Surg Today (2001) 31:780–784

SURGERY TODAY

Pressure-Controlled Ventilation Via a Minitracheostomy Tube: Experimental Study Using a Mechanical Lung Model

Hiroaki Nomori, Hirotoshi Horio, and Keiichi Suemasu

Department of Thoracic Surgery, Saiseikai Central Hospital, 1-4-17 Mita, Minato-ku, Tokyo 108-0073, Japan

Abstract To obtain basic data on pressure-controlled ventilation (PCV) via a minitracheostomy tube (MTT), we conducted an experimental study using a mechanical lung model. MTTs with internal diameters of 4.0, 4.5-, and 5.0mm were used. To examine the effectiveness of PCV via an MTT for the lung with low compliance, the ventilated volumes were measured at compliances ranging from 10 to 50ml/cmH_2O. The alveolar pressures and ventilated volumes of the 4.0-, 4.5-, and 5.0-mm MTTs were about 40%, 50%, and 60% of the values for the 8.0-mm endotracheal tube in the absence of air leakage, respectively, and in the presence of air leakage they fell a further 20%. To obtain a ventilated volume of 500ml, the inspiratory pressures needed were 40, 30, and 20cmH_2O for the 4.0-, 4.5-, and 5.0-mm MTTs, respectively. In the model of low lung compliance (10ml/cmH_2O), the ventilated volumes decreased to 40% of those seen in the normal compliance model (50ml/cmH_2O) at each inspiratory pressure, due to greater air leakage. PCV via an MTT produced acceptable ventilated volumes in the lung model with air leakage. However, our results indicate that under conditions of low lung compliance, PCV via an MTT is insufficient because of the greater air leakage.

Key words Pressure-controlled ventilation · Lung cancer · Respiratory failure · Minitracheostomy tube

Introduction

Tracheal ventilation via a minitracheostomy tube (MTT) is generally used in emergency life-saving procedures when tracheal intubation is not feasible due to total airway obstruction. In such situations, ventilation is usually achieved by jet ventilation, oxygen flush, or the standard anesthesia circle system with high pressure.[1] Gregoretti et al. reported a case of flail chest successfully treated using ventilatory support via an MTT.[2] Since 1997, we have used this procedure for the respiratory management of patients after lung cancer surgery, and found that it improves the gas exchange and reduces the work of breathing by providing adequate ventilatory support, as described in our previous report.[3] Since 1998, we have also used this procedure to manage pump respiratory failure in patients with neuromuscular diseases such as Duchenne's muscular dystrophy (DMD) and myasthenia gravis (MG), with satisfactory results (Fig. 1).[4] Briefly, an MTT without a cuff is introduced via the cricothyroid membrane and attached to a ventilator in pressure-controlled ventilation (PCV) mode. Adequate ventilation with the preservation of speech has been achieved with PCV via an MTT for both patients with DMD and those with MG. Patients breathe out most of the expired volume through their mouth or nose rather than through the tube and are therefore able to speak with a loud voice. This report describes a detailed mechanical experiment conducted to examine the effect of inspiratory pressure, MTT diameter, and lung compliance on the ventilated volumes using a mechanical lung model, to determine the optimal conditions and limitations of this procedure.

Materials and Methods

An MTT with an internal diameter (i.d.) of 4.0 mm (Minitrach II, Portex, Hythe, Kent, UK) and uncuffed tracheostomy tubes with i.d.s of 4.5 and 5.0 mm, designed for use in infants (Portex Blueline Tracheostomy Tube, Portex), were used in these experiments and will be referred to as the 4.0-, 4.5- and 5.0-mm MTTs. These tubes were selected because they are

Reprint requests to: H. Nomori
Received: October 17, 2000 / Accepted: March 6, 2001

generally used in clinical application for respiratory management after lung cancer surgery and for pump respiratory failure due to neuromuscular disease.

