Achieving an adequate minute volume through a 2 mm transtracheal catheter in simulated upper airway obstruction using a modified industrial ejector

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Background. Needle cricothyrotomy and subsequent transtracheal jet ventilation (TTJV) is one of the last options to restore oxygenation while managing an airway emergency. However, in cases of complete upper airway obstruction, conventional TTJV is ineffective and dangerous. We transformed a small, industrial ejector into a simple, manual ventilator providing expiratory ventilation assistance (EVA).

Methods. An ejector pump was modified to allow both insufflation of oxygen and jet-assisted expiration through an attached 75 mm long transtracheal catheter (TTC) with an inner diameter (ID) of 2 mm by alternately occluding and releasing the gas outlet of the ejector pump. In a lung simulator, the modified ejector pump was tested at different compliances and resistances. Inspiration and expiration times were measured and achievable minute volumes (MVs) were calculated to determine the effect of EVA.

Results. The modified ejector pump shortened the expiration time and an MV up to 6.6 litre min⁻¹ could be achieved through a 2 mm ID TTC in a simulated obstructed airway.

Conclusions. The principle of ejector-based EVA seems promising and deserves further evaluation.

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since then, but none has found its way into clinical practice, probably because of the complicated technical set-up. \(^8^9\)

Bernoulli’s \(^10\) principle states that for an inviscid flow of a non-compressible (or, with restrictions, a compressible) fluid, an increase in velocity at a constriction in a tube leads to an increase in dynamic pressure (and thus kinetic energy) and a corresponding decrease in static pressure (and potential energy), obeying the first law of thermodynamics (conservation of energy). An industrial ejector is a multi-purpose device able to create subatmospheric pressure based on Bernoulli’s principle. Comparable with a Venturi nozzle, the driving gas flowing through an ejector entrains gas (e.g. ambient air) through a side port. \(^11\) Application of this principle might facilitate expiration through a small lumen catheter.

We adapted a small industrial ejector into a simple, manual ventilation device providing expiratory ventilation assistance (EVA). The aim of this study was to test the capability of this modified ejector to aid in achieving adequate minute ventilation through a 2 mm ID transtracheal catheter (TTC) in an artificial lung with a completely obstructed upper airway.

**Methods**

An industrial ejector (SBP 07, J. Schmalz GmbH, Glatten, Germany) with a 0.7 mm ID jet orifice (Fig. 1), weighing 7.5 g, was modified to allow both insufflation of oxygen and assisted expiration (Fig. 2A and B). The silencer was removed in order to be able to redirect the flow by occluding the outlet of the ejector. To control the flow to the lung simulator, a T-piece with an extra 4 mm side hole was attached as a bypass and functioned as an on–off switch. In a pre-test bench study, it was shown that with the side hole open, sufficient flow and pressure release occurs and the device thereby is functionally switched off, with no relevant flows and pressures acting in the direction of the artificial lung. However, if the side hole is closed, the ejector becomes ‘active’. By then simply occluding and releasing the gas outlet of the ejector, either an oxygen flow can be directed to the lung simulator or a subatmospheric pressure can be created (by the Bernoulli principle) to assist expiration. The modified ejector was connected to a pressure-compensated oxygen flowmeter (Dräger Medical AG & Co. KG, Lübeck, Germany) by 4 mm ID standard silicone tubing.

In an LS800 lung simulator (Dräger Medical AG & Co. KG), the MV of the modified ejector through a 2 mm ID, 75 mm long TTC (Cook Medical, Bloomington, IN, USA) in a simulated obstructed upper airway was determined at different compliances \([100, 50, 30, \text{ and } 10 \text{ ml (cm H}_2\text{O)}^{-1}]\) and resistances \((2, 8, \text{ and } 32 \text{ cm H}_2\text{O litre}^{-1} \text{ s}^{-1})\), representing healthy and compromised lungs. The catheter was tightly fitted in the proximal tube orifice of the lung simulator, ensuring that the entire gas flow into and out of the artificial lung was directed through the catheter. The time required for insufflation of 1000 ml of oxygen and

**Fig 1** An industrial ejector with a 0.7 mm ID jet orifice (SBP 07, J. Schmalz GmbH; length 45 mm without the silencer, weight 7.5 g) was modified into an EVA device.

