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Ventrain: an ejector ventilator for emergency use

A. E. W. Hamaekers*, P. A. J. Borg and D. Enk

Department of Anaesthesia, Maastricht University Medical Centre, PO Box 5800, 6202 AZ Maastricht, The Netherlands

* Corresponding author. E-mail: a.hamaekers@mumc.nl

Editor's key points

- The Ventrain is a new high-pressure source ventilator that augments expiration of gas by suction.
- The Ventrain generated reasonable minute volumes through a 2 mm ID catheter in an experimental lung model.
- Insufflation pressures were much lower than the driving pressure, with less potential for barotrauma.
- Reduced experimental lung compliance decreased the efficiency of the Ventrain to some degree.

Background. A small, flow-regulated, manually operated ventilator designed for ventilation through a narrow-bore transtracheal catheter (TTC) has become available (Ventrain, Dolphys Medical BV, Eindhoven, The Netherlands). It is driven by a predetermined flow of oxygen from a high-pressure source and facilitates expiration by suction. The aim of this bench study was to test the efficacy of this new ventilator.

Methods. The driving pressure, generated insufflation, and suction pressures and also the suction capacity of the Ventrain were measured at different oxygen flows. The minute volume achieved in an artificial lung through a TTC with an inner diameter (ID) of 2 mm was determined at different settings.

Results. Oxygen flows of 6–15 litre min^{-1} resulted in driving pressures of 0.5–2.3 bar. Insufflation pressures, measured proximal to the TTC, ranged from 23 to 138 cm H_2O. The maximal subatmospheric pressure build-up was −217 cm H_2O. The suction capacity increased to a maximum of 12.4 litre min^{-1} at an oxygen flow of 15 litre min^{-1}. At this flow, the achievable minute volume through the TTC ranged from 5.9 to 7.1 litres depending on the compliance of the artificial lung.

Conclusions. The results of this bench study suggest that the Ventrain is capable of achieving a normal minute volume for an average adult through a 2 mm ID TTC. Further *in vivo* studies are needed to determine the value of the Ventrain as a portable emergency ventilator in a 'cannot intubate, cannot ventilate' situation.

Keywords: airway management; emergencies; jet ventilation, transtracheal

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Transtracheal cannulation and subsequent high-pressure source ventilation (often called 'jet ventilation') can be life-saving in a 'cannot intubate, cannot ventilate' (CICV) situation.[1 2] Although 'jet ventilation' has a low morbidity in elective cases,[3] numerous case reports underline the risk of high-pressure source ventilation in emergency situations.[4–6] Safe application of a high-pressure source ventilator requires an open upper airway to allow the gas to flow out during expiration. Obstruction of the upper airway caused by laryngospasm, oedema or anatomical distortion, combined with over-vigorous jet insufflation can result in air trapping with subsequent barotrauma and haemodynamic instability.[7 8] Suction-generated augmentation of expiration has been proposed to minimize the risk of air trapping[9] and to increase the achievable minute volume through a small-bore airway catheter.[10]

Recently, we described a purpose-built ventilation ejector (DE 5) that achieves *in vitro* a minute volume up to 7.5 litre min^{-1} through a 7.5 cm long transtracheal catheter (TTC) with an inner diameter (ID) of 2 mm by using expiratory ventilation assistance (EVA).[11 12] In a hypoxic animal model with a completely obstructed airway, this ventilation ejector restored oxygenation through the TTC within 20 s and limited hypercarbia for over 15 min.[13] Based on the construction of the DE 5, a portable, flow-regulated, manually operated, and ergonomically shaped ventilation device was developed: Ventrain (Dolphys Medical BV, Eindhoven, The Netherlands; http://www.ventrain.com). Recently, this ventilation ejector has become commercially available. The aim of this study was to evaluate the Ventrain *in vitro*.

Methods

Description of the Ventrain

The Ventrain is a single-use, manually operated, small-lumen ventilation device capable of oxygen insufflation and EVA. The functional inner component is a specially designed ejector (Fig. 1A and B), which is driven by an oxygen flow coming from a high-pressure source with a controllable flow, e.g. a wall-mounted, pressure-compensated flowmeter, or an oxygen cylinder with a flow regulator.[14] Before use, the oxygen tubing attached to the ejector's inlet (1 in Fig. 1A and B) must be connected to the oxygen source, and the short connecting tubing at the side port (2 in Fig. 1A and B) must be attached to the TTC.