The airway resistance values of the MTTs and 8-mm i.d. endotracheal tube were examined by measuring the airway pressure at air flow rates of 10–90 l/min. Airway resistance was calculated as the airway pressure (cmH_2O) divided by air flow (l/min).

The PCV via the MTT was tested using a mechanical lung model (TTL, Michigan Instruments, Grand Rapids, MI, USA) and a ventilator (O'NYX Plus; Nellcor Puritan Bennett France Development, Villers Les Nancy, France). Because MTTs lack cuffs, PCV via an MTT is accompanied by air leakage from the mouth and nose in clinical practice. Therefore, a leakage adapter, 2 mm in diameter, was used to represent clinical air leakage in this lung model. An 8-mm endotracheal tube without air leakage was used as a control to represent conventional mechanical ventilation. Lung compliance was set to 50 ml/cmH_2O, and the ventilator was set to PCV mode with a fixed inspiratory time of 1 s, and a positive endoexpiratory pressure (PEEP) of 0 cmH_2O. The inspiratory pressure was varied from 15 to 40 cmH_2O. The alveolar pressure of the lung model and the inspired volume of the ventilator were measured using a calibration analyzer (RT-200, Timester, St. Louis, MO, USA). The ventilated volume was read from the graduations of the model lung. The volume of air lost through the leakage adapter was calculated by subtracting the ventilated volume from the inspired volume.

To model respiratory failure due to a gaseous exchange impediment with low lung compliance, as occurs in pneumonia, the lung compliance of the model lung was lowered to 30 and 10 ml/cmH_2O; then the inspiratory pressure was varied from 30 to 80 cmH_2O. The ventilated volumes and leakage volumes achieved using the 4.5-mm MTT were measured under these conditions.

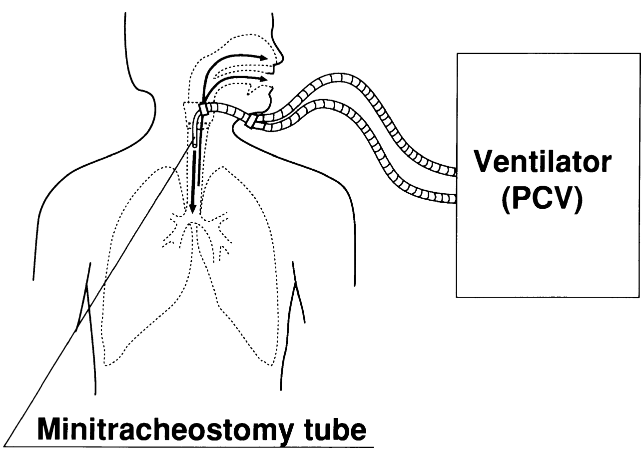

Fig. 1. Schema of pressure-controlled ventilation via a minitracheostomy tube. While inspired volume enters the airway via a minitracheostomy tube, patients breathe out most of the expired volume through their mouth or nose

Results

When air flow was varied from 10 to 90 l/min, the airway resistance values of the 4.0-, 4.5-, and 5.0-mm MTTs were approximately 20, 14, and 10 times higher than that of the 8.0-mm endotracheal tube, respectively (Table 1).

In the absence of air leakage, the alveolar pressures, inspired volumes, and ventilated volumes of the 4.0-, 4.5, and 5.0-mm MTTs were about 40%, 50%, and 60% of the values for the 8.0-mm endotracheal tube, respectively (Tables 2–5). In comparison with the PCV via the MTT without air leakage, the PCV via the MTT with air leakage resulted in 20% lower alveolar pressure and 20% lower ventilated volume for each MTT, whereas the inspired volume increased (Tables 2–5). To produce a ventilated volume of 500 ml via the 4.0-, 4.5-, and 5.0-mm MTTs, while allowing air leakage, inspiratory pressures of 40, 30, and 20 cmH_2O, respectively, were necessary (Tables 2–5).

When the lung compliance was reduced to 30 and 10 ml/cmH_2O, the ventilated volume decreased to 80% and 40% of that seen at 50 ml/cmH_2O at each pressure, respectively, due to greater air leakage (Table 6).

