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ORIGINAL ARTICLE

Tidal volume and airway pressure under percutaneous transtracheal ventilation without a jet ventilator: comparison of high-flow oxygen ventilation and manual ventilation in complete and incomplete upper airway obstruction models

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Abstract

Purpose Percutaneous transtracheal ventilation (PTV) can be life-saving in a cannot ventilate, cannot intubate situation. The aim of this study was to investigate the efficacy of PTV by measuring tidal volumes (VTs) and airway pressure (Paw) in high-flow oxygen ventilation and manual ventilation using a model lung.

Methods We examined 14G, 16G, 18G, and 20G intravenous catheters and minitracheotomy catheters. In high-flow oxygen ventilation, the flow was set to 10 L/min, while the inspiratory:expiratory phases (I:E) were 1 s:4 s in the complete upper airway obstruction model and 1 s:1 s in the incomplete obstruction model. In manual ventilation, I:E were 2 s:4 s in the complete obstruction model and 2 s:3 s in the incomplete obstruction model. We ventilated through each catheter for 2 min and measured VT and Paw.

Results In high-flow ventilation, the average VTs were approximately 150 ml and <100 ml with 14G catheters in complete and incomplete upper airway obstruction, respectively. The VTs obtained were reduced when the bore size was decreased. In manual ventilation, the average VTs were over 300 ml and approximately 260 ml with 14G catheters in complete and incomplete upper airway obstruction, respectively. In high-flow ventilation, the airway pressure tended to be higher. The minitracheotomy catheters produced over 800 ml of VT and created almost no positive end-expiratory pressure.

Conclusions High-flow ventilation tends to result in higher airway pressure despite a smaller VT, which is probably due to a PEEP effect caused by high flow.

Keywords Difficult airway · Tidal volume · Airway pressure

Introduction

In a cannot ventilate, cannot intubate (CVCI) situation, percutaneous transtracheal ventilation (PTV) using an intravenous (i.v.) catheter inserted through the cricothyroid membrane can be life-saving. It is stated in the difficult airway algorithm of the American Society of Anesthesiologists that transtracheal jet ventilation (TTJV) should be performed in a CVCI situation [1]. In such cases, if a jet ventilator is not readily available, or if the upper airway is completely obstructed, ventilation with high-flow oxygen delivered from an oxygen outlet or manual ventilation with a bag can be applied via the tracheal catheter.

Various PTV techniques using high-flow oxygen have been proposed, with inspiratory:expiratory phases (I:E) of 0.5 s:0.5 s to 1 s:4 s and flow rates of 5–15 L/min [2–5]. Manual ventilation by vigorously squeezing a bag is presented as an alternative, but less effective method [4, 6]. Recently, it has been proposed that there is a possible danger of high airway pressure during high-flow oxygen ventilation [7, 8].

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We measured tidal volumes (VTs) and airway pressure (Paw) in high-flow oxygen ventilation and manual ventilation through i.v. catheters and minitracheotomy catheters using a model lung, and tried to prove the hypothesis that manual ventilation with a bag can be effective and may cause less hyperinflation of the lungs compared to high-flow oxygen ventilation in complete or near-complete upper airway obstruction.

Materials and methods

Experimental models

Our experimental model (Fig. 1) consisted of a model lung with a hose (inner diameter (ID) 16 mm, 48 cm long) as a simulated trachea (Vent-Aid TTL; Michigan Instruments, Grand Rapids, MI, USA), a test catheter (A: Surflo; Terumo, Tokyo, Japan, B: Supercath; Medikit, Tokyo, Japan, C: Trahelper, Top, Tokyo, Japan, D: MiniTrach, Smith Medical, Tokyo, Japan), and an oxygen-supplying tube (green bubble tube; Nippon Sherwood, Tokyo, Japan) with a side hole (2.8 × 3.6 mm) or a self-inflating bag (Silicone Resuscitator; Laerdal, Tokyo, Japan) in the model of complete upper airway obstruction. In the model of incomplete upper airway obstruction, a 14G i.v. catheter (ID 1.7 mm, 51 mm long) (Surflo) was added to the other end of an elbow connector as a very narrow upper airway with near-complete obstruction. Each catheter was securely connected and sealed to prevent air from leaking. The oxygen-supplying tube was directly connected to the i.v. catheter tested. The self-inflating bag was connected to the i.v. catheter via a 3.0 tracheal tube adaptor, to the Trahelper™ via a 3.5 tracheal tube adaptor, and to the MiniTrach™ via an adaptor supplied as an accessory.

