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Successful Transtracheal Lung Ventilation Using a Manual Respiration Valve

An In Vitro *and* In Vivo *Study*

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Background: **Lung ventilation through a thin transtracheal cannula may be attempted in patients with laryngeal stenosis or "cannot intubate, cannot ventilate" situations. It may be impossible to achieve sufficient ventilation if the lungs are spontaneously emptying only through the thin transtracheal cannula, which imposes high resistance to airflow, resulting in dangerous hyperinflation. Therefore, the authors describe the use of a manual respiration valve that serves as a bidirectional pump providing not only inflation but also active deflation of the lungs in case of emergency transtracheal lung ventilation.**

Methods: **The effectiveness of such a valve was tested *in vitro* using mechanical lungs in combination with two different cannula sizes and various gas flows. The valve was then tested in five pigs using a transtracheal 16-gauge cannula with three different combinations of inspiratory/expiratory times and gas flows and an occluded upper airway.**

Results: **In the mechanical lungs, the valve permitted higher minute volumes compared with spontaneous lung emptying. *In vivo*, the arterial oxygen and carbon dioxide partial pressures increased initially and then remained stable over 1 h (arterial oxygen tension, 470.8 ± 86.8; arterial carbon dioxide tension, 63.0 ± 7.2 mmHg). The inspiratory pressures measured in the trachea remained below 10 cm H_2O and did not substantially influence central venous and pulmonary artery pressures. Mean arterial pressure and cardiac output were unaffected by the ventilation maneuvers.**

Conclusions: **This study demonstrated *in vitro* and *in vivo* in adult pigs that satisfactory lung ventilation can be assured with transtracheal ventilation through a 16-gauge cannula for a prolonged period of time if combined with a bidirectional manual respiration valve.**

THERE are rare emergency conditions that render it impossible to ventilate a patient with a mask or insert an endotracheal tube into the trachea in a customary way. These situations include but are not limited to mouth or upper airway obstructions such as laryngeal stenosis, foreign bodies, tumors, and injuries.[1] After failure of alternative ventilation devices such as the intubation laryngeal mask, management strategies suggest to approach the trachea through the ventral neck region for transtracheal ventilation.[2–4] Cricothyrotomy is not recommended in children younger than 10 yr or in adults with a difficult anatomy to perform the procedure. A surgical tracheotomy, a technique securely performed only by an experienced physician, is not the first-line emergency measure because of its risks.[5,6] Alternatively, a small transtracheal cannula can be introduced percutaneously into the trachea immediately above or below the cricoid cartilage so that the lungs can be ventilated by intermittently insufflating highly pressurized air or oxygen.[7–9] This kind of ventilation, transtracheal jet ventilation, is sometimes used also in the clinical setting, when abnormalities of the airways or a surgical approach do not permit the use of normal tracheal tubes.[10,11] The equipment available for transtracheal ventilation permits "active" or forced inspiration, but allows only passive expiration, mainly through the patient's proximal airways cephalad around the transtracheal cannula and, to a much lesser degree, through the narrow transtracheal cannula itself.[12–14] Risks therefore include kinking of the transtracheal part of the cannula as well as barotrauma due to outflow airway obstruction.[15,16] Under experimental conditions, 10-gauge cannulas were shown to be effective in pigs with blocked upper airways without expiratory aid for a period of 15 min.[17] However, there is obviously a psychological barrier to inserting large-bore emergency devices transtracheally. Furthermore, if not very rigid, they do not offer many practical advantages compared with smaller ones, because they could easily be squeezed between tracheal rings or kinked both outside and inside the trachea, which would significantly collapse its volume and thereby offer an even higher resistance to the gas flow compared with a cannula of smaller diameter. If smaller-bore cannulas are to be used, the expiration is highly impaired by the resistance of the cannula to gas flow. Because high resistance results in flow reduction, correspondingly higher pressures are needed to achieve appropriate flows and thus satisfactory lung ventilation.

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Currently available sets for transtracheal ventilation are equipped with pressurized gas bottles that assure only high inspiratory flow while the expiration is passive. Because during passive expiration the driving pressure is intrathoracic pressure, which is relatively low, the expiratory flow is also low. This may result in dangerous lung hyperinflation, *i.e.*, buildup of positive end-expiratory pressure and risk of barotrauma and volutrauma. A few relatively complex solutions that permit active expiration have been proposed in the past[18–21] but did not find their place in clinical practice.

Here, we describe an unusual, unique, and simple system for transtracheal lung ventilation, where, in addition to a forced inspiration, active expiration can be assured through a narrow transtracheal cannula. With this technique, the expiratory time can be substantially shortened, which permits better lung ventilation in the case of obstructed upper airways, where expiration predominantly relies on the flow through the transtracheal cannula. Depending on the presence and degree of upper airway obstruction, as well as the size of the inserted cannula, this effect may be more or less relevant for the survival of a potential patient. The ventilator, a manual respiration valve, was tested *in vitro* by using a mechanical lung model, as well as *in vivo* in pigs, under conditions closely resembling a clinical situation, but with an occluded endotracheal tube. The primary outcome measure *in vivo* was the effect of gas flow and respiratory frequency on gas exchange (blood gas analysis). Secondary outcome measures were cardiovascular response and pressures in response to the ventilation maneuvers.

