extra 4 mm side hole (on/off switch; 4 in Figs 1A and 2A) is attached to the side port of the ejector and functions as the flow control unit of the ventilation device.

In a pre-test bench study, it was shown that with the on/off switch open, sufficient flow and pressure release is established and both the SBP 07 and the DE 5 thereby are functionally switched off, with no relevant flows and pressures acting downstream of the flow control unit. However, if the on/off switch is closed, the ejectors become active. By then alternatingly occluding and releasing the jet/EVA switch, either the oxygen flow is directed to the transtracheal catheter or a subatmospheric pressure is created to assist expiration (Fig. 3A and B).

**Part 1: insufflation and suction pressures**

In the first part of our study, the generated pressures of the modified SBP 07 and the DE 5 were studied. Both ejectors were connected to a calibrated, pressure-compensated flowmeter (Dräger Medical AG & Co. KG, Lübeck, Germany) and attached to a transtracheal catheter (75 mm length, 2 mm ID; Cook Medical, Bloomington, IN, USA) by a 15 cm long, 3 mm ID connecting tubing including a distal T-piece (see Fig. S1 in the Supplementary material at *British Journal of Anaesthesia* online).

At oxygen flows of 6, 9, 12, 15, and 18 litre min\textsuperscript{−1}, the insufflation and suction pressures were measured at the distal T-piece, while simulating a static (no gas entrainment with the catheter tip closed) and a dynamic situation.
(continuous gas entrainment with the catheter tip open to the atmosphere). Four repetitive pressure measurements were done using the Calibration Analyzer series RT-200 (Timeter Instrument Corporation, St Louis, MO, USA). Before each measurement, the flowmeter reading was checked.

**Part 2: suction capacities and entrainment ratios**

The suction capacities and entrainment ratios (= entrained flow/driving flow) of both devices through the 75 mm long, 2 mm ID transtracheal catheter were determined at oxygen flows of 6, 9, 12, 15, and 18 litre min$^{-1}$ by insufflation and desufflation of a common 35 litre plastic garbage bag (product number 136146, Albert Heijn, Zaandam, The Netherlands) as a closed ventilation model with an infinite compliance. Four repetitive trials were performed by insufflating the plastic bag for 1 min and measuring the time it took to completely empty the bag by suction.

**Part 3: inspiratory and expiratory times and minute volumes**

In the third part of the study, the efficacy of the DE 5 at different pulmonary compliances and resistances was tested in an LS800 lung simulator (Dräger Medical AG & Co. KG) with a simulated complete upper airway obstruction. The 75 mm long, 2 mm ID transtracheal catheter was tightly fitted in the proximal tube orifice of the lung simulator ensuring that the entire gas flow into and out of the bellows was guided through the catheter.

To determine minute volumes, the times required for insufflation of 1000 ml of oxygen and the times needed for
passive backflow of this volume through the catheter and for assisted expiration using the DE 5 were measured as previously described. Four repetitive tests were performed at different compliances (100, 50, 30, and 10 ml cm H\textsubscript{2}O\textsuperscript{-1}), resistances (2 and 32 cm H\textsubscript{2}O litre\textsuperscript{-1} s\textsuperscript{-1}), and different oxygen flows (6, 9, 12, 15, and 18 litre min\textsuperscript{-1}).

Statistical analysis
For descriptive statistics, MS-Excel 2002 SP3 was used. Results are presented as mean (s). Suction capacities, entrainment ratios, and achievable minute volumes were calculated.

Results
Part 1: insufflation and suction pressures
The modified SBP 07 and the DE 5 generated similar insufflation pressures proportional to the flow rate of the driving gas (Table 1). Subatmospheric pressures in both the static and the dynamic settings were proportional to the flow rate of the driving gas. In all static situations, except at a flow rate of 6 litre min\textsuperscript{-1}, the subatmospheric pressure generated by the DE 5 was less negative compared with that generated by the SBP 07 at the same flow rate. However, in all dynamic situations, the DE 5 maintained a more negative pressure.

Part 2: suction capacities and entrainment ratios
The suction capacity of the DE 5 was higher compared with that of the SBP 07 and ranged from 6.8 to 15.9 litre min\textsuperscript{-1} depending on the flow rate of the driving gas (Table 1). Consequently, also the entrainment ratio of the DE 5 was higher than that of the SBP 07 at all flow rates.

