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Inaccuracy of tidal volume delivered by home mechanical ventilators

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Inaccuracy of tidal volume delivered by home mechanical ventilators. F. Lofaso, R. Fodil, H. Lorino, K. Leroux, A. Quintel, A. Leroy, A. Harf. ©ERS Journals Ltd 2000.

ABSTRACT: Ideally, the inspired (tidal) volume (V_T) provided by a volume-controlled ventilation device should not change when the pressure imposed on the ventilator varies.

A bench study evaluation of V_T *versus* pressure was performed on 10 commercially available devices.

The difference between the desired V_T and the observed V_T reached 100 mL for some devices when inspiratory resistance was at its lowest, rising to 150 mL when inspiratory resistance was increased to obtain peak airway pressure of 60 cmH_2O.

The present data indicate that some home ventilators are inaccurate in delivering the preset tidal volume when the pressure imposed on the ventilator is increased to simulate high airway resistance.

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Volume-controlled ventilation (VCV), which is the mode of mechanical ventilation most often used at home, is intended to deliver a constant tidal volume (V_T). Long-term home VCV was introduced in clinical practice in the 1950s, after the iron lung era. Home VCV is applied intermittently either to the upper airways using a mask or to the trachea *via* a tracheotomy [1]. Ideally, the V_T provided by a VCV device should not decrease when the pressure imposed on the ventilator rises, for instance during acute bronchial obstruction, during nasal congestion when nasal ventilation is used, or during mucus secretion build-up in the tracheal cannula [2] when a tracheotomy is used.

In recent years, several manufacturers have developed a number of ventilators with a variety of features [3]. Although it has been claimed that all of these systems provide the desired V_T even during increases in the pressure imposed on the ventilator, the authors are unaware of any studies designed to substantiate these claims.

Therefore, the efficacy and reliability of 10 commercially available home ventilators (table 1) were evaluated in a bench study involving a gradual increase in the pressure imposed on the ventilator, replicating the situation observed in clinical practice when an airway obstruction occurs.

Methods

Experimental set-up

Standard ventilator circuits were used with all of the devices, and humidifiers were intentionally excluded. The compliance of these circuits was tested at three pressures (20, 40 and 60 cmH_2O) using a calibrated 200 mL syringe and a differential pressure transducer (±100 cmH_2O; MP 45; Validyne, Northridge, CA, USA). Each ventilator device was connected to a lung model consisting of a chamber connected to a circuit comprising an expiratory line and an inspiratory line with adjustable resistance (fig. 1). The compliance of the chamber was set at 30 $mL \cdot cmH_2O^{-1}$. A Fleisch No. 2 pneumotachograph (Fleisch, Lausanne, Switzerland) connected to a differential pressure transducer (±3 cmH_2O on entry ±100 cmH_2O on exit, MP 45) was inserted between the lung model circuit and the ventilator device.

Protocol

Each ventilator was set to volume mode according to the manufacturer's recommendations. During measurements,

Table 1. – The 10 ventilator devices tested, designed specifically for home use

Ventilator type	Ventilator
Compressor/ blower	O'nyx plus (Mallinckrodt, Les Ulis, France)
	Airox Home 1 (Bio MS, Pau, France)
Piston chamber	PV 501 (Breas Medical, Compiègne, France)
	PLV 100 (Repironics, Pittsburgh, PA, USA)
Rotary piston-driven	Companion 2801 (Puritan Bennett, Lenexa, KS, USA)
Standard compressor	Ecole-3-XL (Saime, Savigny Le Temple, France)
	Ecole-3 (Saime)
	Ecole-2-A (Saime)
	Monnal D (TAEMA, Antony, France)
	Monnal DCC (TAEMA)

