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Percutaneous transtracheal ventilation in an obstructed airway model in post-apnoeic sheep

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Editor's key points

- Percutaneous ventilation is recommended in 'can't intubate, can't oxygenate' emergency situations.
- This study compared physiological outcomes using the Ventrain and Manujet devices in a sheep obstructed airway model.
- Rapid re-oxygenation was achieved with both devices but there were marked differences between them.
- Understanding of device differences may help clinicians to select the most suitable percutaneous ventilation devices.

Background. Temporizing oxygenation by percutaneous transtracheal ventilation (PTV) is a recommended emergency technique in 'can't intubate, can't oxygenate' (CICO) situations. Barotrauma risk increases if expiration is obstructed. The Ventrain® is a new PTV device that assists expiration. Our aim was to compare key physiological outcomes after PTV with the Ventrain and the Manujet® in a large animal obstructed airway model.

Methods. Five anaesthetized sheep had post-apnoea PTV performed for 15 min using the Ventrain or Manujet with the proximal airway completely or critically obstructed, yielding four ventilation protocols per sheep. After apnoeic desaturation (Sa_{O_2} 70%), a 4 s rescue breath was delivered. Subsequent 2 s breaths were delivered whenever the airway pressure fell <10 cm H_2O.

Results. Both devices achieved rapid re-oxygenation. There were marked device differences (Ventrain *vs* Manujet) in peak airway pressures with rescue (16 *vs* 40 cm H_2O) breaths, minute ventilation (4.7 *vs* 0.1 litre min^{-1}), and end-protocol pH (7.34 *vs* 7.01). There was no clinical evidence of barotrauma in any sheep after any ventilation protocol. An equilibration phase prevented large subatmospheric intrathoracic pressure development with Ventrain ventilation.

Conclusions. The Ventrain provided stable oxygenation and effective ventilation at low airway pressures during emergency PTV in critically obstructed airways. The Manujet provided effective temporizing oxygenation in this situation with hypoventilation necessary to minimize barotrauma risk. The nature and extent of airway obstruction may not be known in a CICO emergency but an understanding of device differences may help inform optimal ventilation device and method selection.

Keywords: airway management; emergencies; jet ventilation, transtracheal

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Temporizing oxygenation by percutaneous transtracheal ventilation (PTV) using a narrow bore transtracheal catheter and a high-pressure oxygen source is a recommended emergency technique when difficult airway situations deteriorate into life-threatening 'can't intubate, can't oxygenate' (CICO) crises.[1 2] Elective PTV can be performed safely in experienced centres using automated jet ventilators[3] but serious barotrauma-related morbidity can occur.[4 5] The procedural risks of PTV are likely to be increased in a CICO crisis. Limited information is available to optimize patient outcomes in this uncommon emergency situation. It is acknowledged that oxygenation rather than ventilation is the priority[1 2] and that high-pressure oxygen sources are necessary to overcome resistance to flow in narrow catheters.[6 7] Alignment of the transtracheal catheter in the long axis of the tracheal lumen results in more effective ventilation than when the catheter is positioned in the lumen perpendicular to the posterior tracheal wall.[8] It is essential to confirm that the transtracheal catheter is in the tracheal lumen before oxygen delivery.[3 5] The degree of airway obstruction, in relation to gas egress, influences both inspiratory volume and the potential for barotrauma.[9] There is a risk of severe barotrauma in the totally obstructed airway.[10–12] Bilateral pneumothoraces during emergency jet ventilation have been reported.[13] Long expiratory times and low respiratory rates (RRs) are protective against barotrauma but reduce carbon dioxide clearance.[10] Rapid temporizing re-oxygenation of apnoeic sheep with a single breath from a high-pressure source via a transtracheal catheter with emphasis on minimizing subsequent ventilation to avoid barotrauma has been described.[14]

The Manujet® (VBM Medizintechnik GmbH, Sulz am Neckar, Germany) is a pressure-regulated jet ventilation device that is

recommended for emergency PTV.[7] When connected to a 4 bar oxygen supply, the delivery pressure can be varied from 0 to 4 bar. It delivers 250 ml O_2 s^{-1} through a 2 mm diameter catheter when set at 1 bar.[12] It is manually operated and has no expiratory or automatic shut off functions. It therefore has a low margin of safety in a completely obstructed airway.[12]