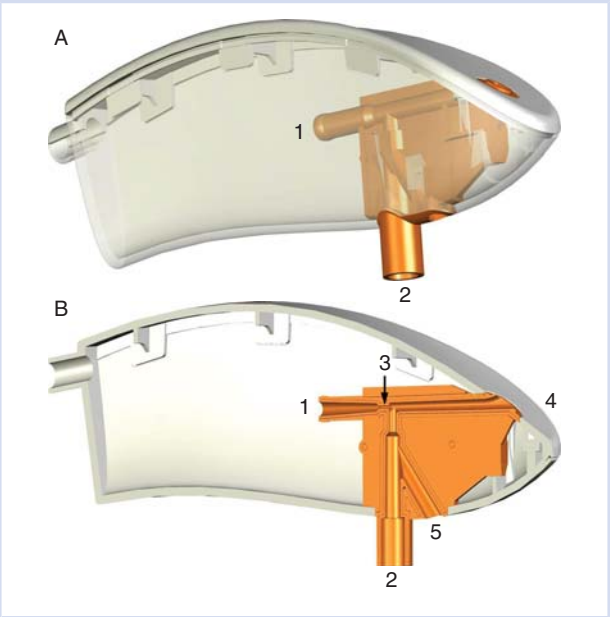

Fig 1 (A) CAD model of the Ventrain. The shell is shown transparently, so the ejector as the functional centrepiece can be seen inside the shell. The oxygen tubing (not shown) is connected to the ejector's inlet (1) and short connecting tubing (not shown) is glued to the side port (2). (B) CAD cross-section of the Ventrain. Again, the oxygen and connecting tubing are not shown. The cross-section reveals the inner construction of the ejector: from the inlet (1) to the jet nozzle (3), the diameter decreases. Oxygen passing the jet nozzle is accelerated and enters the slightly conically shaped exhaust pipe (4) at high speed. Thereby, subatmospheric pressure is created at the side port (2) resulting in assisted expiration if the bypass (5) (functioning as an on/off switch) is completely closed. For inspiration, the flow of oxygen can be redirected to the side port by firmly sealing the aperture of the exhaust pipe (functioning as an inspiration/expiration switch).

The oxygen flow coming from the flowmeter or flow regulator is accelerated by a 0.7 mm ID jet nozzle (3 in Fig. 1B) and enters the exhaust pipe (4 in Fig. 1B) at high speed. As long as the bypass is open, the device is claimed to be functionally switched off with no clinically relevant flows to and from the patient. Closing the aperture of the bypass activates the Ventrain. The high-speed oxygen flow now creates a subatmospheric pressure and entrains gas from the side port (2 in Fig. 1B), thereby facilitating the egress of gas through the small-bore catheter. Closing both the bypass and the aperture of the exhaust pipe (inspiration/expiration switch) redirects the flow to the side port and oxygen is insufflated. By alternately occluding and releasing the aperture of the exhaust pipe, while keeping the bypass closed, either oxygen is insufflated or a subatmospheric pressure is created to assist the egress of gas through the attached small-bore catheter: EVA (details of how to operate the Ventrain are shown in Supplementary Fig. S1A and B).

Experimental set-up

The experiments were performed in two stages. First, the driving pressure and the pressures generated by the Ventrain were determined using the Calibration Analyzer Series RT-200 (Timeter Instrument Corporation, St Louis, MO, USA). A pre-release version of the Ventrain was connected to a calibrated, pressure-compensated flowmeter (Dräger Medical AG & Co. KG, Lübeck, Germany) and attached to a 7.5 cm long, 2 mm ID TTC (Cook Medical, Bloomington, IN, USA). The driving pressure was defined as the pressure in the oxygen tubing between the flowmeter and the ejector part of the Ventrain. It was measured via the side port of a T-piece placed between the oxygen tubing and the flowmeter. To evaluate whether the Ventrain was indeed functionally switched off, pressures at the tip of the TTC were determined with the bypass of the Ventrain open as previously described.[15] The insufflation and suction pressures were measured at the side port of the distal T-piece proximal to the attached catheter. The maximum suction pressure was determined with the tip of the attached catheter blocked. All pressures were measured at oxygen flows of 6, 9, 12, and 15 litre min^{-1}.