Materials and Methods

Manual Respiration Valve

The manual respiration valve (fig. 1) was designed using the Bernoulli and Hagen-Poiseuille flow equations.[22] A gas inlet has its inner opening close to the narrowed outlet of a larger tube, which is T shaped, with its side branch being oriented toward the patient. Gas flowing through the narrow outlet (ID approximately 1.5 mm) produces negative pressure in the side branch ("expiration"), a Venturi effect. Closure of the outlet forces gas to flow back through the side tube into the trachea ("inspiration"). These maneuvers make the device function as a blowing–suctioning pump, depending on the status of the outlet. To operate the device, the outlet was occluded with a thumb during inspirations for the *in vitro* experiments, whereas for the *in vivo* experiments, a flexible tube was attached to the outlet and occluded by an adapted air lock from a dialysis machine (Fresenius, Frankfurt, Germany), which was controlled by a custom-made programmable device including a timer.

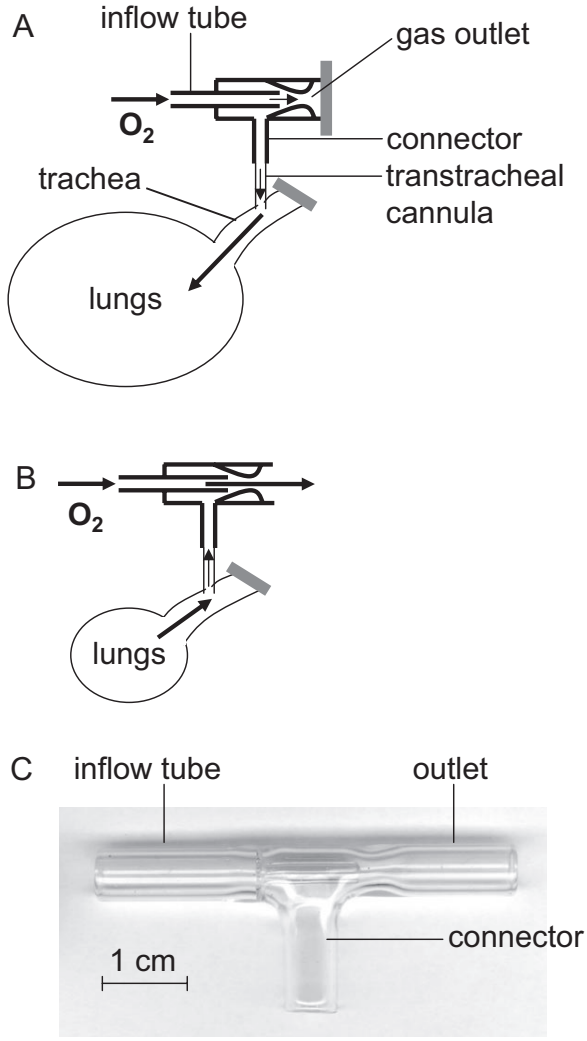

Fig. 1. Schematic representation of the manual respiration valve. (*A*) Inspiration. The closed outlet forces pressurized oxygen into the transtracheal cannula and thus the lungs. (*B*) Expiration. The pressurized oxygen now produces a negative pressure due to the Venturi effect, which drives gas back from the lungs through the transtracheal cannula and out through the opened outlet. (*C*) Glass model of the valve. The oxygen inflow tube and the connector to and from the lungs have IDs of 3 mm, and the narrow part producing the Venturi effect has an ID of approximately 1.5 mm. The other dimensions are in proportion.

In Vitro *Experiments*

The manual respiration valve was tested *in vitro* using mechanical lungs with adjustable compliance and airway resistance (Dräger, Lübeck, Germany). The proximal tube orifice incorporated the "transtracheal" cannula (12 gauge, 2.260 mm ID or 16 gauge, 1.345 mm ID; Insyte venous catheter, Becton Dickinson, Heidelberg, Germany), which was attached to the manual respiration valve and an oxygen source. We measured the inspiratory and expiratory times necessary to inflate and deflate the lungs with the volume of 1 liter (the "1-liter test") using various gas flows (f = 2, 4, 6, and 12 l/min), resistances (R = 128, 32, and 2 mbar $\cdot$ l^{-1} $\cdot$ s^{-1}), and compliances (C = 0.01, 0.03, and 0.1 l/mbar). The pri-

Table 1. Ventilatory Settings Applied during the *In Vivo* Experiments

	Gas Flow, l/min	Target Inspiratory Volume, ml	Inspiratory Time, s	Expiratory Time, s	I/E Ratio	Frequency, /min	Calculated Minute Volume, l/min
A	16	100	0.8	4.5	0.18	11.3	1.1
B	16	200	1.6	8.5	0.19	5.9	1.2
C	12	200	2.0	9.0	0.22	5.5	1.1

The given settings of transtracheal ventilation through a 16-gauge catheter were applied consecutively in random order to each animal enrolled in the study for 60 min with 30 min of regular ventilator-generated ventilation through the endotracheal tube before and in between the experiments.
I/E = inspiratory/expiratory time.

mary outcome measure was the time of the Venturi-facilitated lung emptying, which was compared with the time necessary to empty the lungs spontaneously. Minute volumes were then calculated based on the measured times for inspiration and expiration of 1 liter to compare the efficiencies of the system for the given settings. Each experiment was performed three times.