The Ventrain® (Dolphys Medical B.V., Eindhoven, The Netherlands) is a hand-held single-use flow-regulated ventilation device designed for use with a 2 mm diameter transtracheal catheter in patients with complete airway obstruction.[15 16] The device contains a ventilation ejector positioned between an oxygen inlet and an exhaust channel (Fig. 1). The ejector has a sideport that connects to the transtracheal catheter. A bypass channel, allowing room air to enter the ejector, acts as an on/off switch. The exhaust and bypass channels can be occluded manually at their respective apertures. The pattern of occlusion determines the direction of flow in the sideport (Fig. 2). In inspiration, oxygen flow is directed into the sideport channel by occlusion of both apertures. When only the bypass aperture is occluded, expiratory ventilation assistance occurs as subatmospheric pressure is generated in the sideport. With neither aperture occluded, air is drawn into the injector through the bypass channel and oxygen flows straight through the device. In this situation, there is no significant pressure effect at the transtracheal catheter tip and patient airway pressure can equilibrate with atmospheric pressure. When the inlet tube is connected to a pressure-regulated oxygen flowmeter set at 15 litre min^{-1}, the device produces flow through a 2 mm diameter catheter of ~250 ml s^{-1} in both inspiration and expiration.[15 16] Bench testing using a lung model suggests that the device should provide effective ventilation at low insufflation pressures in a patient with complete airway obstruction.[15]

There is currently little experimental or clinical literature available to inform selection of transtracheal ventilation devices in a CICO situation. We hypothesized that post-apnoeic transtracheal oxygenation would be achievable in the obstructed airway with both the Manujet and Ventrain devices, but would be achieved with lower airway pressures using the Ventrain compared with the Manujet. To test this hypothesis, we assessed differences between our primary outcome measures of oxygenation, airway pressure, and carbon dioxide clearance in post-apnoeic sheep using either the Manujet or Ventrain device.

Methods

All experiments were conducted in accordance with local institutional ethics approval (University of Otago Wellington Animal Ethics Committee Approval 5–12).

Six healthy 2-yr-old Romney cross ewes were obtained from a commercial farm source and housed in a custom-built large animal facility at the University of Otago, Wellington. On admission, animals were weighed and unique identifiers established. Animals were housed in group pens and cared for in accordance with standard large animal care practice, with free access to feed (hay and commercial sheep pellets) and water. The facility is temperature controlled (18°C) and operates a 12:12 light:dark cycle.

On the day before anaesthesia, feed but not water was withdrawn and wool on the anterior neck was clipped. One hour before anaesthesia, 10 mg i.m. morphine was administered. Jugular venous access was obtained and anaesthesia induced with i.v. ketamine 10 mg kg^{-1} and diazepam 0.5 mg kg^{-1}. I.V. rocuronium 0.5 mg kg^{-1} was administered to facilitate tracheal intubation with a size 9.0 cuffed tracheal tube. A large bore oro-gastric tube was passed to empty ruminal contents. Anaesthesia was maintained with isoflurane in 100% oxygen during controlled ventilation and with propofol 120–150 μg kg^{-1} min^{-1} during periods of apnoea and jet ventilation. Analgesia was maintained with 0.1 mg kg^{-1} increments of morphine as clinically indicated. The adequacy of surgical anaesthesia was constantly assured by titration of anaesthetic agents and narcotics in relation to monitoring of end-tidal isoflurane, haemodynamic variables, and clinical signs (blink reflex, jaw tone, movement, and respiratory effort). Additional increments of rocuronium 0.25 mg kg^{-1} were given at the start of each ventilation protocol. Normal saline 10 ml kg^{-1} was given at induction and then infused at

