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Research

Effect of lung compliance and endotracheal tube leakage on measurement of tidal volume

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Abstract

Introduction The objective of this laboratory study was to measure the effect of decreased lung compliance and endotracheal tube (ETT) leakage on measured exhaled tidal volume at the airway and at the ventilator, in a research study with a test lung.

Methods The subjects were infant, adult and pediatric test lungs. In the test lung model, lung compliances were set to normal and to levels seen in acute respiratory distress syndrome. Set tidal volume was 6 ml/kg across a range of simulated weights and ETT sizes. Data were recorded from both the ventilator light-emitting diode display and the CO_2SMO Plus monitor display by a single observer. Effective tidal volume was calculated from a standard equation.

Results In all test lung models, exhaled tidal volume measured at the airway decreased markedly with decreasing lung compliance, but measurement at the ventilator showed minimal change. In the absence of a simulated ETT leak, calculation of the effective tidal volume led to measurements very similar to exhaled tidal volume measured at the ETT. With a simulated ETT tube leak, the effective tidal volume markedly overestimated tidal volume measured at the airway.

Conclusion Previous investigators have emphasized the need to measure tidal volume at the ETT for all children. When ETT leakage is minimal, it seems from our simulated lung models that calculation of effective tidal volume would give similar readings to tidal volume measured at the airway, even in small patients. Future studies of tidal volume measurement accuracy in mechanically ventilated children should control for the degree of ETT leakage.

Keywords: intensive care, lung compliance, mechanical ventilation, monitoring tidal volume

Introduction

Three investigators have reported that tidal volume (V_T) in children is inaccurate when measured at the ventilator, even when effective V_T is used [1-3]. Cannon and colleagues [1] studied 98 infants and children and found a significant discrepancy between expiratory V_T measured at the ventilator and that measured with a pneumotachometer. Calculation of the effective V_T did not alter this discrepancy. Castle and colleagues [2] studied 56 intubated children and found that exhaled V_T displayed by the Servo 300 significantly overestimated V_T measured at the airway by between 2% and 91%. After correcting for gas compression, effective V_T overestimated true V_T by as much as 29% in older children but underestimated the true V_T by up to 64% in the smallest

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ARDS = acute respiratory distress syndrome; ETT = endotracheal tube; FRC = functional residual capacity; PEEP = positive end-expiratory pressure; PIP = peak inspiratory pressure; V_T = tidal volume.

infants. Neve and colleagues [3] studied 27 infants and found that V_T was overestimated by the ventilator in comparison with V_T measured at the Y piece. None of these investigators controlled for endotracheal tube (ETT) leakage, which is more of a problem in children than in adults because of the use of uncuffed ETTs.

Accurate measurement of V_T is increasingly important because the Acute Respiratory Distress Syndrome (ARDS) Network investigators have shown that the use of a low effective V_T leads to decreased mortality in their patient population [4]. The effective V_T goal in their ventilator protocol was 6 ml/kg but could be reduced to as low as 4 ml/kg if the plateau pressure was above 30 cmH$_2$O. At such low V_T values, accurate measurement is imperative to prevent atelectasis and subsequent ineffective minute ventilation.

Clinically, there are three methods to estimate delivered V_T: first, direct measurement at the expiratory limb of the ventilator; second, direct measurement at the ETT with a pneumotachometer; and third, indirect calculation of effective V_T by using set V_T minus calculated compressible volume lost in the ventilator circuit [5]. The principle of Boyle's law (the volume of gas decreases as the absolute pressure exerted by the gas increases, and vice versa) is used to calculate the compressible volume in ventilator circuits.

How effective V_T compares with V_T measured at the airway has not been rigorously tested. Using V_T measured at the ETT as the gold standard, we used three test lung models in a controlled laboratory setting to evaluate the accuracy of ventilator measured V_T and effective V_T under conditions of poor lung compliance, with and without ETT leakage, across a range of simulated patient sizes. We proposed that the discrepancy between effective V_T and V_T measured at the ETT in children was due mainly to ETT leakage around uncuffed ETTs, and that in situations with minimal ETT leakage there would be minimal difference between the effective V_T and V_T measured at the airway.

Materials and methods

Experimental conditions

A Servo 300 ventilator (Siemens-Elema, Solna, Sweden) in the SIMV volume control mode was used. A pressure differential pneumotachometer (CO$_2$SMO Plus; Novametrix Medical Systems, Wallingford, CT) was used between the ventilator and ETT connection. The temperature of the humidifier was set at 37°C. A heated disposable respiratory circuit (Allegiance Healthcare Corporation, McGaw Park, IL) was used. We tested the compliance of the circuit to ensure that it was stable across a range of conditions. To do this, we first set the ventilator on the following: inspiratory time of 1.3 s, positive end-expiratory pressure (PEEP) of 0, respiratory set frequency of 6 breaths per minute, and a pause time of 15%. V_T was increased by increments of 50 ml and the plateau pressure was recorded from the ventilator with the patient outlet occluded. No component other than the humidifier was added to the circuit [6]. A linear relationship was found, with no change of the circuit compliance at high airway pressure.