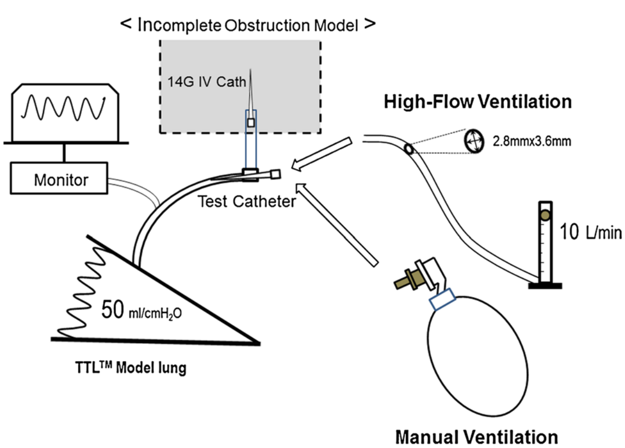

Fig. 1 The experimental model. The model consisted of a model lung with 50 ml/cm H_2O compliance, a connecting hose, and a test i.v. catheter. In the incomplete upper airway obstruction model, a 14G i.v. catheter was added and attached to the other end of an elbow connector as a very narrow upper airway with near-complete obstruction (in the *gray area*). In high-flow oxygen ventilation, an oxygen-supplying tube with a side hole (2.8 × 3.6 mm) was connected to the test catheter, and the oxygen flow was set at 10 L/min. In manual ventilation, a self-inflating bag was attached to the test catheter

Methods

Six anesthesiologists (3 men and 3 women) participated in the study. We examined 14G, 16G, 18G, and 20G i.v. catheters that were 51 mm (A) or 31 mm (B) long. In manual ventilation, we also examined two minitracheotomy catheters (C; ID 3.3 mm, 49 mm long, D; ID 4 mm, 92 mm long), both of which are designed for cricothyrotomy. The compliance of the model lung was set at 50 ml/cm H_2O. In high-flow oxygen ventilation, the oxygen flow was set at 10 L/min and the subjects opened and closed the side hole of the oxygen-supplying tube in order to ventilate. The inspiratory:expiratory phases (I:E) were 1 s:4 s in the complete obstruction model and 1 s:1 s in the incomplete obstruction model. In manual ventilation, the subjects squeezed the self-inflating bag as hard as they could. I:E were 2 s:4 s in the complete obstruction model and 2 s:3 s in the incomplete obstruction model. (The I:E phases were chosen arbitrarily.) The subjects could see the time on a digital clock and could hear a digital tone so that the subjects keep up their pace. The catheters were examined in random order, and the subjects were blinded to the catheter being tested. We ventilated through each catheter for 2 min. Airway pressure (Paw) and inspiratory flow signal were sampled and recorded at 1 kHz using an analog-to-digital converter (Model DI200; Dataq Instruments, Akron, OH, USA) and Windaq™ data acquisition software (Dataq Instruments) running on a personal computer. Breath-by-breath inspiratory tidal volumes (VTs) were measured by integrating the inspiratory flow signals.

Statistical analysis

Data were analyzed with a two-way factorial ANOVA. A p value <0.01 was considered statistically significant.

Results

Complete upper airway obstruction model

VT

A slight decay in the VT over the first several breaths was observed with i.v. catheters in both high-flow and manual ventilation.

Table 1 VTs (ml) in complete upper airway obstruction

		High-flow ventilation (I:E = 1 s:4 s)		Manual ventilation (I:E = 2 s:4 s)	
14G					
	A	148.6 ± 15.2		327.3 ± 45.8	
	B	153.5 ± 19.4		330.5 ± 45.5	
16G			*		†
	A	121.5 ± 16.0		194.4 ± 23.7	
	B	134.9 ± 18.6		208.9 ± 25.1	
18G			**		† †
	A	104.8 ± 8.1		116.4 ± 17.8	
	B	109.7 ± 7.6		118.6 ± 19.3	
20G			***		† † †
	A	76.2 ± 9.9		90.8 ± 8.4	
	B	79.4 ± 8.1		93.9 ± 8.5	
Minitracheotomy					
	C	–		878.5 ± 122.7	
	D	–		974.6 ± 157.1	

Data are presented as mean ± SD. Catheter length; A: 51 mm, B: 31 mm. Catheter size; C: ID 3.3 mm, 49 mm long, D: ID 4 mm, 92 mm long

*,† $P < 0.01$ was considered significant

The average VTs are shown in Table 1. In high-flow ventilation, the average VTs in the 14G catheters were 148.6 ± 15.2 ml (A) and 153.5 ± 19.4 ml (B). In manual ventilation, the average VTs in the 14G i.v. catheters were 327.3 ± 45.8 ml (A) and 330.5 ± 45.5 ml (B). The VTs obtained decreased significantly as the bore of the catheter was downsized ($p < 0.01$). The length of the catheter did not make a significant difference. The minitracheotomy catheters produced VTs of 878.5 ± 122.7 ml (C) and 974.6 ± 157.1 ml (D).