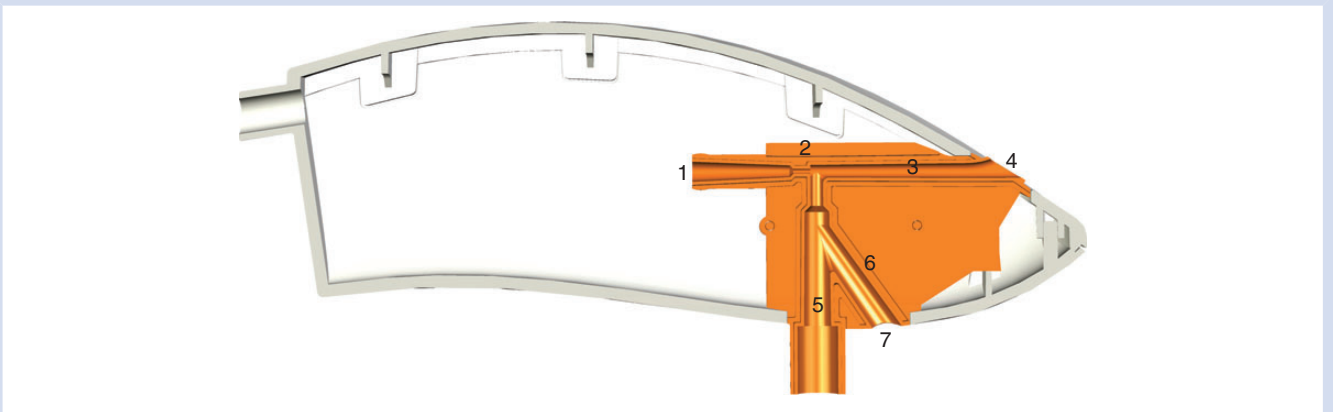

Fig 1 Schematic depiction of the ventilatory ejector within the Ventrain device showing: 1, oxygen inlet channel; 2, jet nozzle; 3, exhaust channel; 4, exhaust channel aperture; 5, sideport; 6, bypass channel; 7, bypass channel aperture.

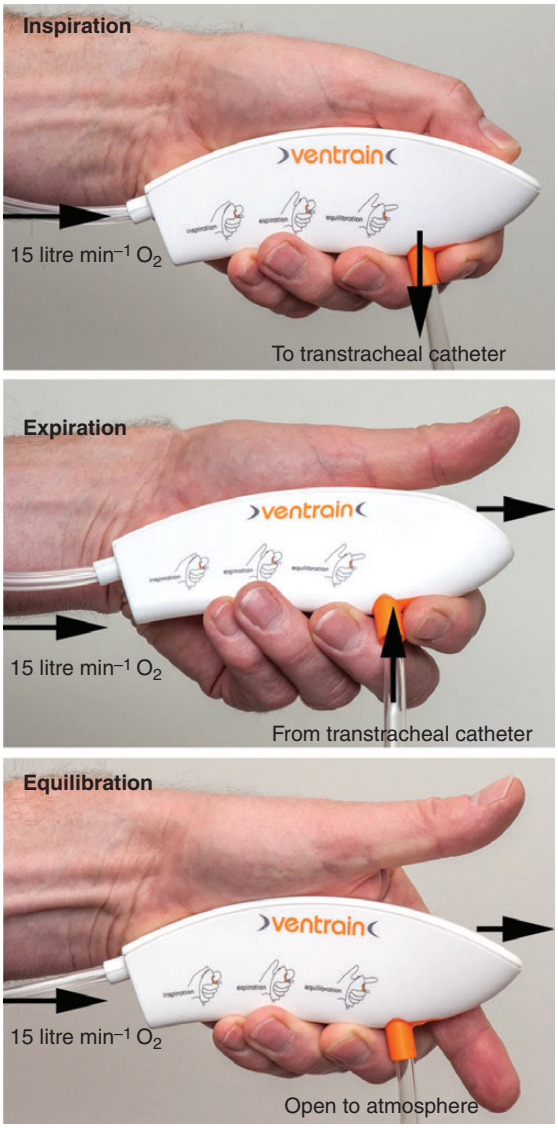

Fig 2 The three phases of ventilation using the Ventrain device.

3 ml kg^{-1} h^{-1}. Central venous (internal jugular) and peripheral arterial (hind tarsal) lines were placed.