**Fig 2** (A) The EVA device: the silicone oxygen tubing (1) is connected to the ejector’s inlet. The silencer has been removed from the outlet (2) to allow closure by a finger for redirecting the flow to the side port (3). A T-piece (4) with an extra 4 mm side hole (shown by the black circle) is attached to the side port as a bypass and functions as an on–off switch to control gas flow through the connecting tubing (5). The side port of the T-piece covered by a cap is intended for capnometry (not a part of this study). (B) Computed tomographic (CT) scan of the EVA device showing also the interior of the industrial ejector. The numbers indicate identical parts as in (A). The scatter in the CT scan is caused by the metal sealings at the inlet and the side port of the ejector.
the time needed for passive backflow of this volume through the catheter and for assisted expiration were measured at oxygen flows of 12 and 15 litre min\(^{-1}\). Timings were recorded by a second operator using a digital stopwatch while observing the bellows’ readings. At a compliance of 100, 50, and 30 ml (cm H\(_2\)O\(^{-1}\)) and a resistance of 2 cm H\(_2\)O litre\(^{-1}\) s\(^{-1}\), only one bellow of the lung simulator was insufflated. Time measurement was started at a bellow volume of 500 ml and, during insufflation on the way to 2000 ml, stopped at 1500 ml. Owing to high-pressure build-up, both bellows of the lung simulator had to be used at a compliance of 10 ml (cm H\(_2\)O\(^{-1}\)) to guarantee correct compliance. Using both bellows, 500 ml was taken as zero and 1000 ml as the endpoint for time measurement. The flowmeter was calibrated before the experiments using the Calibration Analyzer series RT-200 pressure and flow monitor (Timeter Instruments Corporation, St Louis, MO, USA). The flowmeter reading was checked before each measurement, each test was repeated four times, and minute volumes (MVs) and inspiration/expiration (I/E) ratios were then calculated.

### Results

Data are presented as mean (sd). At a compliance of 100 ml (cm H\(_2\)O\(^{-1}\)) and a resistance of 2 cm H\(_2\)O litre\(^{-1}\) s\(^{-1}\), the mean (sd) time needed for passive egress of 1000 ml oxygen through the TTC was 13.4 (0.03) s (Table 1). A decrease in lung compliance resulted in a faster passive backflow of gas through the TTC and the expiration time decreased to 7.8 (0.09) s at a compliance of 30 ml (cm H\(_2\)O\(^{-1}\)) and a resistance of 2 cm H\(_2\)O litre\(^{-1}\) s\(^{-1}\) (representing the lungs of a healthy adult), the passive backflow of 1000 ml through the TTC took 9.9 (0.10) s. With assisted expiration using the modified ejector, this time was shortened to 5.6 (0.07) s at an oxygen flow of 12 litre min\(^{-1}\) and to 5.1 (0.02) s at 15 litre min\(^{-1}\). This resulted in an increase in the calculated MV for this pulmonary setting from 4.0 to 5.6 litre min\(^{-1}\) at 12 litre min\(^{-1}\) oxygen flow and from 4.3 to 6.5 litre min\(^{-1}\) at 15 litre min\(^{-1}\), respectively (Table 2). However, at a compliance of 10 ml (cm H\(_2\)O\(^{-1}\)) and a resistance of 32 cm H\(_2\)O litre\(^{-1}\) s\(^{-1}\), the modified ejector prolonged the expiration time with ~0.7 s at an oxygen flow of 12 litre min\(^{-1}\) and ~0.3 s at 15 litre min\(^{-1}\) compared with passive expiration.

### Discussion

Cricothyroidotomy is one of the last options to restore oxygenation while managing a ‘cannot intubate, cannot ventilate’ (CICV) situation and should be performed without delay.\(^{12,13}\) Introduction of a small-bore catheter or cannula through the cricothyroid membrane is for most anaesthetists the first-choice infraglottic emergency technique\(^{14}\) as it is simple, quick,\(^{15}\) and widely available. For ventilation through a small lumen catheter, a high-pressure

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**Table 1** Mean (sd) times needed for insufflation of 1000 ml oxygen at different compliances and resistances at a flow rate of 12 or 15 litre min\(^{-1}\) and for the same volume of oxygen to egress through a 2 mm ID TTC passively (passive backflow) or with EVA (assisted expiration).