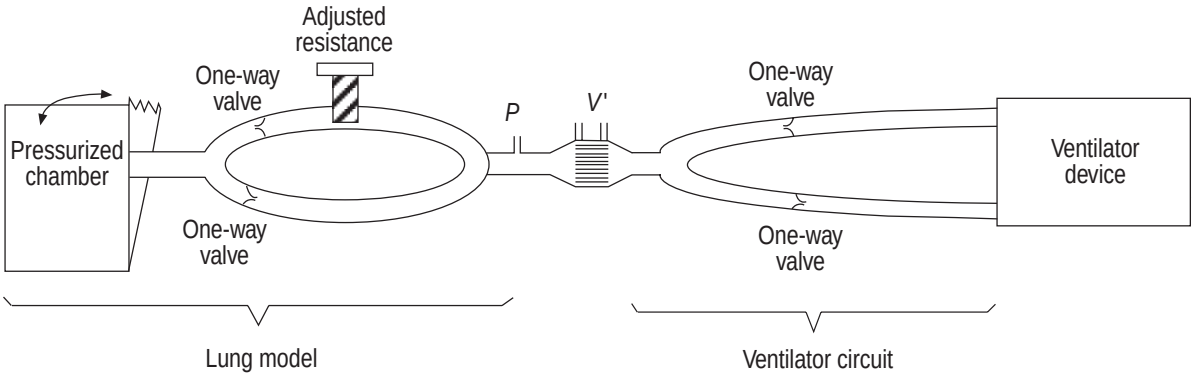

Fig. 1. – The lung model consisted of a pressurized chamber connected to a circuit comprising an expiratory line and an inspiratory line with adjustable resistance. the compliance of the chamber was set at 30 mL·cmH_2O^{-1}. A pneumotachograph (flow (V')) and a differential pressure transducer (pressure (P)) were inserted between the chamber and the circuit of the lung model.

the parameters were set at a respiratory frequency of 20 cycles·min^{-1}; an inspiratory time (tI) to expiratory time (tE) ratio (tI:tE) of 1:2 and VT of 300, 500 and 800 mL. For each condition, the inspiratory resistance of the lung model was set at its lowest level and gradually increased to obtain a peak airway pressure of ~40 then 60 cmH_2O.

Data analysis

For each condition, a recording of 1 min was started when the signals were stable. In order to achieve signal stabilization, the ventilator was always connected to the lung volume for >5 min. The flow and pressure signals were digitized at 128 Hz and sampled for subsequent analysis using an analogic/numeric acquisition system (MP100; Biopac System, Goleta, CA, USA). The VT and respiratory frequency were calculated from the flow signal. For ventilators equipped with a monitor, the accuracy of the monitor was checked.

Statistics

Mean±SD was determined for five ventilators of each ventilator type. Comparisons were performed using analysis of variance for repeated measurements. The level of significance was set at 5%.

Results

The compliances of the standard ventilator circuits were linear and are presented in table 2.

Table 2. – Compliance of the four standard circuits used with the ventilator devices tested

Circuit	Ventilator	Compliance mL·cmH_2O^{-1}
Ref 300/6042; DAR, (Mirandola, Italy)	Ecole, Monnal DCC	1.01
Ref 285/7708; Mallinckrodt (Mirandola, Italy)	O′nyx plus PLV 100	0.50
Ref 200000; Breas Medical (Compiègne, France)	PV 501	0.59
Ref 3283; Smith Industries Medical Systems Inter. Tech (St Myers, FL, USA)	Monnal D	0.68
Ref 133292-00; Puritan Bennett (Lenexa, KS, USA)	Companion Airox Home 1	28010.56

Figure 2 shows the VT provided by each type of ventilator with the VT set at 300, 500 and 800 mL and the inspiratory resistance of the lung model set at its lowest level and increased gradually to obtain a peak airway pressure of 40 and then 60 cmH_2O. The decrease in VT accompanying the gradual increase in pressure was significant for each VT setting and for all ventilator types, except the Monnal DCC and the PLV 100 for each condition and the O′nyx plus for a set VT of 300 mL. For each condition, ventilator inaccuracies in maintaining VT were due only to the inefficiency of the compressors; in no case were they caused by a high-pressure alarm reducing the VT.

The difference between the desired VT and the observed VT reached 100 mL for some devices when inspiratory resistance was at its lowest, rising to 150 mL when inspiratory resistance was increased to obtain a peak airway pressure of 60 cmH_2O.

The relationship between the observed VT and the VT determined by the monitor, if present, is shown in figure 3.

Discussion

The present data clearly demonstrate that some of the commercially available devices tested failed to provide the desired VT. This failure was dramatic when the desired VT was set at the lowest volume tested and the airway pressure at the higher pressure tested: with one type of device, when VT was set at 300 mL, the actual VT fell from 280 mL to 215 mL and then to 142 mL when inspiratory pressure was increased gradually from ~10 cmH_2O and then to 60 cmH_2O, respectively.

Before discussing the implications of these findings, some methodological issues will be addressed.

The compliance of the lung model was 30 mL·cmH_2O^{-1}. This is approximately a third of the normal value for thorax and lung compliance in adults. However, this value is consistent with the compliances seen in paediatric disorders and/or restrictive disease, which are common indications for mechanical ventilation.