A four-way tracheal tube connector from an Arndt Endobronchial Blocker set (Cook Critical Care, Bloomington, IN, USA) was modified to enable four airtight connections using components from an Ayres t-piece kit (Intersurgical Ltd, Wokingham, UK) and a silicon catheter mount (VBM Medizintechnik GmbH). Swivel connections were removed and replaced with female (to tracheal tube) and male (to anaesthesia circuit or occluding cap) sections of the catheter mount. The bronchoscope port was replaced with a 15 mm elastomeric connector into which the de-flanged barrel of a 3 mm luer lock syringe was inserted. This was connected via fluid-filled non-compressible tubing to a P23AC Statham pressure transducer (Statham Laboratories, Puerto Rico) for continuous airway pressure monitoring. The existing endobronchial blocker port provided an airtight seal when a flexible bronchoscope (Ambu® aScope™ Ambu Inc., Glen Burnie, MD, USA) was inserted. This apparatus, connected to a size 9.0 tracheal tube with cuff inflated inside the barrel of a capped 20 ml syringe, was airtight when pressurized to 500 cm H_2O during bench testing.

Trans-illumination from the bronchoscope was used to position the tip of a size 9.0 tracheal tube 2–3 cm distal to the cricoid cartilage. A small skin incision was made between mid-tracheal rings. A 2 mm internal diameter, 7.5 cm length emergency transtracheal airway catheter (ETAC) (Cook Critical Care) was positioned in the trachea with bronchoscopic guidance to ensure orientation in the long axis of the trachea and integrity of the posterior and lateral tracheal walls. A 2.1 mm internal diameter, 4.5 cm length 14G i.v. catheter (BD Insyte, Sandy, UT, USA) was similarly positioned in a mid-tracheal space proximal to the ETAC. Both catheters were sutured in place. A continuous video-bronchoscopic view that included both transtracheal catheters was on-screen throughout the ventilation protocols.

Continuous recorded monitoring of heart rate, arterial blood pressure, airway pressure, and end-tidal CO_2 was performed using a PowerLab Physiological Data Monitoring System (ADInstruments, Dunedin, New Zealand). Monitoring of peripheral (buccal mucosa) oxygen saturation, central venous pressure, and gas analysis was performed using the Datex AS3 monitor on an Ohmeda Excel 210 SE anaesthesia machine (GE Healthcare, USA). Oxygen saturation data were manually recorded at 1 min intervals during ventilation protocols. Blood gas analysis was performed using calibrated iStat cartridges (CG8$^+$ Abbott Laboratories, USA).

A single pilot sheep was used to develop the rescue ventilation methodology. All ventilation protocols were completed in the pilot animal. Initial use of the Ventrain with the airway completely obstructed resulted in significant subatmospheric airway pressure. This briefly approached −200 cm H_2O and was associated with a hypertension of 180/120 mm Hg. The initial technique did not include an equilibration phase in which both apertures on the device are unobstructed, resulting in sustained periods of assisted expiration. The ventilatory pattern was changed to 2 s inspiration, 2 s assisted expiration, and 2 s equilibration and this problem was not subsequently encountered. No clinical consequences of this episode were evident, and subsequent ventilation protocols in the pilot sheep were performed without incident.

Four ventilation protocols were performed in each study sheep. These involved ventilation via the ETAC with the Manujet [proximal 14G transtracheal catheter either capped for complete airway obstruction (MO) or open to air to allow passive expiration (MP)] or the Ventrain [proximal 14G transtracheal catheter either capped (VO) or open to air (VP)]. The sequence of ventilation protocols for each sheep was determined by blind selection of ventilation codes by a member of technical staff not actively involved in the study. The Manujet was connected to a 4 bar piped oxygen supply and set at 1 bar. The Ventrain was connected to a flow meter set at 15 litre min^{-1} supplied by pipeline oxygen at 4 bar.

