Jet or intensive care unit ventilator during simulated percutaneous transtracheal ventilation: a lung model study

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Editor’s key points

- This study evaluates the tidal volume \( V_T \) generated by a conventional ventilator during simulated percutaneous transtracheal ventilation (PTV) compared with jet ventilation (PTJV) in an artificial lung model.
- A conventional ventilator can generate reasonable alveolar ventilation through the transtracheal catheter.
- Insertion of a second catheter as a vent reduces auto-PEEP and improves ventilation during PTJV.
- PTV is less dependent on the directions of catheter insertion and should be considered during transtracheal ventilation.

Background. Percutaneous transtracheal ventilation (PTV) via a jet ventilator (PTJV) is considered a rescue technique in difficult airway management. However, whether a conventional ventilator can generate adequate ventilation via PTV is not known. Our goal was to evaluate the tidal volume \( V_T \) generated by a conventional ventilator during simulated PTV compared with PTJV in a lung model.

Methods. A lung model simulating an adult lung was used. A catheter was inserted through the artificial trachea and connected to either a jet ventilator or a conventional ventilator. The direction of catheter insertion was perpendicular to the trachea, pointing towards the lung and away from the lung. The jet ventilator was operated at 344.7 kPa. The conventional ventilator was operated in the pressure mode at peak inspiratory pressures of 40–90 cm H₂O.

Results. The jet ventilator generated larger \( V_T \) [817 (336) ml] when the catheter was pointing towards the lung than when pointing away from the lung or perpendicular to the trachea [121 (41) and 69 (24) ml, respectively, \( P < 0.01 \)]. With the conventional ventilator, changes in \( V_T \) at different direction of catheter insertion were much less [222 (81) ml catheter pointing towards the lung, 229 (121) ml perpendicular to the trachea, and 187 (97) ml away from the lung].

Conclusions. Our result demonstrated that PTJV was effective only when the catheter was pointing towards the lung and requires high operating pressure. A conventional ventilator can generate reasonable minute ventilation through the transtracheal catheter less dependent on directions of catheter insertion and should be considered during emergent PTV.

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

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Despite advances in airway management technology, difficult mask ventilation and tracheal intubation still challenge anaesthesia providers.¹ Even though these events do not occur frequently, an overall 5.8% incidence of difficult intubation during anaesthesia² and 0.15% of impossible mask ventilation,³ ‘cannot intubate and cannot ventilate’ or CICV are nearly always catastrophic. The inability to provide life-sustaining gas exchange during CICV was the number one cause of major complications related to airway management in anaesthesia⁴ and has been responsible for up to 30% of deaths attributed to anaesthesia.⁵ ⁶

Percutaneous transtracheal jet ventilation (PTJV) has been recommended in the ASA and Difficult Airway Society guidelines for management of the difficult airway during CICV to provide emergent oxygenation.⁷ ⁸ However, there are still some circumstances that a jet ventilator may not be immediately available when an emergent airway happens, including the operating theatre in some rural and remote health institutions⁹ and critical care units in the USA¹⁰ and in Europe.¹¹ On the other hand, since PTJV is not routinely used, whether clinicians can correctly use it in a timely manner is not known and the high driving pressure used during PTJV has been shown to be associated with pneumothorax, emphysema, and other forms of complications.⁴ ¹² Therefore, alternative approaches which are easy to use and immediately available as a rescue technique for CICV are still needed. A self-inflating resuscitation bag or oxygen flush from an anaesthesia machine via cannula
cricothyroidotomy has been previously studied in lung models with its efficiency still not determined.\textsuperscript{13-16}

A regular anaesthesia or intensive care unit (ICU) ventilator is commonly available to anaesthesia care providers. In addition, with its pressure alarm system and continuous monitoring of expiratory flow and end-tidal CO\textsubscript{2}, a conventional ventilator allows clinicians to recognize in a timely manner if the catheter is inserted in the lumen of the trachea. We hypothesized that a conventional ventilator, vs a jet ventilator, can generate reasonable minute alveolar ventilation (MAV) and adequate oxygenation without exposing the patient to the high pressure required with jet ventilators. Because the need for emergent percutaneous transtracheal ventilation (PTV) is unpredictable, human studies to compare the efficacy of these two approaches are not feasible. Therefore, we tested this hypothesis in a lung model. Using this model, the lung compliance, airway pressure, and anatomic dead space can be precisely controlled to compare the efficacy of PTV with a jet and a conventional ventilator.