Paw

Slow but progressive elevation of the peak and end-expiratory airway pressures were observed for the first minute with all of the i.v. catheters, but not with any of the minitracheotomy catheters.

Figures 2 and 3 show the end-expiratory airway pressure right before the last inspiration and the peak airway pressure of the last inspiration after 2 min of ventilation. The data are presented as the mean ± SD of A (51 mm long) and B (31 mm long) combined in each i.v. catheter.

In high-flow ventilation, the airway pressure was very high despite the lower VTs, especially with smaller-bore catheters. In manual ventilation, high airway pressures occurred in 14G and 16G catheters, whereas the two minitracheotomy catheters did not create a significant positive end-expiratory pressure (PEEP) (Fig. 2).

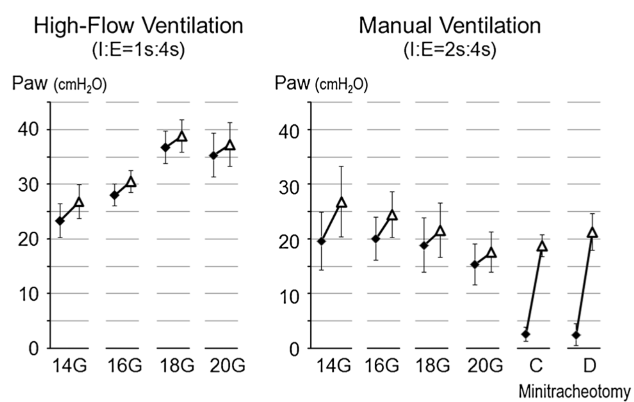

Fig. 2 Airway pressure in complete upper airway obstruction. The graphs show the end-expiratory airway pressure right before the last inspiration (*filled diamond*) and the peak airway pressure of the last inspiration (*unfilled triangle*) with high-flow oxygen ventilation (*left panel*) and with manual ventilation (*right panel*). Very high airway pressure occurred in high-flow ventilation. Manual ventilation with the two minitracheotomy catheters did not create a significant positive end-expiratory pressure. Data are presented as the mean ± SD. Catheter size; C: ID 3.3 mm, 49 mm long, D: ID 4 mm, 92 mm long

Incomplete upper airway obstruction model

VT

The average VTs are shown in Table 2. In high-flow ventilation, the average VTs were <100 ml in the 14G catheters. The other catheters generated even smaller VTs ($p < 0.01$). In manual ventilation, the average VTs were

Table 2 VTs (ml) in incomplete upper airway obstruction

		High-flow ventilation (I:E = 1 s:1 s)		Manual ventilation (I:E = 2 s:3 s)	
14G					
	A	93.8 ± 17.3		258.9 ± 42.7	
	B	96.4 ± 16.6		276.8 ± 31.8	†
16G			*		
	A	72.8 ± 13.9		144.9 ± 15.3	
	B	72.7 ± 14.5		147.4 ± 18.4	
18G			**		† †
	A	44.0 ± 5.7		65.7 ± 5.6	
	B	45.8 ± 5.4		69.8 ± 2.6	
20G			***		† † †
	A	31.2 ± 5.1		46.0 ± 5.5	
	B	33.1 ± 5.4		47.0 ± 5.4	
Minitracheotomy					
	C	–		778.6 ± 123.5	
	D	–		891.5 ± 117.2	

Data are presented as mean ± SD. Catheter length; A: 51 mm, B: 31 mm. Catheter size; C: ID 3.3 mm, 49 mm long, D: ID 4 mm, 92 mm long