Anaesthetized study sheep were ventilated (tidal volume 5–10 ml kg^{-1}, positive end expiratory pressure 4–10 cm H_2O, peak

inspiratory pressure 10–30 cm H_2O, $F_{I_{O_2}}$ 1.0) to an end-tidal CO_2 between 30 and 40 mm Hg and a blood gas was obtained. Integrity of the tracheal tube cuff was checked *in situ* by pressurizing the circuit to 30 cm H_2O. The anaesthetic circuit was disconnected and apnoea, with the airway open to room air, was permitted until the Sa_{O_2} decreased below 70%. Another blood gas was taken and the airway was obstructed with the occlusion cap. Transtracheal rescue ventilation was initiated with a 4 s breath. Subsequent inspiratory periods of 2 s duration were delivered whenever the airway pressure decreased <10 cm H_2O. The time interval between first and second breaths was derived from the PowerLab monitoring system. Minute ventilation was derived from the measured RRs, the published device flow rates,[12 16] and the calculated tidal volume based on manual control of inspiration.

At the end of each PTV protocol, the occlusion cap was removed from the four-way tracheal tube connector and the anaesthesia circuit was re-attached. Steady-state ventilation was re-established and maintained for at least 15 min before beginning the next protocol. Criteria for protocol interruption were inability to maintain oxygen saturation $>80\%$ for >1 min, inability to re-establish baseline ventilation parameters, and the occurrence of clinically detectable barotrauma. This was monitored by inspection for subcutaneous or bronchial mucosa emphysema and monitoring of ventilatory and haemodynamic parameters.

At the conclusion of the experiment, animals were killed with an overdose of pentobarbital.

PowerLab data were analysed using LabChart7 (ADInstruments). All analysed traces were free of movement artifact or signal degradation. Physiological outcome data were analysed using JMP v.10 (SAS Institute Inc., Carey, NC, USA). Unless otherwise indicated, data are shown as median (range).

Results

All ventilation protocols were completed. There was no clinical evidence of barotrauma or haemodynamic instability during or after any ventilation protocol. The median (range) weight of the study sheep was 55 (50–61) kg.

A single post-apnoea 4 s breath increased oxygen saturations to at least 90% within 1 min of delivery in all sheep regardless of device used. Stable oxygenation was achieved in both Ventrain groups and in the MP group with little difference in Po_2 after 15 min of PTV (Table 1). Brief desaturation was evident before delivery of secondary breaths in the MO group and the Po_2 at the end of 15 min was markedly lower than in the three other groups (Table 1, Fig. 3). The median (min, max) time to the second breath in the MO group was 7 min 20 s (6 min 15 s, 8 min 12 s). Representative patterns of airway pressure, oxygen saturation, and arterial pH from single sheep are shown (Figs 4 and 5).

The range of airway pressures generated differed between devices. Maximum airway pressures with both the initial breaths and the secondary breaths were higher in the Manujet groups (Table 1). Minimum airway pressures were lower in the Ventrain groups with modest negative pressures generated (Table 1).

Minute ventilation was markedly higher in the Ventrain groups compared with the Manujet groups (Table 1). Arterial blood gas analysis at the end of the ventilation protocols showed greater CO_2 clearance and higher pH in the Ventrain groups (Table 1).

Discussion

Rapid re-oxygenation using a 2 mm diameter transtracheal catheter was achieved in post-apnoeic sheep with total or critical airway obstruction using both the Ventrain and Manujet devices. The Ventrain achieved this objective and could maintain oxygenation, with lower airway pressures and near normal minute ventilation.

The effectiveness of conventional PTV and the associated risk of barotrauma are influenced by the degree of proximal airway obstruction and whether the obstruction is fixed or dynamic. Tidal volume and minute ventilation increase during PTV as proximal airway obstruction increases.[9] With

Table 1 Blood gas analysis, maximum and minimum airway pressures, and minute ventilation after 15 min of post-apnoea transtracheal ventilation in sheep with complete or partial airway obstruction using either a Manujet or Ventrain device. $n=5$. RR, respiratory rate; MV, minute ventilation; pH (change), difference in pH from the end of the apnoeic period to the end of the transtracheal ventilation period