In Vivo *Experiments*

All animal treatment and experimental procedures were in accordance with the local Instructions for Animal Care of Greifswald University and approved by the state animal care authority (Landesveterinär- und Lebensmitteluntersuchungsamt Mecklenburg-Vorpommern, Rostock, Germany). Female pigs (40.8 ± 4.1 kg, n = 5) were prepared as previously described.[23] In brief, the animals were premedicated with intramuscular 0.2 mg/kg flunitrazepam (Hoffmann-La Roche, Grenzach-Wyhlen, Germany) and 15 mg/kg ketamine (Parke-Davis, Freiburg, Germany) after overnight fasting while receiving water *ad libitum*. Anesthesia was induced intravenously *via* an ear vein with 1.6–3.3 mg/kg ketamine and 3 μg/kg fentanyl (Janssen-Cilag, Neuss, Germany). The trachea was intubated after injection of 0.3 mg/kg vecuronium (Organon Teknika, Eppelheim, Germany). Anesthesia was maintained by continuous infusion of 0.07–0.1 mg · kg^{-1} · h^{-1} flunitrazepam, 7–10 mg · kg^{-1} · h^{-1} ketamine, and 0.5–0.7 mg · kg^{-1} · h^{-1} vecuronium. Volume-controlled mechanical ventilation was provided with a ventilator (Servo 900; Siemens, Nürnberg, Germany). The preparation included an arterial line, a central venous line, and a Swan-Ganz catheter (Edwards, Irvine, CA) connected *via* pressure transducers (Medex, Rossendale, United Kingdom) to a multichannel recorder (Hugo-Sachs, March, Germany) and a digital data acquisition system (Plugsys, Simsbury, CT). All animals received full-electrolyte solution at 12 ml · kg^{-1} · h^{-1} (Fresenius, Homburg, Germany). Blood gases were measured using an ABL615 analyzer (Radiometer, Copenhagen, Denmark).

The trachea was exposed by a vertical skin incision, and a 16-gauge intravenous catheter was inserted as a transtracheal cannula and affixed appropriately using short rubber tubing and a third-hand device, resulting in a distance between the trachea and the manual respiration valve of approximately 10 cm. The valve was connected to the cannula, and the endotracheal tube was proximally occluded for each experiment. After being ventilated *via* the endotracheal tube (30 min, fraction of inspired oxygen 30%, tidal volume 200 ml), the animals were subsequently ventilated for 60 min with one of three inspiratory time/oxygen gas flow combinations. The volumes given in table 1 are minimal estimates and thus smaller than the delivered volumes. These precautions assured sufficient ventilation to the animal even if respiratory system compliance and resistance were most unfavorable. In preliminary experiments, we confirmed that delivered tidal volumes used with our valve *in vitro* closely corresponded to those achieved *in vivo* for low tidal volumes using a capacitive thoracic excursion monitor (Hoffrichter, Schwerin, Germany; n = 3, data not shown). A gas flow of 16 l/min required 1.6 s inspiratory time, whereas 12 l/min required 2.0 s (table 1). The two low-frequency combinations (5.9 and 5.5 per min) ought to resemble thoracic excursions (tidal volume) of the previous ventilator setting (approximately 200 ml) with two different gas flows (16 and 12 l/min), whereas the higher frequency mode (11.3 per min) was introduced to show the influence of a doubled respiratory rate on the parameters studied if the 16-l/min flow was used. The expiratory times were adjusted to permit lung emptying, but allowed some positive end-expiratory pressure, consistent with previous ventilator settings. All experiments were conducted with a proximally occluded endotracheal tube to exclude influences from leakages and to concentrate on the effect of the respiration valve. The intratracheal pressure was measured continuously at the tip of the tube.

After each experiment, the animals were ventilated *via* the endotracheal tube for 30 min for recovery before the next experiment was initiated, resulting in a total of three experiments per animal used. Arterial blood gas saturation quickly decreased with spontaneous emptying of the lungs through a 16-gauge cannula in preliminary experiments, which is why these experiments could not be conducted for comparison.

Statistical Analysis

The main results are given descriptively as means of three successive measurements (*in vitro*) and as means ± SDs of five independently performed experiments (*in vivo*). For statistical analysis of the three *in vivo* tested

Table 2. The "1-Liter Test" Using an Artificial Lung Model, the 12-Gauge Cannula, and the Manual Respiration Valve

				Expiratory Time, s		Ratio Inspiratory/ Expiratory Time		Calculated Minute Volume, l/min		Calculated Increase of Ventilated Volume by Use of Valve, %	
Gas Flow, l/min	Compliance, l/mbar	Airway Resistance, mbar · l^{-1} · s^{-1}	Inspiratory Time, s	With Valve	Without Valve	With Valve	Without Valve	With Valve	Without Valve	Inspiration + Expiration	Expiration Only
6	0.01	128	11.9	11.7	12.6	1.02	0.94	2.54	2.45	4	8
6	0.03	128	9.2	12.7	12.7	0.72	0.73	2.73	2.74	0	0
6	0.1	128	8.5	13.5	14.1	0.63	0.60	2.73	2.66	3	5
6	0.01	32	12.3	11.1	11.3	1.11	1.09	2.56	2.54	1	2
6	0.03	32	9.5	13.0	14.6	0.73	0.65	2.66	2.49	7	12
6	0.1	32	8.0	12.6	14.7	0.63	0.54	2.92	2.65	10	17
6	0.01	2	12.5	10.7	10.8	1.17	1.15	2.60	2.58	1	1
6	0.03	2	8.7	11.5	12.3	0.76	0.70	2.98	2.86	4	8
6	0.1	2	8.0	12.2	12.8	0.66	0.63	2.97	2.88	3	5
12	0.01	128	6.3	9.5	12.6	0.67	0.50	3.80	3.17	20	34
12	0.03	128	5.1	9.6	12.7	0.53	0.40	4.07	3.37	21	32
12	0.1	128	4.8	10.0	14.1	0.48	0.34	4.04	3.16	28	41
12	0.01	32	6.9	8.6	11.3	0.80	0.47	3.86	3.30	17	30
12	0.03	32	5.5	9.5	14.6	0.57	0.37	4.01	3.00	34	53
12	0.1	32	5.2	9.8	14.7	0.53	0.35	4.00	3.01	33	50
12	0.01	2	6.8	8.6	10.8	0.80	0.63	3.90	3.40	15	26
12	0.03	2	5.7	9.4	12.3	0.60	0.46	3.97	3.34	19	31
12	0.1	2	5.3	9.7	12.8	0.55	0.41	4.01	3.31	21	33