Furthermore, the suction capacity of the Ventrain was determined for oxygen flows of 6–15 litre min^{-1} by insufflating a 35 litre plastic garbage bag (product number 136146, Albert Heijn, Zaandam, The Netherlands), as a closed ventilation model with an infinite compliance, for 1 min and measuring the time to completely empty the bag through the TTC by suction. In addition, entrainment ratios (=entrained flow/oxygen flow) were calculated.

In the second part of the experiment, the efficacy of the Ventrain was studied at different pulmonary compliances and resistances in an LS800 lung simulator (Dräger Medical AG & Co. KG, Lübeck, Germany) with a simulated complete upper airway obstruction. The TTC 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 directed through the catheter. The measurements were performed at compliances of 100, 50, 30, and 10 ml $mbar^{-1}$ and resistances of 2, 8, and 32 mbar $litre^{-1}$ s^{-1}. The achievable minute volume was determined as previously described[15] by measuring the time required for insufflation of 1000 ml of oxygen and the times needed for passive backflow of this volume through the TTC (with the Ventrain disconnected) and for assisted expiration using the Ventrain connected to oxygen flows of 6, 9, 12, and 15 litre min^{-1}.

Statistical analysis

Each experiment was repeated four times. Means and standard deviations (SDS) were determined and used for further calculations. Suction capacities, entrainment ratios (ER), achievable minute volumes, and inspiration/expiration ratios (*I*/*E* ratios) were calculated. For descriptive statistics, MS-Excel 2002 SP3 was used.

Results

Increasing the oxygen flow created higher driving pressures (Table 1). Values of 2300 cm H_2O (2.3 bar) were measured in the oxygen tubing to the ejector at a flow of 15 litre min^{-1}.

With the bypass open (Ventrain 'off'), closure of the exhaust pipe resulted in a maximal pressure at the tip of the TTC of 2.3 cm H_2O at a flow of 15 litre min^{-1}, whereas a slight subatmospheric pressure of −6.5 cm H_2O was found at this flow rate if the aperture of the exhaust pipe was released (Table 1).

The insufflation pressure and the suction pressure of the Ventrain were related to the oxygen flow. At an oxygen flow of 15 litre min^{-1}, the insufflation pressure was 138 cm H_2O. The suction pressure was −97 cm H_2O while continuously aspirating air through the TTC and reached a maximum of −217 cm H_2O when the tip of the TTC was blocked (Table 1).

At a flow rate of 15 litre min^{-1}, the Ventrain shortened the expiratory time in all simulated pulmonary settings. This effect was for all flows most pronounced at a compliance of 100 ml $mbar^{-1}$ (Table 2 and Supplementary Tables S1 and S2). At this compliance, the expiratory time for 1 litre of oxygen decreased from 14.03 s in the case of passive egress through the TTC to 4.58 s with expiratory

Table 1 Physical characteristics of the Ventrain at different oxygen flows; measured data are presented as mean (SD). 'Driving pressure' indicates the pressure measured in the upstream oxygen tubing with oxygen flowing through the Ventrain, while the device is functionally switched off; 'PACT' means pressure at the TTC's tip; 'insufflation pressure' and 'suction pressure' have been measured proximal of the attached TTC during inspiration and expiration, respectively; 'maximal suction pressure' indicates the maximal subatmospheric pressure build-up that can be created by the Ventrain

Oxygen flow (litre min^{-1})	6	9	12	15
Driving pressure (cm H_2O)	459 (7.2)	1017 (8.5)	1665 (4.4)	2297 (8.5)
Ventrain 'off' (bypass open)				
PACT, exhaust pipe closed (cm H_2O)	0.5 (0.06)	0.8 (0.05)	1.9 (0.06)	2.3 (0.10)
PACT, exhaust pipe open (cm H_2O)	−1.7 (0.05)	−3.5 (0.05)	−5.2 (0.05)	−6.5 (0.12)
Ventrain 'on' (bypass closed)				
Insufflation pressure (cm H_2O)	22.5 (0.58)	50.8 (0.50)	90.5 (1.00)	137.8 (2.06)
Suction pressure (cm H_2O)	−25.5 (0.58)	−51.3 (0.96)	−75.5 (0.58)	−96.8 (1.50)
Maximal suction pressure (cm H_2O)	−57.8 (1.26)	−112.8 (0.50)	−171.0 (2.16)	−217.3 (3.95)
Suction capacity (litre min^{-1})	6.5	9.3	11.0	12.4
Entrainment ratio	1.08	1.03	0.92	0.83