*,† $P < 0.01$ was considered significant

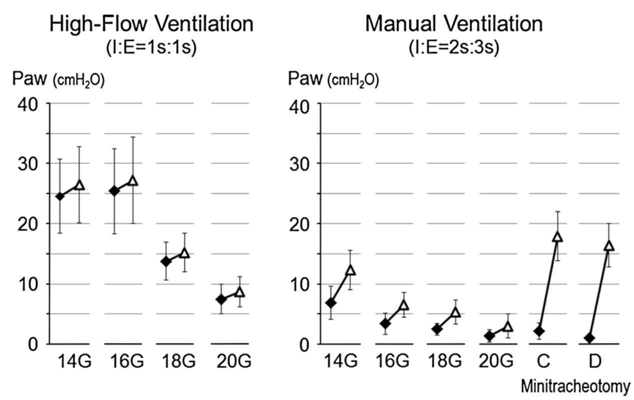

Fig. 3 Airway pressure in incomplete upper airway obstruction. The graphs show the end-expiratory airway pressure right before the last inspiration (*filled diamond*) and the peak airway pressure of the last inspiration (*unfilled triangle*) with high-flow oxygen ventilation (*left panel*) and with manual ventilation (*right panel*). In high-flow oxygen ventilation, the airway pressure is higher than in manual ventilation despite smaller VTs (refer to the results shown in Table 2). Data are presented as the mean ± SD. Catheter size; C: ID 3.3 mm, 49 mm long, D: ID 4 mm, 92 mm long

258.9 ± 42.7 ml (A) and 276.8 ± 31.8 ml (B) in the 14G catheters. The VTs obtained decreased significantly as the bore of the catheter was downsized ($p < 0.01$). Catheter length did not make a significant difference. The minitracheotomy catheters produced VTs of 778.6 ± 123.5 ml (C) and 891.5 ± 117.2 ml (D).

Paw

In high-flow ventilation, despite the smaller VTs, the airway pressure was very high, especially in the 14G and 16G catheters. In manual ventilation, however, the airway pressure was much lower compared to that in complete airway obstruction (Fig. 3).

Discussion

We have demonstrated that ventilating manually with a bag through a 14G i.v. catheter can produce approximately 300 ml of VT delivered in 2 s in complete and near-complete upper airway obstruction, and that the minitracheotomy catheters produced 800 ml of VTs without PEEP. We also found that high-flow ventilation tends to result in higher airway pressure along with a smaller VT.

Needle cricothyrotomy can provide temporary, supplemental, but crucial oxygenation to sustain life in a desperate CVCI situation. It is a simple and relatively safe technique. The ASA difficult airway algorithm shows that TTJV following cricothyrotomy should be performed if a laryngeal mask airway fails [1].

Since Reed et al. [9] first reported successful oxygenation through the cricothyroid membrane in 1954, several different methods of PTV— jet ventilation with a high-pressure oxygen source, high-flow oxygen ventilation, and manual ventilation with a bag—have been proposed.

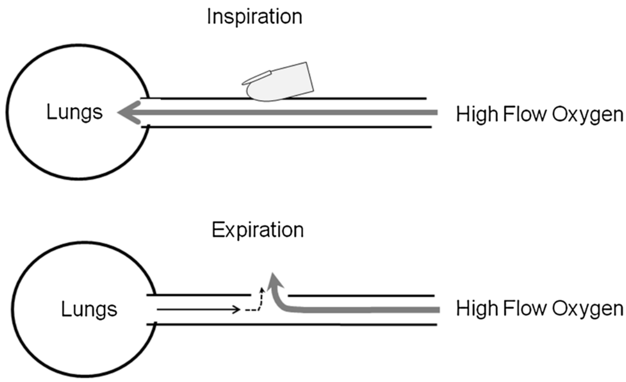

Fig. 4 Mechanism underlying the PEEP effect in high-flow oxygen ventilation. During inspiration, the flow enters the lungs (*upper panel*). The flow continues during the expiration phase and exits through the side hole. Since the flow rate is very high, substantial pressure is created in the oxygen-supplying tube, and this hinders exhalation (*lower panel*)

Benumof recommended three acceptable systems of PTV: a jet ventilator/injector, a flush valve of an anesthesia machine, and a high flow (15 L/min) of oxygen from a wall outlet or oxygen tank with a 1:1 I:E ratio to provide adequate tidal volume. He also mentioned that manual ventilation with a self-inflating bag would not achieve a significant amount of ventilation through an i.v. catheter [4]. Recent studies, however, showed a possible danger of high airway pressure in high-flow oxygen ventilation [7, 8].