The given times were obtained by inflating and deflating the lung model to the 1-liter mark in triplicate. Although the manual respiration valve does not change inspiratory times, expiratory times obtained using the valve are in part substantially shorter as compared with spontaneous expiration, especially using the higher flow.

ventilatory settings, two-way analysis of variance with *post hoc* pairwise multiple comparison (Student-Newman-Keuls method) was performed using SigmaStat for Windows version 3.11 (SyStat, San Jose, CA), and $P < 0.05$ was considered significant.

Results

In Vitro *Experiments*

The manual respiration valve allowed for effective inflation and deflation of the artificial lungs. When the valve was used to insufflate 1 liter of air into the artificial lungs, it produced fast lung inflation, which depended on the gas flow applied as well as on the preset compliance and airway resistance, but was not different from inflation without the valve. Spontaneous deflation of the same volume out of the artificial lungs occurred much more slowly than inflation because of the lack of a driving force other than the "lungs" itself. The time necessary for expiration was determined not only by the gas flow but also by diameter and length of the transtracheal cannula. As expected, large-bore cannulas (12 gauge) allowed for reasonably fast spontaneous expiration. Use of our manual respiration valve resulted in a noticeable increase of minute ventilation of up to 50% (or 1 l/min), as compared with spontaneous emptying of the lungs (table 2). When using 16-gauge cannulas, however, none of the tested lung conditions (various flows, resistances, compliances, and variations of inspiratory *vs.* expiratory time) allowed for acceptable spontaneous expiration (fig. 2). Using our manual respiration valve, we were able to substantially shorten the expiration through a 16-gauge cannula (table 3 and fig. 2). The Venturi effect being flow dependent, it was no surprise that low flows (below 6 l/min) did not improve results (data not shown).

From the large amount of obtained data, we present only the most illustrative in tables 2 and 3 and figure 2. For example, in the first row of table 3, it could be seen that if flow, compliance, and airway resistance remain unchanged, a flow of 6 l/min delivered 1 liter of air to the artificial lungs in 13.9 s and "aspirated" the same volume in 28.4 s. In contrast, the same volume of air was spontaneously "exhaled" in 37.3 s. Therefore, as the further rows on the right show, the use of the manual respiration valve permitted a higher inspiratory/expiratory time ratio and thus a higher respiratory frequency. The shorter total respiratory cycle consequently resulted in a larger minute volume (1.42 l/min) as compared with spontaneous emptying of the lungs (1.17 l/min). This corresponds to a 31% expiratory or 21% total gain in minute ventilation as compared with the nonfacilitated approach. Therefore, the calculated volumes per second ($R = 128$, $C = 0.01$) were 71.9 ml/s during inspiration and 35.2 ml/s during expiration, for a flow of 6 l/min with the use of the valve and 26.8 ml/s without it. The same conditions tested with a gas flow of 12 l/min (data given in row 10, table 3) resulted in 130.2 ml/s for inspiration and 45.1 ml/s for expiration with, and again 26.8 ml/s without, the manual respiration valve. Conse-