Table 1. Minitracheostomy and endotracheal tube airway resistance

	Air flow (l/min)								
Resistance (cmH_2O/l/s)	10	20	30	40	50	60	70	80	90
MTT 4 mm i.d.	17	30	42	56	68	77	91	98	111
MTT 4.5 mm i.d.	15.6	18.3	27	35.1	44.2	52.5	61.6	68.4	77.7
MTT 5 mm i.d.	7.8	12.9	18.4	24.3	29.4	36.4	41.1	47.3	52.6
Endotracheal tube	1.1	1.6	2.0	2.6	3.1	3.6	4.2	4.9	5.2

MTT, minitracheostomy tube; i.d., internal diameter

Table 2. Alveolar pressure, inspired volume, and ventilated volume via an endotracheal tube 8 mm in internal diameter without air leakage

	Set pressure (cmH_2O)					
	40	35	30	25	20	15
Alveolar pressure (cmH_2O)	35.2	32.0	28.6	24.7	21.0	14.9
Inspired volume (1)	1.71	1.55	1.39	1.21	1.10	0.80
Ventilated volume (1)	1.71	1.55	1.39	1.21	1.10	0.80

Table 3. Alveolar pressure, inspired volume, ventilated volume, and leakage volume via a minitracheostomy tube, 4 mm in internal diameter, with or without air leakage

	Set pressure (cmH_2O)					
	40	35	30	25	20	15
Without air leakage						
Alveolar pressure (cmH_2O)	14.6	13.7	12.6	11.5	10.2	8.2
Inspired volume (1)	0.68	0.62	0.56	0.50	0.45	0.38
Ventilated volume (1)	0.68	0.62	0.56	0.50	0.45	0.38
With air leakage						
Alveolar pressure (cmH_2O)	11.8	10.9	10.0	9.0	8.0	7.0
Inspired volume (1)	0.69	0.64	0.58	0.52	0.45	0.40
Ventilated volume (1)	0.50	0.45	0.40	0.38	0.32	0.30
Leakage volume (1)	0.19	0.19	0.18	0.14	0.13	0.10

Table 4. Alveolar pressure, inspired volume, ventilated volume, and leakage volume via a minitracheostomy tube, 4.5 mm in internal diameter with or without air leakage

	Set pressure (cmH_2O)					
	40	35	30	25	20	15
Without air leakage						
Alveolar pressure (cmH_2O)	17.0	15.8	14.5	13.1	11.9	9.6
Inspired volume (1)	0.79	0.72	0.65	0.58	0.5	0.4
Ventilated volume (1)	0.8	0.72	0.65	0.58	0.5	0.4
With air leakage						
Alveolar pressure (cmH_2O)	13.8	12.8	11.7	10.5	9.3	7.6
Inspired volume (1)	0.9	0.87	0.70	0.63	0.55	0.49
Ventilated volume (1)	0.65	0.55	0.50	0.45	0.40	0.35
Leakage volume (1)	0.25	0.22	0.20	0.18	0.15	0.14

Table 5. Alveolar pressure, inspired volume, ventilated volume, and leakage volume via a minitracheostomy tube, 5 mm in internal diameter with or without air leakage

	Set pressure (cmH_2O)					
	40	35	30	25	20	15
Without air leakage						
Alveolar pressure (cmH_2O)	20.3	17.8	16.3	14.8	12.9	10.7
Inspired volume (1)	0.98	0.9	0.81	0.72	0.62	0.58
Ventilated volume (1)	0.98	0.9	0.81	0.72	0.62	0.58
With air leakage						
Alveolar pressure (cmH_2O)	17.2	15.9	14.5	13.0	11.0	10.3
Inspired volume (1)	1.01	0.93	0.85	0.75	0.65	0.60
Ventilated volume (1)	0.8	0.75	0.65	0.60	0.50	0.46
Leakage volume (1)	0.21	0.18	0.20	0.15	0.15	0.14