Methods
A lung model (Dual adult TTL training/test lung, Model 1600, Michigan Instruments Inc., MI, USA) with functional residual capacity of 1020 ml was connected to the distal end of an artificial trachea with anatomical dead space 150 ml. The respiratory system compliance was set at 20, 40, and 60 ml cm\textsuperscript{-2}. The proximal end of the trachea was connected to a Pneuflo\textsuperscript{TM} resistor (5 cm H\textsubscript{2}O litre\textsuperscript{-1} min\textsuperscript{-1}) and a PEEP valve with pressures of 7.5 and 15 cm H\textsubscript{2}O simulating two levels of critical opening pressure of the upper airway or a sealing cap simulating complete upper airway obstruction. The PEEP valve was unidirectional allowing out flow of air only. A 14 G i.v. catheter of 1 in length was inserted through the wall of the artificial trachea ensuring 50\% (75 ml) of the anatomic dead space was on each side of the catheter. This setting was intended to simulate the situation where a catheter is inserted through the cricothyroid membrane dividing the anatomical space \~50\% on each side of the catheter insertion. The catheter was connected either directly to a jet ventilator or to an ICU ventilator via a 3 ml plastic syringe connected to an adaptor of a 7.0 mm inner diameter tracheal tube (Fig. 1).

Ventilators
The jet ventilator (Acutronic Monsoon Deluxe Jet Ventilator, Autronic Medical Systems AG, Hirzel, Switzerland) was operated at 50 pounds in\textsuperscript{-2} (344.7 kPa) using the hospital central air supply system. The distal end of the jet ventilator hose was connected to the 14 G i.v. catheter. The insertion direction of the catheter was perpendicular to the tracheal axis, pointing towards the lung at an angle of 45\degree (10\textsuperscript{10}) to the tracheal axis and pointing away from the lung at an angle of 45\degree (10\textsuperscript{10}) to the tracheal axis. Ventilation was performed at rates of 6, 8, and 10 bpm. I:E ratios of 1:1, 1:2, and 1:3 were achieved manually by the operator guided by a timer.

Jet ventilation with a second 14 G i.v. catheter inserted parallel and adjacent to the first catheter was evaluated to determine if jet ventilation generated air trapping and auto-PEEP with a single catheter. The second catheter was kept open to ambient pressure during the entire respiratory cycle and functioned as a venting catheter.

The ICU ventilator (Puritan Bennett\textsuperscript{TM} 840 Ventilator, Mallinckrodt Inc., Carlsbad, CA, USA) was operated in the pressure-controlled mode. Exhaled tidal volumes were measured with the ICU ventilator at peak inspiratory pressures (PIP) of 40, 60, 75, and 90 cm H\textsubscript{2}O, I:E ratios of 1:1, 1:2, and 1:3, and respiratory rates (RRs) of 6, 8, and 10 bpm with the catheter inserted perpendicularly to the trachea axis, pointing towards and away from the lung.

Flow/pressure sensor
A flow/pressure sensor (NICO Cardiopulmonary Management System, Model 7300, Respironics Corp., Murrysville, PA, USA) was placed between the distal end of the artificial trachea and the model lung (Fig. 1). Pressure and gas flow were continuously measured through the sensor at a sampling rate of 100 Hz. The expiratory tidal volumes (\(V\text{\textsubscript{E}}\)) measured with the sensor were automatically recorded. The sensor was automatically calibrated before data collection.

Data collection and statistics
Data from each experimental setting were continuously collected using the NICO Analysis Plus data management system. However, data were analysed only after measurement reached a steady state at each setting. The steady state was generally achieved after two to three breaths. After reaching steady state, data from three consecutive breaths were analysed and data were then averaged at each setting. Data are expressed as mean (SD). The PASW statistics package (IBM Corporation, New York, NY, USA) was used for statistical analysis. For main effects, the general linear model for univariate analysis was used to identify the significance of different direction of catheter insertion, PEEP level, I:E ratio, RR, and compliance on expiratory tidal volume generated by the jet and ICU ventilators. A \(P\)-value of <0.05 was considered statistically significant.

Results
The mean \(V\text{\textsubscript{T}}\) generated by the jet and ICU ventilators at three different directions of catheter insertion (towards the lung, away from the lung, and perpendicular to the tracheal axis), at critical opening pressure of 7.5 and 15 cm H\textsubscript{2}O and I:E ratio of 1:1 are presented in Figure 2. When the catheter was directed towards the lung, jet ventilation resulted in an average \(V\text{\textsubscript{T}}\) of 817 (336) ml and a maximal \(V\text{\textsubscript{T}}\) of 1496 ml, which were significantly larger than those obtained when the catheter was directed away from the lung [121 (41) ml] or perpendicular to the tracheal axis [69 (24) ml] (\(P<0.01\)). With the ICU ventilator, \(V\text{\textsubscript{E}}\)’s were 187 (97), 229 (121), and 222 (81) ml when the catheter was pointing away from the lung, perpendicularly to the tracheal axis,
and towards the lung, respectively \( (P < 0.01) \). The difference in the \( V_T \) obtained at the three directions was <20%. At critical opening pressure of 15 cm H\(_2\)O, both ventilators generated larger \( V_T \) than at 7.5 cm H\(_2\)O \( (P < 0.01) \).