Table 2 Achievable minute volumes through the 2 mm ID TTC at an oxygen flow of 12 and 15 litre min^{-1}; measured data presented as mean (SD)

Oxygen flow of 12 litre min^{-1}				
Compliance (ml $mbar^{-1}$)	100	50	30	10
Resistance (mbar $litre^{-1}$ s^{-1})	2	2	8	32
Insufflation time (s)	4.96 (0.04)	5.14 (0.04)	5.42 (0.04)	6.63 (0.02)
Expiration time (s), passive	14.03 (0.07)	10.20 (0.02)	8.09 (0.10)	5.69 (0.09)
MV (litre min^{-1}), passive	3.2	3.9	4.4	4.9
I/E ratio, passive	1/2.83	1/1.99	1/1.49	1/0.86
Expiration time (s), Ventrain	5.11 (0.04)	5.14 (0.02)	5.07 (0.03)	5.21 (0.07)
MV (litre min^{-1}), Ventrain	6.0	5.8	5.7	5.1
I/E ratio, Ventrain	1/1.03	1/1.00	1/0.93	1/0.79
Oxygen flow of 15 litre min^{-1}				
Compliance (ml $mbar^{-1}$)	100	50	30	10
Resistance (mbar $litre^{-1}$ s^{-1})	2	2	8	32
Insufflation time (s)	3.91 (0.08)	4.15 (0.02)	4.32 (0.05)	5.38 (0.03)
Expiration time (s), passive	14.03 (0.07)	10.20 (0.02)	8.09 (0.10)	5.69 (0.09)
MV (litre min^{-1}), passive	3.3	4.2	4.8	5.4
I/E ratio, passive	1/3.59	1/2.46	1/1.87	1/1.06
Expiration time (s), Ventrain	4.58 (0.07)	4.56 (0.05)	4.62 (0.03)	4.85 (0.03)
MV (litre min^{-1}), Ventrain	7.1	6.9	6.7	5.9
I/E ratio, Ventrain	1/1.17	1/1.10	1/1.07	1/0.90

assistance by the Ventrain at an oxygen flow of 15 litre min^{-1}, resulting in a calculated minute volume of 7.1 litre min^{-1}. A decrease in compliance, however, limited the efficacy of the Ventrain. At a compliance of 10 ml $mbar^{-1}$, the (theoretically) achievable minute volume decreased to 5.9 litre min^{-1}.

Discussion

Passive outflow of gas during ventilation through a narrow-bore TTC is limited by the high internal resistance of the catheter.[16] One solution to facilitate the egress of gas is to apply suction during the expiratory phase.[10] The novel emergency ventilation ejector evaluated in this study (Ventrain) achieved a minute volume of up to 7.1 litre min^{-1} through a 2 mm ID catheter, by generating expiratory suction applying the Bernoulli principle.

The Bernoulli principle states that for an inviscid fluid, an increase in flow velocity at a constriction leads to an increase in dynamic pressure (~kinetic energy) and causes a corresponding decrease in static pressure (~potential energy). The Ventrain turns the high driving pressure (up to 2.3 bar), measured in the oxygen tubing, into high velocity of the oxygen stream. As can be estimated from the driving pressure and the diameter of the jet nozzle, the 0.7 mm ID jet nozzle of the Ventrain accelerates the oxygen at a flow rate of 15 litre min^{-1} to a flow velocity close to the speed of sound. The subatmospheric pressure of up to -97 cm H_2O caused by the Bernoulli effect facilitates the egress of gas through the small-bore catheter. The degree of expiratory assistance is flow-dependent, with a maximum suction capacity of 12.4 litre min^{-1} at an oxygen flow of 15 litre min^{-1}.