In the pediatric and infant models, a valve distal to the ETT was used to adjust volume leaks of 0%, 10%, 20%, and 30%. A shown in Fig. 1, a separate pneumotachometer (NVM-1; Thermo Respiratory Group, Palm Springs, CA) was used for independent measurement of the percentage of ETT leakage.

The Servo 300 was used for all test conditions. To control for differences between the ventilators, we tested each set of experimental conditions on three different ventilators. The CO$_2$SMO Plus respiratory mechanics monitor was used to measure the V_T at the ETT. This monitor measures flow with a fixed-orifice differential pressure pneumotachometer located at the ETT. Respired gas flowing through the flow sensor produces a small pressure decrease across the two tubes connected to the sensor. This pressure decrease is transmitted through the tubing sensor to a differential pressure transducer inside the monitor and is correlated with flow according to a factory-stored calibration. The pressure transducer is automatically 'zeroed' to correct for changes in ambient temperature. Data are filtered and sampled at 100 Hz. The monitor continuously displays a range of ventilatory variables, including both V_T and airway pressures. Three CO$_2$SMO Plus sensors are available: neonatal, pediatric, and adult. The manufacturer recommends that the choice of sensor be based on various criteria: first, the diameter of the tracheal tube; second, the patient's age; third, the expected flow/volume range; and fourth, the acceptable levels of dead space and resistance. Table 1 lists the experimental conditions for all lung models. Before data collection, all ventilators, respiratory mechanics monitors, and tachometers used in this study were calibrated in accordance with the manufacturer's recommendation.

To ensure that different ventilators and monitors did not influence the results, all data were repeated three times, each time with a different Servo 300 ventilator and a different CO$_2$SMO Plus monitor.

Adult lung model

A TTL™ adult test lung (Vent Aid; Michigan Instruments Inc., Grand Rapids, MI) was used. This device has two separate lungs, each with a functional residual capacity (FRC) of 900 ml. The lung compliance can be adjusted by moving a spring up and down with a compliance ranging from 10 to 150 ml/cmH$_2$O per lung. Each lung is tested before use to assess for leakage. Lung–thorax compliance levels were set at 10, 20, 40, 60, 100, and 150 ml/cmH$_2$O.

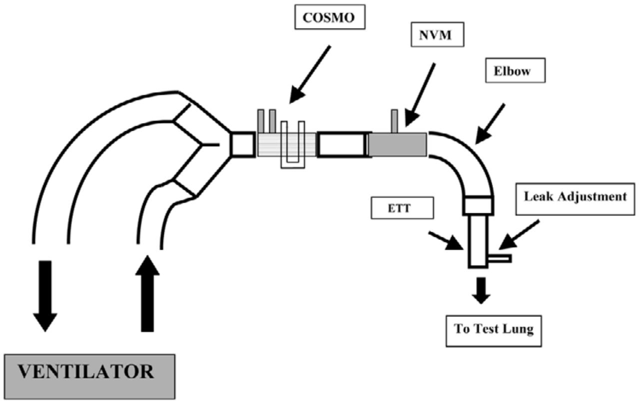
Table 1

Experimental conditions for test lung model

Parameter		Infant			Pediatric		Adult
Simulated weight (kg)	4	7	10	20	31	50	70
ETT internal diameter (mm)	3.0	3.5	4.0	5.0	6.5	7.0	7.5
Tidal volume at 6 ml/kg (ml)	24	42	60	120	186	300	420
PEEP (cmH_2O)	5	5	5	5	5	5	5
Rate per minute	20	20	20	20	20	12	12
Inspiratory time (s)	1	1	1	1	1	1.2	1.2
FiO_2 (%)	21	21	21	21	21	21	21
Circuit compliance (ml/cmH_2O)	1	1	1	1.5	1.5	2.9	2.9
Servo 300 set range		Neonatal			Pediatric		Adult
CO_2SMO Plus sensor		Neonatal			Pediatric		Adult

ETT, endotracheal tube; FiO_2, fraction of inspired oxygen; PEEP, positive end-expiratory pressure.

Figure 1



Schematic diagram demonstrating the placement of CO_2SMO and NMV pnueumotachometers in infant and pediatric models.

Pediatric lung model

A TTL™ adult test single lung was used with the FRC adjusted to give 30 ml/kg by displacing the extra volume with water-filled bags. Lung–thorax compliance levels were set at 5, 10, 20, 40 and 60, ml/cmH_2O.

Infant lung model

An infant lung simulator (D.B&M products, Redlands, CA) was used. The model has three different preset compliances of 1, 3, and 10 ml/cmH_2O.

Data recording

Data were recorded from both the ventilator light-emitting diode display and the CO_2SMO Plus monitor display by a single observer. Variables recorded were inspired V_T, expired V_T, peak inspiratory pressure (PIP), PEEP, and plateau pressure. Effective V_T was calculated from the following equation [2]: set inspired V_T - [circuit compliance × (PIP - PEEP)].