Increasing RR from 6 to 10 bpm, which reduced inhalation time of each breath from 5 to 3 s at \( I:E \) ratio of 1:1, led to a decrease in \( V_T \) from 852 (457) to 633 (281) ml and from 245 (102) to 201 (53) ml with the jet and ICU ventilators, respectively, when the catheter pointed towards the lung. However, the minute ventilation (MV) increased from 5.1 (2.7) to 6.3 (2.8) litre min\(^{-1}\) with the jet ventilator and from 1.5 (0.6) to 2.0 (0.5) litre min\(^{-1}\) with the ICU ventilator as RR increased from 6 to 10 bpm when the catheter was pointed towards the lung (Fig. 3). The average MV generated by the ICU ventilator at an RR of 10 bpm, \( I:E \) ratio of 1:1, and obstruction level of 15 cm H\(_2\)O was 2.5 (0.5) litre min\(^{-1}\).

With the ICU ventilator, increasing PIP from 40 to 90 cm H\(_2\)O led to an increase in \( V_T \) of 23.5% \( (P < 0.01) \) from 167.9 to 207.3 ml. Higher \( I:E \) ratio, that is, longer inhalation time, resulted in increases in \( V_T \) \( (P < 0.001) \) (Fig. 4).

The addition of a second catheter during jet ventilation resulted in an increase in \( V_T \) \( (146 (91) \text{ and } 236 (158) \text{ ml, at critical opening pressure of } 7.5 \text{ and } 15 \text{ cm } H_2O, \text{ respectively}) \) when the catheter was perpendicular to the trachea. The \( V_T \) was 10.2 times and 3.6 times larger than the corresponding \( V_T \) obtained with a single catheter at obstruction levels of 7.5 and 15 cm H\(_2\)O, respectively \( (P < 0.001, \text{ Fig. 5}) \).

During complete upper airway obstruction, significant air trapping occurred with the manual jet ventilation even after two consecutive breaths at a ventilation rate of 10 bpm and \( I:E \) ratio of 1:2. The amount of air accumulated in the model lung after two breaths was 2162 (10) ml at a compliance of 40 ml cm H\(_2\)O\(^{-1}\) and no exhaled air flow was recorded. The peak airway pressure measured from the NICO sensor was 67.4 (0.4) cm H\(_2\)O after two consecutive breaths. With the conventional ventilator at the same \( I:E \) ratio (1:2) and ventilation rate (10 bpm) and at a driving pressure of 75 cm H\(_2\)O, the amount of air accumulated in the model lung was 192 (13) and 552 (30) ml and the total ventilation 256 (28) and 1027 (58) ml after two and 10 consecutive breaths, respectively. The peak airway pressures were 6.9 (0.5) and 15.8 (0.7) cm H\(_2\)O with the jet ventilator after two and 10 consecutive breaths, respectively.

**Discussion**

The major findings of this study are: (i) manual jet ventilation through a single transtracheal catheter was effective but
produced a large \( V_T \) if the catheter was inserted with its tip pointing towards the lung; (ii) the ICU ventilator produced reasonable \( V_T \) less dependent on the direction of the catheter insertion requiring PIP in the range obtainable with a standard ICU ventilator; and (iii) the addition of a second catheter (vent) during PTJV resulted in an increase in \( V_T \) even when the catheter was inserted perpendicularly to the trachea. Our results demonstrated that with the jet ventilator, the direction of catheter insertion is critical to achieving effective ventilation during PTJV. If the catheter is inserted perpendicularly to the axis of the trachea or pointing away from the lung, the efficacy of ventilation is markedly diminished. The large tidal volume generated by the jet ventilator when the catheter is pointing towards the lung in our model is most likely related to the high velocity flow that pushes gas into the lung. Because a unidirectional PEEP valve was used in our lung model which represents the critical opening pressure of the upper airway obstruction and allows outflow only, there was no entrainment of air or ‘Venturi effect’\(^{17}\) in our simulation. The one-way valve was used to simulate the common clinical situation where it is difficult or impossible to force oxygen under positive pressure into the lung, but egress of gas is relatively unimpeded at the critical opening pressure of the upper airway. This likely simulates a true CICV scenario as CICV cannot co-exist with a patent upper airway which allows entraining air by Venturi effect during PTJV.