The DAS guidelines recommend using a high-pressure device capable of delivering a high minute volume to re-oxygenate a patient in a CICV situation through a narrow-bore cricothyroidotomy.[2] Although the Ventrain is a high-pressure oxygen source device (as defined by its driving pressure), the insufflation pressure measured proximal to the TTC is significantly lower than the pressure usually used for conventional 'jet ventilation'. In contrast to conventional high-pressure source ventilation devices, the Ventrain is flow-regulated and the insufflated oxygen is only slightly compressed. This might decrease the risk of barotrauma as the volume of insufflated oxygen can easily be estimated (e.g. redirecting an oxygen flow of 15 litre min^{-1} for 1 s results in insufflation of 250 ml of oxygen).

To ensure a stable inspiratory flow, a pressure-compensated flowmeter or flow regulator capable of handling back-pressure is mandatory. Insufflation and also suction pressures, suction capacity, inspiration and expiration times, and resulting inspiration/expiration ratio depend highly on the flow resistance of the attached catheter. The Ventrain has been specified to be used in combination with a 75 mm long, 2 mm ID TTC allowing manual control of ventilation in healthy adults with an inspiration/expiration ratio of about 1 to 1 at oxygen flows of 12–15 litre min^{-1}. Changes in oxygen flow, pulmonary compliance, and flow resistance of the catheter might change the inspiration/expiration ratio. Therefore, it needs to be emphasized that during use of the Ventrain, one should always watch the chest movements of the patient. Failure to do so could lead to hyperinflation or the development of negative intrathoracic pressure.

In the case of hyperinflation or negative intrathoracic pressure, one needs to adjust the duration of the inspiration or expiration, or one might allow (slow) equilibration of the intrathoracic pressure with the atmosphere by releasing the aperture of the exhaust pipe and the bypass of the Ventrain. If the Ventrain is connected to an oxygen flow, low levels of subatmospheric pressure (maximally -6.5 cm H_2O at 15 litre min^{-1}) are generated with both openings released. This subatmospheric pressure can compensate for the flow resistance of the connecting tubing with the distal T-piece. Thus, with the exhaust pipe and the bypass open, the Ventrain will be not only switched off, but also functionally disconnected from the catheter.

The maximal subatmospheric pressure created by the Ventrain in this bench study was -217 cm H_2O. In a clinical setting, this pressure can only be reached if the upper airway is completely obstructed and if more gas is suctioned out of the patient than has been insufflated. Negative pressure pulmonary oedema, however, is a potential complication that might develop even after a short period of high subatmospheric intrapulmonary pressure. Therefore, ongoing *in vivo* trials are needed to determine the clinical effects of any subatmospheric pressure potentially generated by the Ventrain.

However, if used correctly, the Ventrain provides positive pressure ventilation with controlled expiration with a minute volume of up to 7.1 litre min^{-1}, an increase in minute volume of 112% at a compliance of 100 ml $mbar^{-1}$ compared with the minute volume achievable through a narrow-bore catheter with passive expiration. This minute volume would not only be enough for re-oxygenation, but it would also prevent hypercarbia in most adults. The value of the Ventrain compared with ventilation with passive backflow is influenced by pulmonary compliance and upper airway resistance. The Ventrain is proved to be most efficient at a high compliance, whereas a decrease in pulmonary compliance limited the effect of expiratory assistance. However, at a compliance of a healthy adult patient (50 ml $mbar^{-1}$), the minute volume at an oxygen flow of 15 litre min^{-1} was still 6.9 litre min^{-1}.

EVA can be regarded as a hybrid technique for small-lumen ventilation between intermittent positive pressure ventilation with passive expiration, which requires a wide-bore and sealed airway, and conventional 'jet ventilation' through a narrow-bore catheter, which requires an open upper airway. The Ventrain applies EVA efficiently *in vitro*. If ongoing studies confirm the safety and efficacy of this ventilation ejector *in vivo*, it may become a beneficial tool in modern airway management, for example, as a portable ventilator for transtracheal emergency ventilation.

Supplementary material

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

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Declaration of interest

A.H. is a member of the medical advisory board of Ambu and has received free samples of airway equipment for teaching and clinical evaluation from several companies. She has no financial interest in any company. D.E. is the inventor of the Ventrain and receives royalty payments from Dolphys Medical, Eindhoven, The Netherlands. Also the Maastricht University Medical Centre receives royalty payments from Dolphys Medical.

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