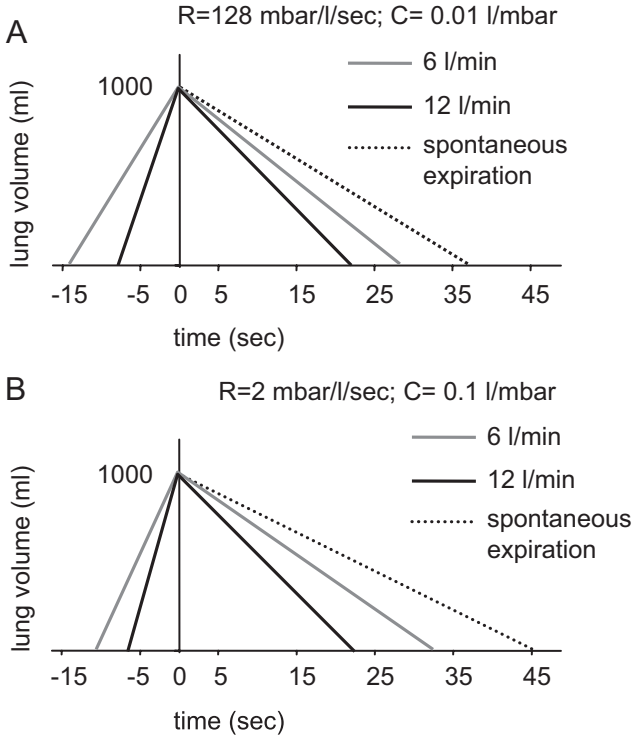

Fig. 2. Examples of inflation and deflation times: the 1-liter test (times recorded at start [empty lung] and 1 liter, respectively). Given are the "inspiratory" and "expiratory" times of the artificial lungs when using the 16-gauge cannula at two different gas flows to achieve 1,000 ml lung volume with the manual respiration valve used in this study. The artificial lung airway resistance and compliance were preset to 128 mbar · l^{-1} · s^{-1}, 0.01 l/mbar (*A*) and 2 mbar · l^{-1} · s^{-1}, 0.1 l/mbar (*B*). On the time scale, inspiration is on the left from zero and expiration on the right. The *dotted line* on the right side represents the expiratory time, which was achieved without the manual respiration valve ("spontaneous expiration").

quently, when increasing the flow rate, both inflation and deflation times for the 1-liter test shortened, but the inspiration/expiration ratio decreased because the increased flow decreased inspiratory time more effectively than expiratory time, which lags progressively behind inspiratory time, a result of an increased turbulent flow, as predicted by the mathematical model. The differences in the inspiratory-*versus*-expiratory time ratios with and without use of the manual respiration valve described previously, however, were also observed with higher gas flows.

Calculated minute volumes for the experiments using the 12-gauge cannula ranged from 2.45 to 3.40 l/min for the spontaneous lung emptying as compared with 2.54 to 4.07 l/min for the manual respiration valve, the maximum increase in expiratory calculated minute volume being 53% for a flow of 12 l/min (C = 0.03 l/mbar, R = 32 mbar · l^{-1} · s^{-1}; table 2). Using the manual respiration valve with the 12-gauge cannula and a low flow did not make a remarkable difference compared with nonfacilitated lung emptying under these circumstances (12% gain). The calculated minute volumes for the experiments using the 16-gauge cannula were in a range between 1.07 and 1.37 l/min for spontaneous expiration as compared with 1.39 and 2.11 l/min for the manual respiration valve, with a maximally achieved increase of 101% (by 12 l/min gas flow, C = 0.1 l/mbar, R = 2 mbar · l^{-1} · s^{-1}; table 3). High airway resistance had little impact on the expiration, whereas low compliance seemed to facilitate expiration, thereby reducing the difference between facilitated and spontaneous expiration.

In Vivo *Experiments*

After adjusting the respiratory times to result in equal volumes being insufflated and "suctioned" (table 1), the pigs used in this study could be successfully ventilated using our manual respiration valve and a 16-gauge cannula for the duration of the experiment (1 h). After the beginning of the facilitated transtracheal ventilation, the arterial oxygen and carbon dioxide partial pressures (the primary outcome measure) quickly increased from normal to a hyperoxic and moderately hypercapnic state in all three tested conditions (high flow [16 l/min]/high frequency [11.3/min], high flow [16 l/min]/low frequency [5.9/min], and low flow [12 l/min]/low frequency [5.9/min]; table 1). After 10 min, arterial oxygen tension (Pa_{O_2})/arterial carbon dioxide tension (Pa_{CO_2}) partial pressures for the three tested ventilation modes were 430.7 ± 114.1/54.0 ± 4.2 mmHg (high-flow/high-frequency mode), 517.6 ± 50.2/54.3 ± 8.4 mmHg (high-flow/low-frequency mode), and 497.1 ± 66.3/49.4 ± 1.1 mmHg (low-flow/low-frequency mode). Thereafter, the Pa_{O_2}/Pa_{CO_2} partial pressures remained stable over a period of 1 h to result in 462.5 ± 75.3/84.4 ± 16.8, 490.5 ± 59.2/64.9 ± 10.0, and 470.8 ± 86.8/63.0 ± 7.2 mmHg after 60 min, respectively (fig. 3). All final Pa_{O_2}/Pa_{CO_2} partial pressures were significantly higher than the initial values before starting transtracheal ventilation (analysis of variance, $P < 0.01$). *Post hoc* pairwise multiple comparison (Student-Newman-Keuls method) confirmed significant differences between initial and final blood gas values ($P < 0.05$, respectively). Within the final Pa_{O_2} values, results did not differ significantly. However, significantly higher Pa_{CO_2} levels were measured in the high-frequency group compared with either one of the low-frequency groups ($P < 0.01$ respectively; figs. 4A–C).

Among the secondary outcome measures, the mean arterial blood pressure was stable during all periods of the study, whereas the cardiac output increased from 4.5 ± 1.1 to 5.0 ± 2.2 l/min ($P > 0.05$) in the high-flow/high-frequency mode but slightly decreased in both low-frequency modes (table 4). Tracheal pressures, which were determined by the ventilatory times in relation to the preset gas flows, were reflected in the central venous pressures. The pulmonary artery pressures revealed significant increases ($P > 0.05$) after 10 min only for the 12-l/min flow experiments and after 60 min for both

Table 3. The "1-Liter Test" Using an Artificial Lung Model, the 16-Gauge Cannula, and the Manual Respiration Valve