Part 3: inspiratory and expiratory times and minute volumes
Applying EVA using the DE 5 at a flow rate of 6 litre min\textsuperscript{-1} resulted, at a compliance of 100 ml cm H\textsubscript{2}O\textsuperscript{-1} and a resistance of 2 cm H\textsubscript{2}O litre\textsuperscript{-1} s\textsuperscript{-1}, in a decrease in the expiratory time from 13.4 (0.03) to 8.0 (0.10) s (Table 2). Raising the flow rate of oxygen resulted in a further decrease in expiratory times and consequently in an increase in the calculated MV, achievable through the transtracheal catheter for this pulmonary setting, from 3.58 to 8.27 litre min\textsuperscript{-1} (Table 3). The maximum effect of the DE 5 on the expiratory time was reached at 15 litre min\textsuperscript{-1} (Table 2). The increase in the achievable minute volume at a flow rate of 18 litre min\textsuperscript{-1} compared with that at a flow rate of 15 litre min\textsuperscript{-1} only resulted from a shorter inspiratory time due to the higher flow rate of the driving gas. A decrease in compliance reduced the effect of EVA (Table 3). At a compliance of 10 ml cm H\textsubscript{2}O\textsuperscript{-1}, the expiratory time with EVA using the DE 5 at a flow rate of 6 litre min\textsuperscript{-1} was 1.1 s longer compared with passive backflow (Table 2), resulting in a decrease in calculated minute volume of 170 ml min\textsuperscript{-1} (Table 3). At higher flow rates, the minute volume achieved by EVA at this low compliance was similar (at 9 litre min\textsuperscript{-1}) or slightly higher compared with passive backflow.

Further data relating to the experimental set up and results using cannulae of different sizes and non-compliant tubing (2 mm ID) are found in the supplementary material.

Discussion
Employment of Bernoulli’s principle can facilitate expiration through a small-bore transtracheal catheter. The results of the present study show that the novel ventilation ejector (DE 5) is more suitable for ventilation purposes than the modified industrial ejector (SBP 07). The DE 5 substantially shortened the required expiratory time and achieved a minute volume of up to 8.27 litre min\textsuperscript{-1} through a 75 mm long, 2 mm ID transtracheal catheter.

At a pulmonary setting representing a healthy adult (compliance 50 ml cm H\textsubscript{2}O\textsuperscript{-1}, resistance of 2 cm H\textsubscript{2}O litre\textsuperscript{-1} s\textsuperscript{-1}), passive backflow of 1000 ml oxygen through the transtracheal catheter takes 9.9 (0.10) s. Thus, at an oxygen flow of 15 litre min\textsuperscript{-1} repetitively connecting and disconnecting

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**Table 1** Results of Part 1: insufflation and suction pressures and Part 2: suction capacities and entrainment ratios. $P_{\text{insp}}$, $P_{\text{stat}}$, and $P_{\text{dyn}}$ indicate pressures during inspiration and during expiration in a static situation (no gas entrainment with the catheter tip closed) and a dynamic situation (continuous gas entrainment with the catheter tip open to the atmosphere), respectively, using flow rates of 6–18 litre min\textsuperscript{-1}. Data given as mean (s). Suction capacity (SC) and entrainment ratio (ER=entrained flow/driving flow) are calculated values.

<table>
<thead>
<tr>
<th>Flow (litre min\textsuperscript{-1})</th>
<th>$P_{\text{insp}}$ (cm H\textsubscript{2}O)</th>
<th>$P_{\text{stat}}$ (cm H\textsubscript{2}O)</th>
<th>$P_{\text{dyn}}$ (cm H\textsubscript{2}O)</th>
<th>SC (litre min\textsuperscript{-1})</th>
<th>ER</th>
</tr>
</thead>
<tbody>
<tr>
<td>SBP 07</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>19.4 (0.24)</td>
<td>-53.8 (1.14)</td>
<td>-9.8 (0.14)</td>
<td>4.1</td>
<td>0.68</td>
</tr>
<tr>
<td>9</td>
<td>43.6 (0.38)</td>
<td>-196.1 (1.23)</td>
<td>-31.3 (0.21)</td>
<td>7.8</td>
<td>0.87</td>
</tr>
<tr>
<td>12</td>
<td>75.4 (0.41)</td>
<td>-377.3 (0)</td>
<td>-51.0 (0.29)</td>
<td>10.1</td>
<td>0.84</td>
</tr>
<tr>
<td>15</td>
<td>113.0 (0.32)</td>
<td>-540.4 (0)</td>
<td>-63.1 (0.14)</td>
<td>11.4</td>
<td>0.76</td>
</tr>
<tr>
<td>18</td>
<td>148.8 (0.71)</td>
<td>-660.3 (5.1)</td>
<td>-70.4 (0.24)</td>
<td>12.5</td>
<td>0.69</td>
</tr>
<tr>
<td>DE 5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>19.8 (0.39)</td>
<td>-70.6 (0.92)</td>
<td>-22.9 (0.43)</td>
<td>6.8</td>
<td>1.13</td>
</tr>
<tr>
<td>9</td>
<td>43.7 (0.1)</td>
<td>-161.9 (0.54)</td>
<td>-49.0 (0.38)</td>
<td>10.2</td>
<td>1.13</td>
</tr>
<tr>
<td>12</td>
<td>75.5 (0.41)</td>
<td>-263.5 (0.75)</td>
<td>-76.4 (0.34)</td>
<td>12.6</td>
<td>1.05</td>
</tr>
<tr>
<td>15</td>
<td>110.9 (0.5)</td>
<td>-346.7 (0)</td>
<td>-94.7 (0.23)</td>
<td>14.3</td>
<td>0.95</td>
</tr>
<tr>
<td>18</td>
<td>147.2 (2.06)</td>
<td>-400.2 (5.1)</td>
<td>-108.5 (0.19)</td>
<td>15.9</td>
<td>0.88</td>
</tr>
</tbody>
</table>
the oxygen tubing and the transtracheal catheter could result in a theoretical minute volume of 4.27 litre min\(^{-1}\). However, in an emergency situation, a continuously connected bidirectional ventilation system is highly preferable, because of the risk of dislodging the transtracheal catheter by manipulations. The Oxygen Flow Modulator (OFM; Cook Medical) is a bidirectional emergency tool for transtracheal oxygenation. In an in vitro study, it achieved a calculated minute volume of 3.24 litre min\(^{-1}\) in case of a completely obstructed upper airway.\(^{17}\) Although this minute volume would be sufficient to re-establish oxygenation, hypercapnia seems to be inevitable.
To speed up expiration through a small-bore catheter, the driving force can be increased, for example, by applying compression to the thorax, abdomen, or both. The resistance of the outflow tract may also be diminished by inserting an additional transtracheal catheter to facilitate expiration.\textsuperscript{5,18,19} To minimize trauma to the airway and to get more control over the expiration, it has also been suggested to augment the outflow of gas through a single small-bore catheter by the application of suction.\textsuperscript{12,14}