	Manujet		Ventrain	
	Complete obstruction Median (min, max)	Partial obstruction Median (min, max)	Complete obstruction Median (min, max)	Partial obstruction Median (min, max)
Pa_{O_2} (kPa)	23 (11, 35)	57 (44, 69)	48 (29, 82)	53 (34, 78)
Initial breath P_{max} (cm H_2O)	40 (33, 35)	43 (38, 48)	16 (13, 31)	12 (10, 29)
Secondary breath P_{max} (cm H_2O)	21 (13, 32)	32 (17, 47)	18 (16, 27)	11 (7, 20)
Secondary breath P_{min} (cm H_2O)	9 (5, 10)	6 (0, 9)	−1 (−17, 4)	−1 (−9, 4)
RR (bpm)	0.2 (0.2, 0.3)	1.3 (1.0, 4.1)	9.3 (4.6, 10.6)	9.0 (5.8, 10.1)
MV (litre min^{-1})	0.14 (0.14, 0.16)	0.70 (0.54, 2.06)	4.70 (2.34, 5.34)	4.54 (2.94, 5.06)
pH (final)	7.01 (6.98, 7.02)	7.18 (7.04, 7.28)	7.34 (7.22, 7.36)	7.28 (7.18, 7.36)
pH (change)	−0.14 (−0.20, −0.12)	0.01 (−0.04, 0.08)	0.17 (0.16, 0.22)	0.18 (0.12, 0.20)
Pa_{CO_2} (kPa)	15 (13, 17)	10 (7, 14)	7 (6, 9)	7 (6, 10)

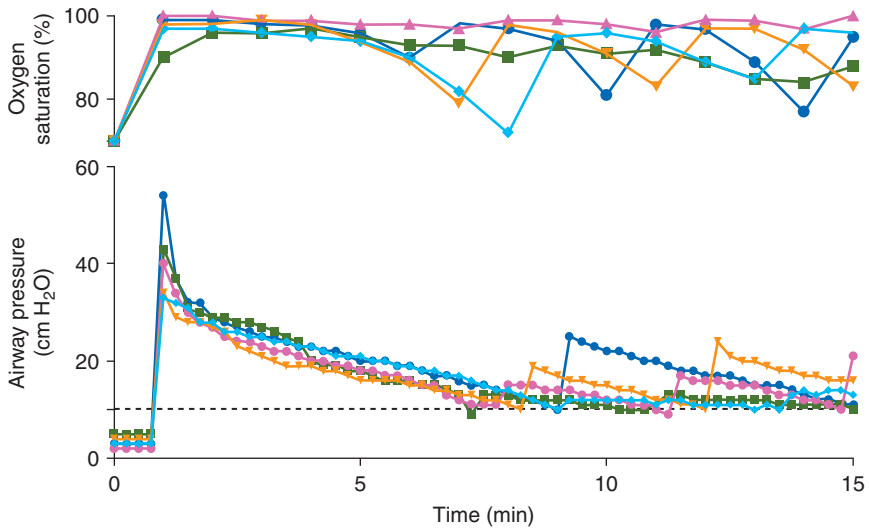

Fig 3 Oxygen saturation and airway pressure in five study sheep with completely obstructed airways undergoing post-apnoea transtracheal ventilation using a Manujet (MO group). Individual sheep are identified by colour. The median (min, max) time to the second breath was 7 min 20 s (6 min 15 s, 8 min 12 s). The single initial rescue breath provides a 're-oxygenation window' of at least 5 min which may be sufficient time in clinical practice to resolve the CICO situation without further barotrauma risk.