Gas Flow, l/min	Compliance, l/mbar	Airway Resistance, mbar · l^{-1} · s^{-1}	Inspiratory Time, s	Expiratory Time, s		Ratio Inspiratory/ Expiratory Time		Calculated Minute Volume, l/min		Calculated Increase of Ventilated Volume by Use of Valve, %	
				With Valve	Without Valve	With Valve	Without Valve	With Valve	Without Valve	Inspiration + Expiration	Expiration Only
6	0.01	128	13.9	28.4	37.3	0.49	0.37	1.42	1.17	21	31
6	0.03	128	11.2	29.7	38.2	0.38	0.29	1.47	1.22	21	29
6	0.1	128	9.9	31.0	42.2	0.32	0.23	1.47	1.15	28	36
6	0.01	32	15.0	26.0	35.0	0.58	0.43	1.46	1.20	22	34
6	0.03	32	10.7	30.0	39.1	0.36	0.27	1.48	1.21	22	30
6	0.1	32	10.2	32.4	40.9	0.32	0.25	1.41	1.17	20	26
6	0.01	2	14.3	26.6	34.8	0.54	0.41	1.47	1.22	20	31
6	0.03	2	11.1	30.7	42.3	0.36	0.26	1.44	1.12	28	38
6	0.1	2	10.4	32.6	45.5	0.32	0.23	1.39	1.07	30	40
12	0.01	128	7.7	22.2	37.3	0.35	0.21	2.01	1.33	51	68
12	0.03	128	6.5	22.5	38.2	0.29	0.17	2.07	1.34	54	70
12	0.1	128	5.9	23.4	42.2	0.25	0.14	2.05	1.25	64	80
12	0.01	32	9.1	19.3	35.0	0.47	0.26	2.11	1.36	55	81
12	0.03	32	7.2	22.3	39.1	0.32	0.18	2.03	1.30	57	75
12	0.1	32	6.5	22.6	40.9	0.29	0.16	2.06	1.27	63	81
12	0.01	2	9.0	19.5	34.8	0.46	0.26	2.10	1.37	54	78
12	0.03	2	7.7	22.5	42.3	0.34	0.18	1.99	1.20	66	88
12	0.1	2	6.3	22.6	45.5	0.28	0.14	2.07	1.16	79	101

The given times were obtained by inflating and deflating the lung model to the 1-liter mark in triplicate. Although the manual respiration valve does not change inspiratory times, expiratory times obtained using the valve are in part substantially shorter as compared with spontaneous expiration, especially using the higher flow.

low-frequency modes (table 4). There were no further changes observed over time, so that the experiments could be halted after 60 min. When the expiratory time was shortened in preliminary experiments, central venous and peak tracheal pressures (and thus presumably intrathoracic pressure) quickly increased due to hyperinflation, resulting in a deterioration of both cardiovascular and blood gas parameters (data not shown).

Discussion

The current investigation demonstrates that a manual respiration valve, functioning as a bidirectional self-sufficient air pump operated by a single person, can provide not only active inflation but also active and satisfactory deflation of the lungs when used with a transtracheal small-diameter cannula and an occluded upper airway. The objective of this study was to test the limits of such a valve *in vitro* and *in vivo*. It was demonstrated that the valve could achieve a substantial gain in ventilated minute volume compared with spontaneous expiration through the cannula *in vitro* as well as satisfactorily ventilate adult pigs using a 16-gauge cannula and gas flows up to 12 l/min. The demonstrated assisted transtracheal ventilation assured remarkable oxygenation with relatively small minute volume and without producing unacceptable carbon dioxide retention. The employed respiration valve thus may solve a known obstacle for the emergency transtracheal ventilation approach by means of a simple mechanism and limited resources.

In airway emergencies, a cricothyrotomy is often not attempted by the first responder because of lack of experience, potential risks associated with the procedure in inexperienced hands, or lack of recommendation for the specific situation. Instead, transtracheal ventilation is attempted by means of commercially available kits or small-bore cannulas. Various but in essence quite similar methods have been developed.[7,14] A number of studies aimed to compare several options for the "cannot intubate, cannot ventilate" situation.[7,12–14,24] These techniques are essentially all similar because none of them have an expiratory aid, and therefore they rely on sufficient passive expiration bypassing the cannula through unobstructed or partially obstructed upper airways. The compressed gas (air or oxygen, 2–4 bars) is driven with force through the transtracheal cannula during inspiration, which overrides the cannula's flow resistance, and the lungs are quickly expanded. The source of the compressed gas is then turned off or is diverted to the outside, and expiration is achieved passively. Here, the driving force for the expiration is the energy stored in the viscoelastic property of the respiratory system during the inspiratory phase (mirrored in the raised intrapulmonary pressure, which is normally 7–15 cm H_2O). Depending on the necessity of the inspired gas to exit the lungs solely through the transtracheal cannula (the degree of upper airway obstruction), it could increasingly accumulate inside the patient's respiratory system after each breath. The stepwise buildup of positive end-expiratory pressure increases the risk for dangerous lung