When performing PTV through an i.v. catheter, several factors need to be considered. If a jet ventilator is not feasible—i.e., if equipment is not readily available, or in the case of complete upper airway obstruction—ventilation with high-flow oxygen or with manual bagging can be employed. In high-flow oxygen ventilation, various techniques have been proposed, with I:E phases of 0.5 s:0.5 s to 1 s:4 s and flow rates of 5–15 L/min [2–5]. The results of the present study suggest that an I:E phases of 1 s:4 s in complete upper airway obstruction and 1 s:1 s in incomplete upper airway obstruction using an oxygen flow of 10 L/min or more can result in dangerously high airway pressure, despite a low VT. This is compatible with the instruction in The American Trauma Life Support (ATLS)® textbook, which recommends an I:E phase of 1 s:4 s with high flow ventilation, and also cautions that, in cases of complete obstruction, the flow rate should be lower (5–7 L/min), and that 4 s of exhalation can be inadequate [5]. There appears to be no universal optimal I:E phase to perform PTV, since many factors, such as the patient's lung and chest compliance, the degree of upper airway obstruction, body weight, and pre-existing lung disease, vary from patient to patient. It is very important to closely observe the rise and fall of the chest to confirm that the lungs are not overinflating.

Also, according to our results, in cases of complete or near-complete upper airway obstruction, manual ventilation through a 14G i.v. catheter could provide approximately 300 ml of VT in 2 s, which can provide approximately 3 L of minute volume. This could be useful to provide adequate oxygenation to sustain life for a while, possibly preventing rapid elevation of CO_2. However, when the degree of upper airway obstruction is not severe and the leakage from the upper airway is high, less VT can be delivered. In addition, it is extremely tiresome to squeeze the bag vigorously, and hence the personnel need to be changed frequently. Moreover, manual ventilation cannot be effective with smaller-bore catheters. We also found that the minitracheotomy catheters, which have IDs of 3.3 and 4.0 mm, can provide large VTs and create almost no PEEP in manual ventilation with a self-inflating bag. In addition, they are less kinkable, while i.v. catheters are easily kinked [10]. Therefore, a minitracheotomy catheter may be a better choice if available and if time allows.

One of the most serious complications of PTV is hyperinflation of the lungs due to inadequate venting of inspired gases in the presence of complete or near-complete upper airway obstruction [4, 11]. Since oxygenation is more important than the efficacy of CO_2 elimination in order to sustain life for a relatively short time until a definitive airway is secured, it may be more important to give the patient enough time to exhale than to provide normal minute volume to maintain normocapnia in cases of complete or near-complete upper airway obstruction. This is especially true when a smaller-bore catheter, such as an i.v. catheter, is used.

The most likely mechanism by which higher airway pressure occurs in high-flow ventilation is follows (Fig. 4). During inspiration, the flow enters the lungs; it then continues during the expiration phase and exits through the side hole. Since the flow rate is very high, substantial pressure is created in the oxygen-supplying tube. This hinders exhalation and hence causes a pile-up in lung volume and overinflation of the lungs. The higher the flow rate is, and the smaller the side hole is, the higher the airway pressure becomes [8]. Therefore, the side hole in the oxygen supplying tube should be large enough to minimize the PEEP effect. We recommend that a three-way stopcock never be used as a flow splitter, as its IDs is small (usually ~2 mm or less) and the airway pressure could be dangerously high [8]. An oxygen flow modulator, which has multiple side openings to adjust flow [12], can help minimize PEEP in the oxygen-supplying tube by releasing all of the openings [7, 8]. Otherwise, it may be necessary to periodically discontinue oxygen flow in order to allow adequate exhalation. More importantly, during PTV, the natural airway must be maintained as well as possible [4, 6, 10] in order to minimize the trapping of air and overdistension of the lungs.

This study has some important limitations. First, 50 ml/cm H_2O of lung compliance was chosen arbitrarily, whereas, in a clinical setting, compliance varies among individuals and changes with lung volume. Secondly, using a 14G i.v. catheter as an upper airway with near-complete obstruction may not be an accurate simulation. In actual cases, expiration from the upper airway occurs only when the airway pressure increases and opens the airway, and the amount of expiration varies among clinical cases depending on how much the airway is obstructed. Therefore, our data cannot be extrapolated directly to patients.

In conclusion, when performing PTV through an i.v. catheter for complete or near-complete upper airway obstruction, the airway pressure can be dangerously high due to difficulty with exhalation. In particular, high-flow oxygen ventilation tends to result in a higher airway pressure despite smaller VTs, probably due to a PEEP effect. Therefore, it is very important to closely observe the rise and fall of the chest to verify inflation and deflation of the lungs. Most importantly, a definitive airway must be secured as quickly as possible.

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