The mechanism of both tested devices (modified SBP 07 and DE 5) is based on the ejector's principle. An ejector is a multipurpose device able to create a subatmospheric pressure by the Bernoulli principle and to entrain air from a side port. The amount of entrainment and consequently the degree of expiratory assistance depend on the velocity of the driving gas and the resistance of the ejector. Although an ejector's resistance to flow is primarily defined by its inner geometry, the velocity of the driving gas jet passing through the ejector modulates the effective resistance while the ejector is active. If, at a given flow, the velocity of the driving gas is decreased (e.g. by turbulent mixing with entrained gas), an ejector will become less efficient.

The SBP 07 was modified and the DE 5 was specifically designed to serve as emergency ventilation ejectors, allowing both insufflation of oxygen and EVA. Although the modified SBP 07 has previously been reported to achieve a minute volume of more than 6 litre min \textsuperscript{-1} through a 75 mm long, 2 mm ID transtracheal catheter,\textsuperscript{15} this industrial ejector has been designed to create a maximum negative pressure to pick up and hold parts during manufacturing processes in industrial assembly lines and is not specified for ventilation. The results of this study show that the SBP 07 is indeed capable of generating a high negative pressure in a static situation, that is, no gas is entrained. However, in a dynamic situation, when gas is continuously entrained through the transtracheal catheter, the generated pressure was considerably less negative. Compared with the SBP 07, the DE 5 built up a less negative pressure in a static situation, but maintained a higher negative pressure in a dynamic situation, leading to an improved suction capacity and a higher entrainment ratio. The differences in test results prove that the design of the DE 5 turns it into being better suited for ventilation purposes than the SBP 07.

As shown in Figure 2A and B, the outflow tract and the side port of the SBP 07 and the DE 5 are designed differently. The outflow tube of the SBP 07, having a constant diameter over three-quarters of its length, has an optimal shape for creating a maximum negative pressure build-up in a static situation. In contrast, the slightly conical shape of the outflow pipe of the DE 5 has a length and an internal diameter that were designed to maximize entrainment from the side port while minimizing inner turbulence and thus optimizing the egress of entrained gas.

We are aware of the fact that application of results from this in vitro study into clinical practice has its limitations. Completely blocking the upper airway is an extreme simplification of clinical reality. The diameter of the upper airway is dynamically variable, and in clinical practice, it will open up at a certain intratracheal (intrathoracic) pressure in most cases. Although this situation resembles a relatively rare event, we decided to simulate a completely blocked upper airway as the best experimental setting for the evaluation of the DE 5. Thus, the current study did not address the usefulness of the DE 5 in various degrees of upper airway obstruction and did not determine the influence of patency of the upper airway on the effect of EVA. Furthermore, the effects of EVA on gas exchange, lung tissue, and circulation have not yet been fully studied. Ongoing \textit{in vivo} experiments will have to address these clinical questions.

In summary, our novel EVA applying ventilation ejector DE 5 is capable of achieving an adequate minute volume through a small-bore transtracheal catheter. If further research confirms the safety and applicability of EVA \textit{in vivo}, the DE 5 might be used as a portable emergency ventilator for small-bore catheters in the future.

**Supplementary material**

Supplementary material is available at *British Journal of Anaesthesia* online.

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**Conflict of interest**

D.E. is the inventor of the Oxygen Flow Modulator and receives royalty payments from Cook Medical. Furthermore, D.E. has applied for a patent on the DE 5.

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