Table 6. Ventilated volume and leakage volume via a minitracheostomy tube, 4.5 mm in internal diameter, with air leakage in relation to lung compliance and set pressure

Lung compliance (ml/cmH_2O)	Ventilated volume (l)/Leakage volume (l) MTT in the set pressure (cmH_2O) of		
	30	50	80
50	0.50/0.19	0.69/0.20	0.95/0.35
30	0.40/0.21	0.55/0.32	0.72/0.41
10	0.19/0.32	0.28/0.51	0.36/0.73

Discussion

From 1997 to 1998, we conducted PCV via an MTT using a 4.0-mm MTT for the respiratory management of 32 patients following lobectomy for lung cancer.[3] The PCV conditions used were an inspiratory pressure of 20 cmH_2O, and an inspiratory time of 1.0 s to produce a 450-ml supported volume via the MTT per breath. As a result, compared with spontaneous breathing, this procedure produced a significantly higher ventilated volume, increased PaO_2, decreased $PaCO_2$, and decreased the respiratory rate. Since 1998, we have conducted PCV via an MTT to manage neuromuscular disease patients with pump respiratory failure, using a 4.5- or 5.0-mm MTT.[4] The PCV conditions we use are an inspiratory pressure of 20–30 cmH_2O, an inspiratory time of 1.0 s, a positive end-expiratory pressure of 0 cmH_2O, and a respiratory rate of 15/min. The present study indicates that these conditions produce a ventilated volume of 400–650 ml in the presence of air leakage. To date, we have successfully conducted PCV via an MTT for ten patients with DMD for a mean period of 303 days, and for five patients with MG for a mean period of 64 days. Our experimental results clearly support the effectiveness of PCV via an MTT for respiratory management after lung surgery and for pump respiratory failure in patients with neuromuscular diseases.

Using a mechanical lung model, we have shown that PCV via an MTT can produce an acceptable ventilated volume despite high airway resistance. The airway resistance values of the 4.0-, 4.5-, and 5.0-mm MTTs were 20, 14, and 10 times higher, respectively, than that of the conventional 8-mm endotracheal tube. Despite the high airway resistance of these MTTs, PCV via an MTT without air leakage was able to maintain 40%, 50%, and 60% of the ventilated volume achieved using a 8-mm endotracheal tube, respectively, which was attributed to the fact that the PCV system increased air flow in the condition of high airway resistance to maintain the set pressure.

Because PCV via an MTT is accompanied by air leakage via the mouth or nose during inspiration in clinical situations, we also measured the alveolar pressure and ventilated volume using the air leakage adapter of the lung model. The data showed that even when the air leakage adapter was used, PCV via an MTT was able to maintain 80% of the ventilated volume and alveolar pressure achieved without air leakage because the PCV system increased air flow to maintain a set pressure, despite the presence of air leakage.

We have employed PCV via an MTT clinically for the respiratory management of five patients with pneumonia; two with DMD and three with chronic obstructive pulmonary disease. Although some improvement in their respiratory condition was seen, conversion to conventional mechanical ventilation via a tracheal tube was required for a mean period of 26 days (range 1–40 days) due to worsening pneumonia and inadequate ventilation. Table 6 shows that with low lung compliance (10 ml/cmH_2O) PCV via an MTT with air leakage produced a ventilated volume of only 190 ml when the inspiratory pressure was 30 cmH_2O, because of the greater air leakage. Therefore, in our opinion, PCV via an MTT is not appropriate for patients with pneumonia because high alveolar pressure is necessary to achieve adequate gaseous exchange and PCV via an MTT does not achieve high peak alveolar pressures due to the air leakage from the mouth and/or nose.

In conclusion, we tested the efficiency of PCV via an MTT using a mechanical lung model. Our results indicate that this procedure is suitable for the respiratory management of patients with neuromuscular disease, but not those with pneumonia.

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