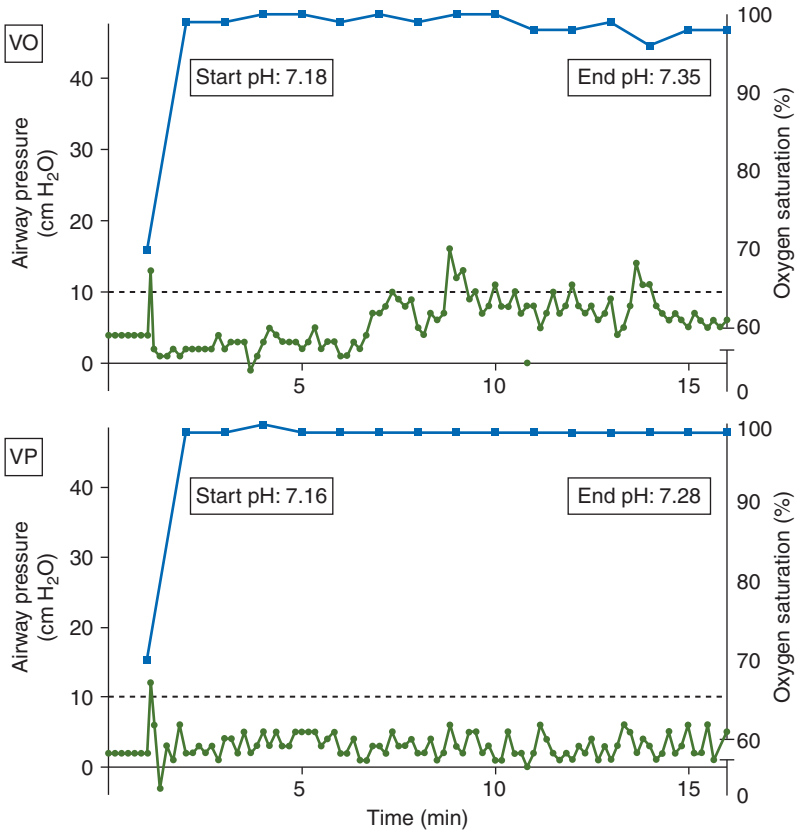

Fig 4 Airway pressure, oxygen saturation, and arterial pH from a single representative study sheep undergoing post-apnoea transtracheal ventilation using a Ventrain with airway either completely obstructed (VO) or limited to a 2.1 mm transtracheal catheter (VP).

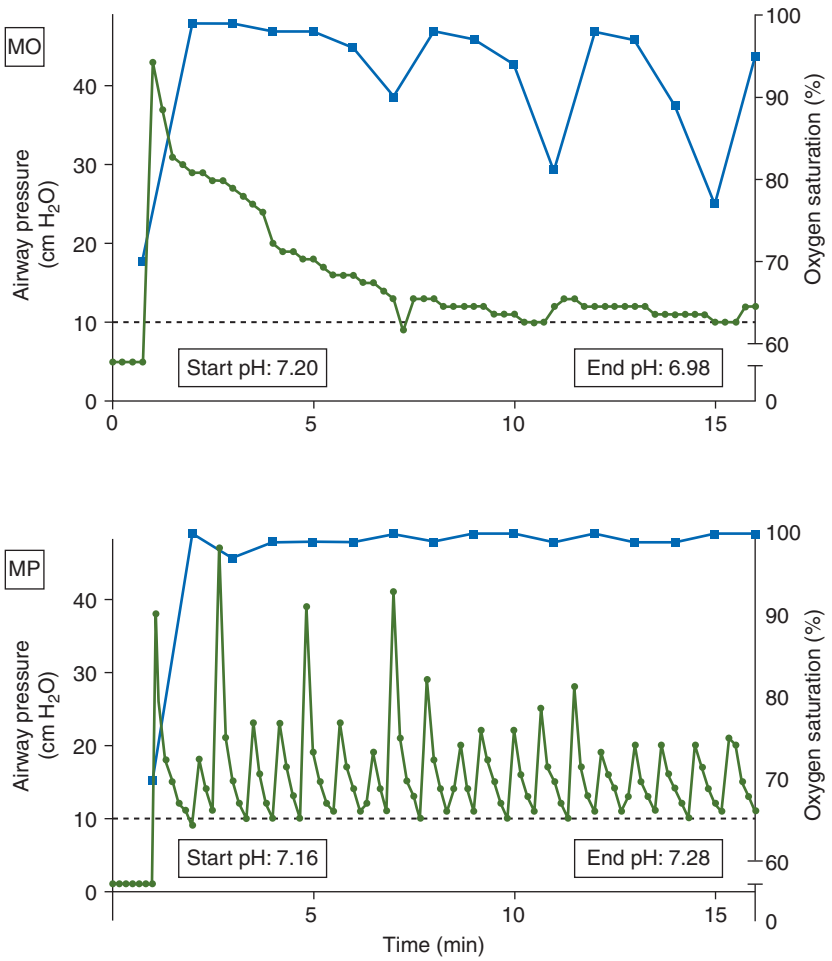

Fig 5 Airway pressure, oxygen saturation, and arterial pH from a single representative study sheep undergoing post-apnoea transtracheal ventilation using a Manujet with airway either completely obstructed (MO) or limited to a 2.1 mm transtracheal catheter (MP).