<table>
<thead>
<tr>
<th>Compliance [ml (cm H(_2)O(^{-1})]</th>
<th>100</th>
<th>50</th>
<th>30</th>
<th>30</th>
<th>30</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (cm H(_2)O litre(^{-1}) s(^{-1}])</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>12 litre min(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insufflation time (s)</td>
<td>4.9 (0.04)</td>
<td>5.1 (0.07)</td>
<td>5.4 (0.04)</td>
<td>5.4 (0.03)</td>
<td>5.4 (0.09)</td>
<td>6.7 (0.06)</td>
</tr>
<tr>
<td>Assisted expiration (s)</td>
<td>13.4 (0.03)</td>
<td>9.9 (0.10)</td>
<td>7.8 (0.09)</td>
<td>7.9 (0.12)</td>
<td>8.0 (0.06)</td>
<td>5.6 (0.23)</td>
</tr>
<tr>
<td>15 litre min(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Insufflation time (s)</td>
<td>4.0 (0.08)</td>
<td>4.1 (0.06)</td>
<td>4.3 (0.09)</td>
<td>4.3 (0.06)</td>
<td>4.2 (0.04)</td>
<td>5.4 (0.11)</td>
</tr>
<tr>
<td>Assisted expiration (s)</td>
<td>13.4 (0.03)</td>
<td>9.9 (0.10)</td>
<td>7.8 (0.09)</td>
<td>7.9 (0.12)</td>
<td>8.0 (0.06)</td>
<td>5.6 (0.23)</td>
</tr>
</tbody>
</table>

**Table 2** Mean calculated MV and I/E ratios achievable through a 2 mm ID TTC in a simulated obstructed upper airway by passive backflow and assisted expiration using the modified ejector connected to an oxygen flow of 12 or 15 litre min\(^{-1}\).

<table>
<thead>
<tr>
<th>Compliance [ml (cm H(_2)O(^{-1})]</th>
<th>100</th>
<th>50</th>
<th>30</th>
<th>30</th>
<th>30</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resistance (cm H(_2)O litre(^{-1}) s(^{-1}])</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>8</td>
<td>32</td>
<td>32</td>
</tr>
<tr>
<td>12 litre min(^{-1})</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MV, passive backflow (litre min(^{-1}))</td>
<td>3.28</td>
<td>4.01</td>
<td>4.55</td>
<td>4.51</td>
<td>4.49</td>
<td>4.87</td>
</tr>
<tr>
<td>I/E ratio, passive backflow</td>
<td>1/2.72</td>
<td>1/1.95</td>
<td>1/1.43</td>
<td>1/1.47</td>
<td>1/1.50</td>
<td>1/0.84</td>
</tr>
<tr>
<td>MV, assisted expiration (litre min(^{-1}))</td>
<td>5.73</td>
<td>5.60</td>
<td>5.37</td>
<td>5.42</td>
<td>5.43</td>
<td>4.60</td>
</tr>
<tr>
<td>I/E ratio, assisted expiration</td>
<td>1/1.13</td>
<td>1/1.11</td>
<td>1/1.06</td>
<td>1/1.05</td>
<td>1/1.06</td>
<td>1/0.94</td>
</tr>
<tr>
<td>15 litre min(^{-1})</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MV, passive backflow (litre min(^{-1}))</td>
<td>3.46</td>
<td>4.27</td>
<td>4.98</td>
<td>4.92</td>
<td>4.90</td>
<td>5.47</td>
</tr>
<tr>
<td>I/E ratio, passive backflow</td>
<td>1/3.37</td>
<td>1/2.39</td>
<td>1/1.81</td>
<td>1/1.85</td>
<td>1/1.89</td>
<td>1/1.04</td>
</tr>
<tr>
<td>MV, assisted expiration (litre min(^{-1}))</td>
<td>6.64</td>
<td>6.46</td>
<td>6.24</td>
<td>6.34</td>
<td>6.33</td>
<td>5.32</td>
</tr>
<tr>
<td>I/E ratio, assisted expiration</td>
<td>1/1.27</td>
<td>1/1.24</td>
<td>1/1.24</td>
<td>1/1.22</td>
<td>1/1.24</td>
<td>1/1.10</td>
</tr>
</tbody>
</table>
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oxygen source ventilator is mandatory. In experienced hands, this ventilation technique has a low morbidity as long as the egress of gas is secured. However, 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. Several cases of barotrauma and circulatory collapse due to obstruction of the upper airway during jet ventilation have been reported, although the majority of barotraumas probably result from partial airway obstruction with over-vigorous transtracheal jet ventilation combined with inadequate expiratory pause. The ideal ventilation system in this setting would act as a bidirectional airway, so both the delivery of oxygen to and the egress of gas from the lungs are controlled.