PTV via a conventional ventilator has been tested in an animal model by Zornow and colleagues.\(^{14}\) Their results showed that PTV via a conventional ventilator was able to reverse pre-existing hypoxia, but no detectable effective alveolar ventilation was observed and the increase in the arterial partial pressure of oxygen was slower than that achieved with PTJV. It should be noted that the experimental set up of Zornow and colleagues\(^{14}\) applied a one-way valve at the proximal end of the tracheal tube to simulate upper airway, which did not include the component of expiratory airway obstruction. In our study, the critical opening pressure of the upper airway was set at a clinically relevant level by using a one-way PEEP valve to simulate a scenario of CICV when PTJV is used. We obtained an average MAV of 1.25 litre min\(^{-1}\) at a ventilation rate of 10 cycles min\(^{-1}\), an \( I:E \) ratio of 1:1, and PIP of 40–90 cm H\(_2\)O. At PIP of 90 cm H\(_2\)O, the highest pressure we tested, MAV averaged 2.35 litre min\(^{-1}\). If one assumes that normal MAV for a 70 kg human is 3.5 litre min\(^{-1}\), a conventional ventilator can produce 67% of the normal MAV through a large-pore catheter. Therefore, we consider the MAV generated by a conventional ventilator via a transtracheal catheter a reasonable value and oxygenation should be adequate if \( O_2 \) supplement
is provided. In addition, the $V_T$ produced with the ICU ventilator is not sensitive to the direction of catheter insertion. This is likely because the single catheter functions as a channel for inspiration and expiration. Our result during complete upper airway obstruction proved that a certain amount of expiration could be generated through the transtracheal catheter with the conventional ventilator but not with the jet ventilator. Furthermore, end-expiratory airway

**Fig 3** MV generated by the jet and ICU ventilators when the catheter was inserted towards the lung. Data shown are obtained at an $I:E$ ratio of 1:1. Data in (a) and (b) were collected with the jet ventilator at PEEP 15 and 7.5 cm H$_2$O, respectively. Data in (c) and (d) were collected with the ICU ventilator at PEEP 15 and 7.5 cm H$_2$O, respectively.

**Fig 4** Exhaled tidal volumes generated by the ICU ventilator through a transtracheal catheter at an RR of 10 bpm when the catheters was inserted towards the lung. Data in (a) and (b) were collected at PEEP 15 and 7.5 cm H$_2$O, respectively. Data are pooled data obtained at three compliance levels (20, 40, and 60 ml cm H$_2$O$^{-1}$).
pressure was dramatically increased with PTJV, over 60 cm H₂O after just two consecutive breaths. At such a high level of pressure, venous blood return must be diminished. In contrast, the expiratory airway pressure was 16 cm H₂O after 10 consecutive breaths when the conventional ventilator was used. This result implies that a conventional ventilator may be more advantageous than a jet ventilator when complete upper airway obstruction exists.

We further tested our hypothesis by introducing a second catheter during jet ventilation. Insertion of a second catheter left open to ambient pressure during the entire breathing cycle and was inserted adjacent and parallel to the primary catheter. Data shown are the average of three breaths at each setting. Data in (a) and (a) were collected using a single catheter at PEEP 15 and 7.5 cm H₂O, respectively. Data in (c) and (a) were collected using two catheters at PEEP 15 and 7.5 cm H₂O, respectively.

There are several limitations of this study. First, the study was not conducted in patients, although the mechanical properties of the model lung were precisely controlled to simulate those of an adult patient in a range of possibilities encountered by anaesthesia providers. Results of this study should be cautiously extrapolated to clinical practice until further study in patients is conducted. Secondly, only two pressure levels of critical opening pressure of the upper airway, 7.5 and 15 cm H₂O, were tested in our lung model. Since there is no existing study reporting retrograde opening pressure of upper airway obstruction in patients, we chose these two levels of pressure based on studies in sleep apnoea which revealed that the critical opening pressure of the upper airway is 10.8 (2.4) cm H₂O¹⁸ and a PEEP level of 15 cm H₂O could maintain the upper airway open in the majority of patients with sleep apnoea treated with nasal continuous positive airway pressure.¹⁹ Thirdly, since the model lung and artificial trachea used in this study only simulated an adult patient, the conclusions from this study may not apply to paediatric patients since the
respiratory mechanics of a paediatric patient are very different from those of an adult. Finally, this study was performed with an ICU ventilator, not an anaesthesia machine. However, the ventilator settings we used in this study can be obtained with any modern anaesthesia machine.

**Conclusion**
Our results using a model lung demonstrate that manual jet ventilation through a transtracheal membrane catheter was effective only if the catheter was inserted pointing towards the lung and requires high operating pressure. A conventional ventilator can generate reasonable alveolar ventilation through the transtracheal catheter less dependent on the directions of catheter insertion and should be considered during transtracheal ventilation. Insertion of a second catheter as a vent reduces auto-PEEP and improves ventilation during PTJV. Further study is needed to confirm these findings in patients.

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**Declaration of interest**
R.M.K. is a consultant for Covidien/Newport medical and has received honorarium from Maquet for lecturing.

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