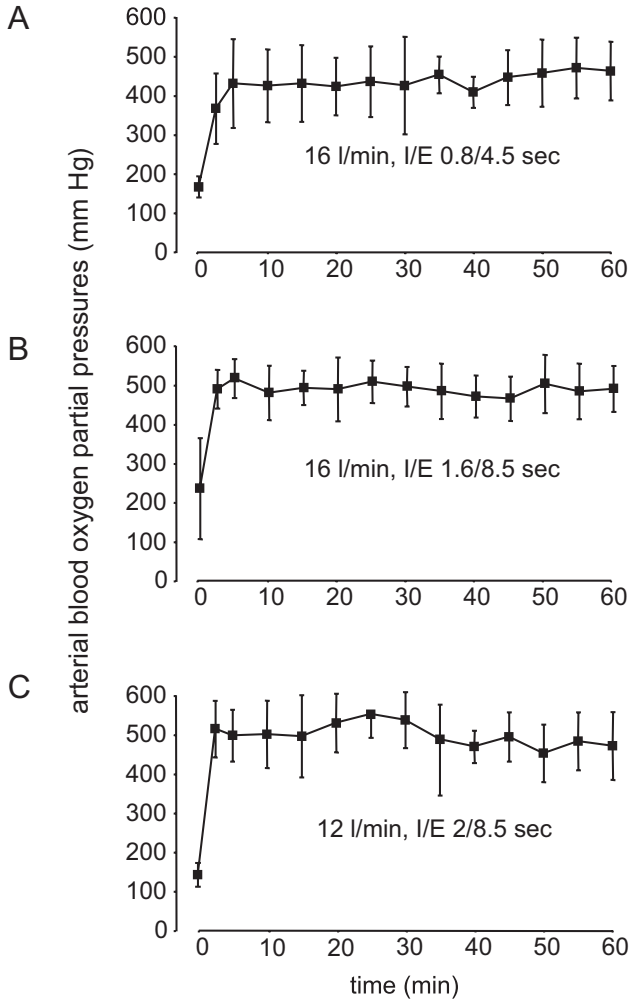

Fig. 3. Time course of the arterial blood oxygen partial pressures. Arterial blood partial pressures for oxygen of the three subsequently tested experimental conditions for flow (in l/min) and inspiration/expiration ratios (I/E) are given over time (*A–C*).

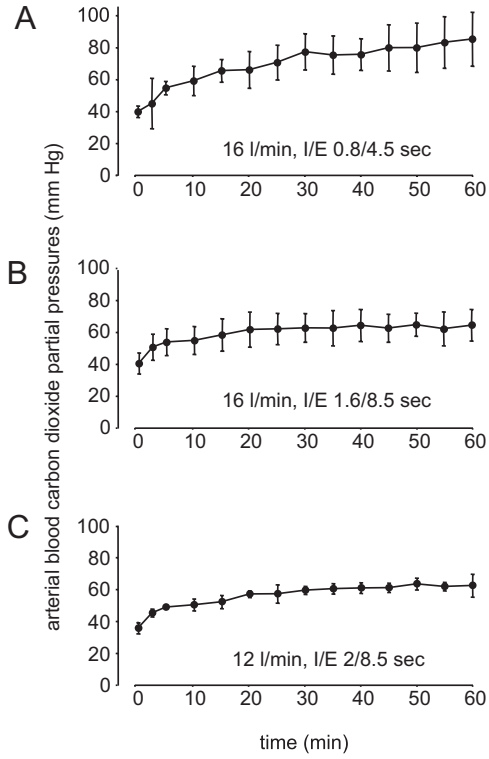

Fig. 4. Time course of the arterial blood carbon dioxide partial pressures. Arterial blood partial pressures for carbon dioxide of the three subsequently tested experimental conditions for flow (in l/min) and inspiration/expiration ratios (I/E) are given over time (*A–C*).

hyperinflation and baro-volutrauma along with cardiovascular compromise with every breath.[25–28] On the other hand, pulmonary ventilation attempting both an adequate tidal volume and complete emptying of the lungs to the functional residual capacity at the end of each expiration could be achieved only by prolonging the expiratory time (given constant inspiratory flow). This attempt would be at the expense of the number of respiratory cycles per minute, which would result in reduced minute ventilation and thus reduced gas exchange compared with the approach described in this study. Therefore, an active expiration through the same cannula as a security measure might help to prevent hyperinflation when performing transtracheal ventilation through a narrow cannula in the case of upper airway obstruction (*e.g.*, due to severe edema, foreign body, inflammation, or nasal, oropharyngeal, or tracheolaryngeal tumors),[29] and enable sufficient ventilation at the same time. Active expiration may also be necessary if the driving force for lung emptying is small, for instance, in very compliant lungs and thoraces (*e.g.*, children), where it could potentially solve the problem of hyperinflation.[29] Alternative devices constructed for use in the operating room deliver active expiration by means of a necessarily wider double-lumen cannula and concomitant suction from a wall outlet.[18,19,21] Dividing the limited diameter of any transtracheal cannula into inlet and outlet canals further diminishes the available diameter for either flow. Moreover, these transtracheal ventilation devices rely on a source of suction for expiratory support. Because of the required additional equipment and the inferior performance for a given cannula diameter, none of these systems would be suitable in the preclinical emergency setting. The manual respiration valve depicted in this study could provide fast inflation and deflation of the lungs by using only oxygen gas flow. The expiration would always be longer than the inspiration, because the outward flow elicited by the Venturi effect is considerably smaller than the chosen flow from the gas source, which is directed into the cannula in full during inspiration.