Clearly, the use of an isolated inspiratory resistance did not replicate reality. However, use of a resistance affecting both inspiration and expiration may induce variations in the end-expiratory volume of the lung model; this end-expiratory volume may vary with the VT tested and the resistance imposed on the ventilator, and may influence the

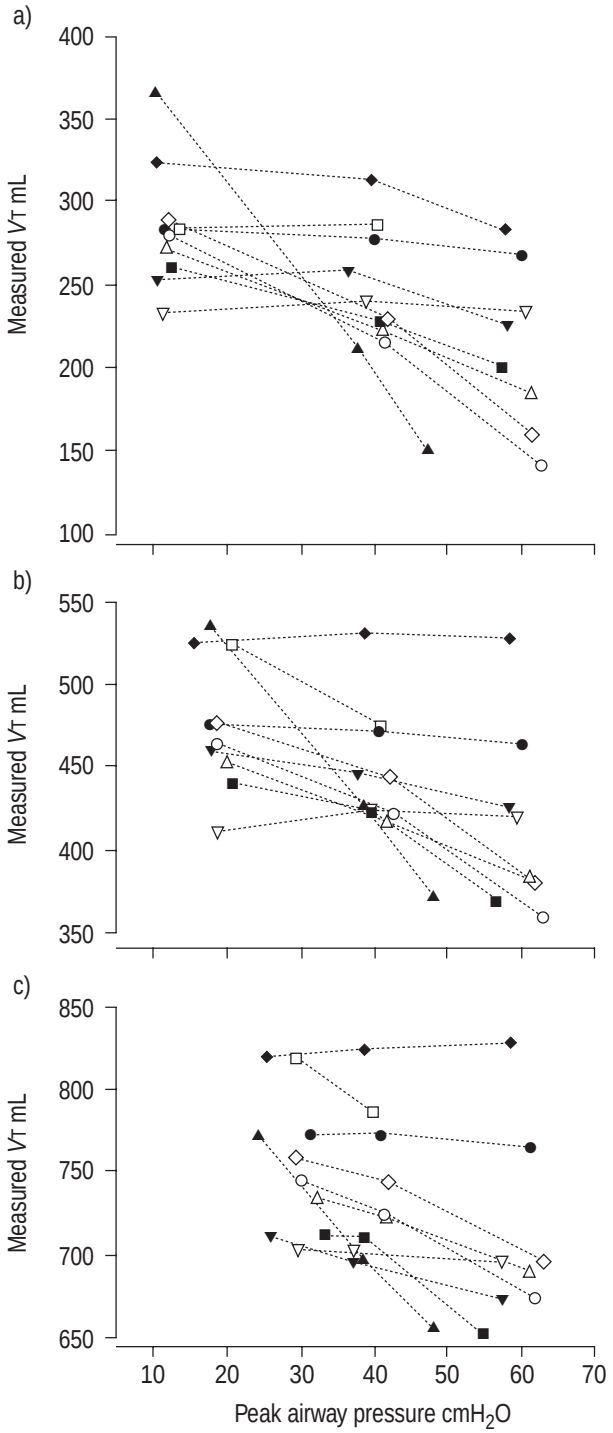

Fig. 2. – Tidal volumes (V_T) observed for the various ventilator devices tested (□: O′nyx plus; ◇: Ecole-3-XL; ○ : Ecole-3; △: Ecole-2-A; ■: Airox Home 1; ●: Companion 2801; ▼: Monnal D; ▽: Monnal DCC; ▲: PV 501; ◆: PLV 100) with the V_T set at: a) 3; b) 500; and c) 800 mL and the inspiratory resistance of the lung model set at its lowest level and gradually increased to obtain a peak pressure of 40 and then 60 cmH_2O. Data obtained at a peak airway pressure 60 cmH_2O were not available with the O′nyx plus or the PV 501 because these devices did not reach such high pressures.

next V_T independent of ventilator performance. Therefore, in order to be sure that the end-expiratory volume of the lung model was identical for all ventilators and under all conditions, an isolated inspiratory resistance was used.