When an airway catheter is restricted below a critical diameter, exhalation time becomes rapidly prolonged. In our study, the time needed for passive backflow of 1000 ml oxygen through the 2 mm ID TTC was 13.4 s at a compliance of 100 ml (cm H2O)−1. One option to accelerate expiration when the upper airway is obstructed is to establish a separate egress pathway by the insertion of an additional transtracheal cannula (preferably large bore). However, this is not always feasible. Alternatively, the egress of gas through a single, small lumen catheter can also be facilitated by applying suction. Several techniques to apply subatmospheric pressure have been proposed in the past. Dunlap and Oregon demonstrated the efficacy of a thumb-operated three-way valve (actually a simple T-piece) attached to a connector for piped oxygen. Oxygen was insufflated at a rate of 800 ml s−1 and respiratory gas could be withdrawn from the trachea at about 185 ml s−1 (11.1 litre min−1). Unfortunately, the oxygen consumption for suctioning was very high (almost 50 litre min−1) and the oxygen flow was difficult to control: in both dogs and post-mortem humans s.c. emphysema was described. The computer-controlled pressurized injection/suction ventilation device equipped with separate, highly pressurized injection and suction tubings described by Schapera and colleagues efficiently maintained pulmonary gas exchange in 25–35 kg dogs through a 2.5 mm ID, 45 cm long ventilating stylet for more than 15 min during a period of total occlusion of the airway except for the passage offered by the catheter. Adequate tidal volumes were also achieved by the ‘total laryngeal bypass device’, which had an inner cannula to provide high-pressure oxygen insufflation and an outer cannula through which suction was applied throughout both inspiratory and expiratory phases.

However, none of the above-mentioned techniques and devices found its way into clinical practice, probably because of specific drawbacks and requirements (high oxygen demand, complex set-up, and/or bulky equipment). Our modified ejector ventilator is portable and ready to use after simply connecting it to a pressure compensated flowmeter set at an oxygen flow of 12–15 litre min−1. In a simulated upper airway obstruction, an MV of up to 6.6 litre min−1 can be achieved through a 2 mm ID TTC over a broad range of different pulmonary conditions. Furthermore, gas flow to and from the TTC can easily be controlled by the integrated on–off switch.

We appreciate the limitations of applying results from this simplified in vitro model into clinical practice. The effects of EVA on gas exchange, circulation, and lung tissue have not been studied. Additional in vivo experiments should elucidate this.

Small, industrial ejectors are designed to pick up and hold parts until these are, for example, dropped into feeders of automated assembly lines. These ejectors cannot be expected to work perfectly as a ventilator. As the data demonstrate, the modified ejector/ventilator works most effectively at high compliances. At lower compliances, expiratory assistance becomes less effective, and at a compliance of 10 ml (cm H2O)−1, the ejector does not support expiration, but even slightly prolongs the expiration time. Possible explanations are the build-up of high pressure (up to 100 mbar) in the artificial lung during the inspiratory phase in this extreme setting and a disturbed way of gas egress from the ejector caused by turbulent mixing of the jet flow with the gas pressed back into the ejector by low compliance during the expiratory phase. However, redesigning the ejector might solve this problem.

The principle of expiratory assistance during jet ventilation is not new, although different expressions have been used to describe the concept. The tested modified ejector is, however, the first device that is simple and portable, will work with an oxygen cylinder at flows of 12 to 15 litre min−1 and is capable of achieving an adequate MV through a 2 mm ID TTC even in the case of an obstructed upper airway. Nevertheless, improvement of the design seems to be required and further in vivo evaluation of the efficiency and safety of EVA is needed.

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The authors would like to thank J.E. Wildberger, Department of Radiology, Maastricht University Medical Centre, for the CT scan of the trachea. We appreciate the limitations of applying results from this simplified in vitro model into clinical practice. The effects of EVA on gas exchange, circulation, and lung tissue have not been studied. Additional in vivo experiments should elucidate this.

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