The current study did not address the usefulness of the device considering various degrees of upper airway obstruction. However, because an open upper airway may render the facilitated expiratory aid provided by our valve unnecessary, the current study might provide a

Table 4. Vital Signs, Tracheal Pressures, and Arterial Blood Gas Analysis Results before, 10 min after, and 60 min after the Initiation of Ventilation Using a Manual Respiration Valve and a 16-Gauge Cannula in Five Pigs

Time, min	Heart Rate, 1/min	Mean Arterial Pressure, mmHg	Cardiac Output, l/min	Mean Pulmonary Artery Pressure, mmHg	Mean Central Venous Pressure, cm H_2O	Maximum Tracheal Pressure, cm H_2O	Minimum Tracheal Pressure, cm H_2O	pH	HCO_3^-, mEq/l	Base Excess, mM	Sa_{O_2}, %
A											
0	87.6 ± 11.2	86.4 ± 21.9	4.5 ± 1.1	14.2 ± 3.5	2.8 ± 1.5	—	—	7.49 ± 0.10	29.7 ± 6.4	5.5 ± 6.9	99.2 ± 0.4
10	93.6 ± 19.6	80.4 ± 18.8	4.1 ± 0.8	16.4 ± 2.5	4.2 ± 2.2	7 ± 2.8	1.8 ± 0.8	7.37 ± 0.08	31.8 ± 9.5	7.5 ± 10.2	99.8 ± 0.1
60	100.8 ± 15.1	75.4 ± 13.0	5.0 ± 2.2	18.4 ± 2.7	5 ± 1.6	6.2 ± 2.4	1.8 ± 0.8	7.24 ± 0.07	30.6 ± 3.3	6.7 ± 3.4	99.8 ± 0.1
B											
0	102.8 ± 9.4	83.8 ± 17.7	4.9 ± 1.0	13.6 ± 1.8	4.2 ± 2.2	—	—	7.49 ± 0.10	30.9 ± 7.0	6.7 ± 7.4	99.4 ± 0.2
10	88.0 ± 14.0	81.0 ± 25.0	3.9 ± 0.8	15.8 ± 2.2	6.6 ± 2.2	7.2 ± 1.3	2.0 ± 1.9	7.33 ± 0.07	26.2 ± 2.8	1.9 ± 3.1	99.8 ± 0.1
60	106 ± 15.9	69.4 ± 8.3	3.9 ± 1.1	17.0 ± 0.7	5.6 ± 1.7	7.6 ± 2.1	1.6 ± 1.1	7.30 ± 0.03	28.6 ± 5.0	4.4 ± 5.4	99.9 ± 0.1
C											
0	106.8 ± 9.2	87.2 ± 19.7	5.3 ± 0.9	13.0 ± 1.4	3.2 ± 1.1	—	—	7.46 ± 0.05	25.8 ± 1.4	1.5 ± 1.6	98.8 ± 0.5
10	92.4 ± 11.5	80.4 ± 24.7	3.9 ± 1.0	16.2 ± 1.1	5.8 ± 1.3	7.8 ± 2.8	2.2 ± 1.5	7.34 ± 0.03	25.4 ± 2.1	1.0 ± 2.3	99.8 ± 0.1
60	95.8 ± 16.3	74.8 ± 10.8	4.1 ± 1.1	19.0 ± 1.4	7.0 ± 2.0	9.4 ± 1.1	3.6 ± 1.9	7.30 ± 0.05	27.6 ± 4.2	3.4 ± 4.6	99.8 ± 0.1

See figure 3 for arterial oxygen tension and arterial carbon dioxide tension values. The three subsequently tested experimental conditions for flow and inspiration/expiration ratios (I/E) were 16 l/min, I/E 0.8/4.5 s (A); 16 l/min, I/E 1.6/8.5 s (B); and 12 l/min, I/E 2/9.0 s (C).

HCO_3^- = bicarbonate; Sa_{O_2} = arterial oxygen saturation.

promising addition to established transtracheal emergency ventilation solutions. When a large transtracheal cannula is used, spontaneous expiration may occur more rapidly. Moreover, at very low flows, a manual respiration valve has little advantage over spontaneous expiration. With a smaller cannula and flows of 12 l/min or higher, the expiratory aid provided by the Venturi effect becomes significant (tables 2 and 3 and fig. 2). Therefore, it is conceivable that when using a 16-gauge transtracheal cannula, which offers high resistance to the gas flow, spontaneous expiration through the cannula becomes even less effective, and the use of the manual respiration valve offers obvious advantages in this model (fig. 2). Changing only airway resistance *in vitro* did not remarkably affect ventilatory times, the obvious point of high resistance always being the transtracheal cannula itself. However, compliance changes remarkably affected both inspiratory and expiratory time. More compliant lungs, which could be inflated rather quickly, emptied slower and needed more time to return to their functional residual capacity as compared with less compliant lungs, and our manual respiration valve was beneficial under these conditions (tables 2 and 3 and fig. 2). The extent to which these findings might also work in an adult patient weighting twice as much as the studied animals depends on a variety of variables and therefore needs further investigation.

Taken together, the results of the current study prove the concept of facilitated transtracheal lung ventilation through a narrow cannula in case of an occluded upper airway *in vitro*, and show that a 16-gauge transtracheal cannula may provide satisfactory lung ventilation in a 40-kg animal *in vivo*. The proposed manual respiration valve is able to provide the necessary expiratory support in case of an occluded upper airway in this model. If a narrow transtracheal cannula, high oxygen gas flows, and an adjusted inspiration/expiration ratio are to be used, the manual respiration valve tested in this study may help to increase minute ventilation and thus oxygen delivery compared with spontaneous expiration through the cannula. For adequate transtracheal ventilation of human lungs, additional studies are necessary to investigate required gas flows, airway pressures, and the influence of only partial upper airway occlusion. Security measures such as end-expiratory airway pressure monitoring may then be required to prevent hyperinflation.

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