fixed airway obstruction, air trapping occurs as total obstruction is approached and the risk of barotrauma is substantial as lung volume exceeds total lung capacity.[9 11] Dynamic expiratory obstruction may be protective during PTV when the critical opening pressure for expiration is reached. This is estimated to be 10.8 (2.4) cm H_2O from studies in obstructive sleep apnoea patients.[8 17] The risk of barotrauma with the Manujet may be reduced when expiratory obstruction is dynamic and higher insufflation pressures may assist distal inspiratory flow when the proximal airway is relatively unobstructed.

Passive expiration through the open 2.1 mm Insyte® cannula increased minute ventilation in the MP group compared with the MO group (Table 1). With a cannula this size, 1 litre of oxygen passively exits a normally compliant lung model in ~10 s.[15] While peak airway pressures generated by the initial breath were no different between Manujet groups, the time to second and subsequent breaths were shorter and oxygenation was more stable in the MP group (Fig. 5). However, the risk of inserting a second transtracheal catheter in a CICO situation for the benefit of stable oxygenation and improved CO_2 clearance would need to be considered carefully.

The low insufflation pressure and assisted expiration characteristics of the Ventrain with a single transtracheal catheter suggest a significant clinical advantage in terms of efficacy and safety in the critically obstructed airway.

The Manujet provided effective rescue oxygenation but at higher airway pressure. Minute ventilation was limited by the study methodology to avoid barotrauma, but increased significantly even with a 2.1 mm diameter expiratory airway allowing some passive expiration. If a Manujet is used during emergency PTV in a critically obstructed airway, our findings suggest that with single rescue breath re-oxygenation achieved, emphasis can be placed on minimizing the risk of barotrauma. The 're-oxygenation window' of at least 5 min (Fig. 3) in our sheep model may be sufficient time to secure the airway without the need for additional breaths. It may also provide sufficient time to convert the narrow transtracheal catheter to a larger bore cuffed tracheal airway to allow conventional ventilation. Airway pressure monitoring below the level of obstruction may not be available in an emergency. A minimum acceptable Sa_{O_2} (e.g. 5% below the peak Sa_{O_2} achieved) is a clinically relevant trigger to minimize breaths delivered and barotrauma

risk.[14] Further work is needed to optimize use of the Manujet in obstructed airway situations.

Our study has several limitations. The study size is small although this is mitigated by the marked differences between the devices. The minute ventilation achieved with the two devices was a function of the airway pressure during each respiratory cycle. Although this strategy was effective in preventing clinically evident barotrauma, it may have artificially reduced both the stability of oxygenation in the MO group and the minute ventilation achievable with the Manujet. Subclinical barotrauma cannot be excluded in our study as histology was not performed. Device performance when the degree of airway obstruction is relatively modest has not been addressed in our study.

When using the Ventrain, manual co-ordination and an understanding of the equilibration phase are important to minimize the risk of clinically significant subatmospheric airway pressures. Device ventilatory phases are described in the manufacturer's instructions, but more emphasis could be placed on a tri-phasic ventilatory pattern during initial re-oxygenation to optimize safety in a CICO emergency.

Our findings suggest that the Ventrain provides effective oxygenation and ventilation at low airway pressures during PTV when the airway is critically obstructed. In this situation, the Manujet provides rapid temporizing oxygenation but poor CO_2 clearance, because minute ventilation is limited by high airway pressures. The nature and extent of airway obstruction may not be known in a CICO emergency but an understanding of device differences may help inform optimal ventilation device and method selection.

Authors' contributions

M.B. contributed to study design and conduct and data analysis, and critically revised the manuscript; Y.C.T. contributed to study design and conduct and data collection; C.M. contributed to study design and conduct and data analysis, and drafted the manuscript. All the authors approved the final manuscript.

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Declaration of interest

The authors have no conflicts of interest in relation to this work.

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