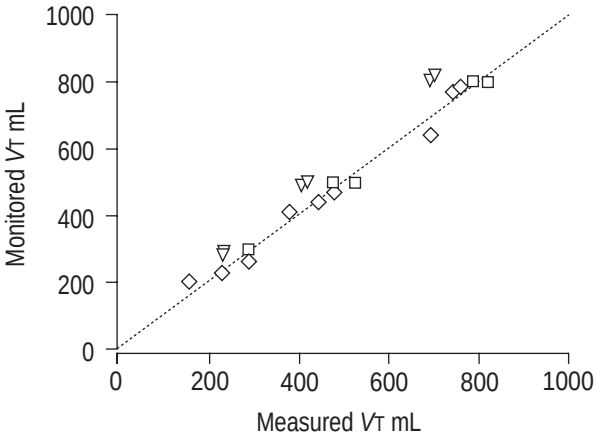

Fig. 3. – Relationship between the observed V_T and the monitored V_T for the three ventilators providing V_T monitoring (□: O′nyx plus; ◇: Ecole-3-XL; ▽: Monnal DCC).

Because, at a given pressure, the induced flow varied from one ventilator to another and/or from one prescribed volume to another, the inspiratory resistance used also varied. For a given ventilator, the resistance was highest when the prescribed volume was lowest because, in this situation, the inspiratory flow was also at its lowest. This explains why the V_T inaccuracies were most marked at the lowest set V_T. In addition, this experimental condition magnified differences between ventilators: with the less efficient ventilators, higher resistances were used to maintain the set pressure. Despite this drawback, it was decided to compare the ventilators at a given pressure rather than at a given resistance, because pressure is commonly and easily monitored at home, whereas total lung resistance is generally unknown. It is easy in practice to follow the peak inspiratory pressure, detect an abrupt increase in peak pressure and use figure 2 to approximate the volume decrease for each device.

The ventilators were tested over a broad range of pressures, up to 60 cmH_2O. This value was chosen based on the authors′ clinical experience. Indeed, many of the authors′ tracheotomized patients with neuromuscular disease and a restrictive ventilatory pattern have a peak inspiratory pressure of 60 cmH_2O with no leaking around the tracheostomy tube. By contrast, an inspiratory pressure >30 cmH_2O during nasal ventilation can induce considerable leakage around the mask. Therefore, during nasal ventilation, the decrease in alveolar ventilation seen when inspiratory pressure is increased is ascribable primarily to leakage at the mask rather than to ventilator inaccuracy in producing the desired V_T. The ventilators tested in the present study can be divided into four categories according to whether they use a piston chamber (PV 501, PLV 100), a rotary piston-driven system (Companion 2801), a standard compressor (Eoles, Monnals) or the more recent compressor/blower system (Airox Home 1, O′nyx plus). The rotary piston-driven ventilator was among the devices that provided a V_T closest to that desired even during pressure increases. With the O′nyx plus device, similar results were obtained, but the inspiratory pressure of 60 cmH_2O could not be tested because of the presence in this ventilator of a system that prevents pressure increases in excess of 40 cmH_2O. The good performance characteristics of the

O′nyx plus device can be ascribed to the presence in this device of a pneumotachometer that is connected to the inspiratory line inside the ventilator and uses the mean V_T from the three last cycles to servomotor control the compressor/blower during the next cycle.

Part of the V_T decrease seen during inspiratory pressure elevation may be ascribable to the compliance of the circuitry, which may lead to part of the volume generated by the ventilator accumulating in the circuitry rather than being blown into the lungs. In order to test this possibility, the circuitry compliance of each ventilator type was measured. The circuitry compliance was linear and varied from 0.50 $mL \cdot cmH_2O^{-1}$ (for the O′nyx plus and the PLV 100) to 1 $mL \cdot cmH_2O^{-1}$ (for the Eoles and the Monnal DCC). It is therefore reasonable to assume that, when the pressure increases from ~10 to 60 cmH_2O, the part of the ventilator-generated volume that can accumulate in the tubing and is ascribable to circuitry compliance is not >50 mL.

Various modes of ventilation can be used with home ventilators. It is well known that during pressure-controlled ventilation [4] with a predetermined t_I, a decrease in V_T is usually observed independent of the performance of the ventilator: for a constant pressure, flow and therefore V_T are dependent on the resistance of the respiratory system. During pressure support [5], t_I may vary and pressure support is generally stopped when the inspiratory flow falls below 25% of peak flow. In this situation, an increase in resistance is accompanied by an increase in t_I, so that V_T remains relatively stable. By contrast, in volume-controlled ventilation, the delivered volume is in theory constant whatever the respiratory system load. The present results clearly indicate that most of the ventilators tested deserve to be considered volume-controlled ventilators only over a limited range of load.

It was concluded that some commercially available home ventilators are inaccurate in providing the desired tidal volume and/or in maintaining tidal volume constant in the face of a gradual increase in inspiratory pressure. This must be taken in account during titration of mechanical ventilation and/or when airway resistance increases abruptly.

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