Analysis

The major outcome variable was the calculated difference between the effective V_T and the exhaled V_T measured either at the ventilator or at the ETT in each experiment. For each set of test conditions (Table 1) we used the mean of the three replicate measurements and also give the highest and lowest values. V_T was adjusted for the simulated weights and expressed as ml/kg. We determined a priori that the difference between the V_T values would be considered excessive if it exceeded 10% of the 6 ml/kg goal (0.6 ml/kg).

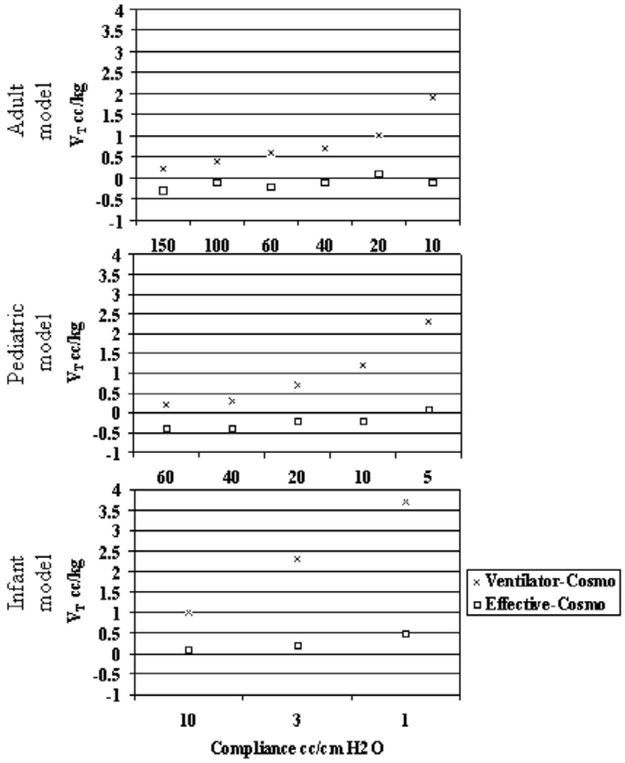
Results

Test lung models

As shown in Fig. 2, for the adult, pediatric, and infant models with no ETT leak, the difference between V_T measured at the ETT and at the ventilator increased with decreasing lung compliance. V_T measured at the ventilator was always higher than that measured at the ETT. The ventilator measurement overestimated V_T by more than 10% (0.6 ml/kg) as lung compliance dropped to moderately low values and the difference exceeded 20% (1.8 ml/kg) at the lowest lung compliances in each model. The standard deviation of the difference was 0–0.2 ml/kg for all sets of measurements.

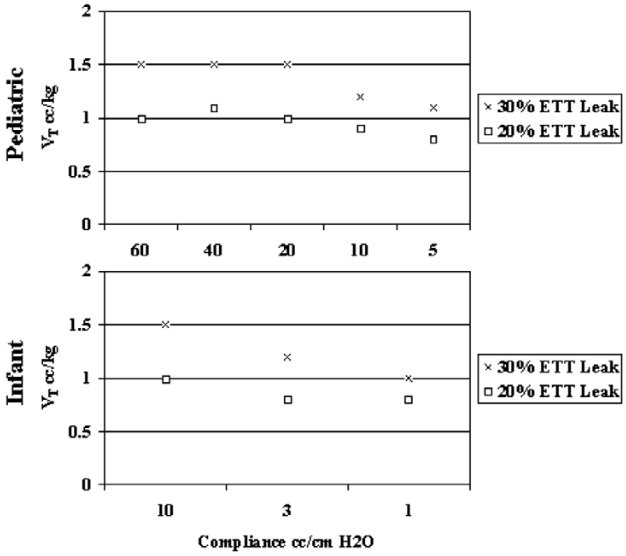
In all models, in the absence of ETT leakage the difference between effective V_T and V_T measured at the ETT was less than 10% across the range of lung compliances with a standard deviation of 0–0.2 ml/kg for all sets of measurements. As shown in Fig. 3, however, the agreement between effective V_T and V_T measured at the ETT was poor when a 20% and 30% simulated ETT leak was added in the infant and pediatric test lung models. Under these conditions, the effective V_T was at least 10% higher than that measured at the ETT for all simulated conditions, and the standard deviation was 0.1–0.4 ml/kg for all sets of measurements.

Figure 2



Effect of decreasing lung compliance on the difference between effective tidal volume and tidal volume at the endotracheal tube (ETT) in the infant, pediatric, and adult test lungs with no leak around the ETT.

Figure 3



Effect of decreasing lung compliance on the difference between effective tidal volume and tidal volume at the endotracheal tube (ETT) in the infant and pediatric test lung models with 20% and 30% simulated ETT leakage.

Discussion

Using well-controlled experimental conditions, we showed that in the absence of ETT leakage, effective V_T approximated the V_T measured at the ETT in the test lung even when lung compliance was poor. As expected, exhaled V_T measured at the ventilator became increasingly inaccurate with poor lung compliance. In the presence of ETT leakage, effective V_T overestimated the V_T measured at the ETT by at least 0.6 ml/kg. It is clear that in the presence of ETT leakage, effective V_T is inaccurate and V_T is most accurately estimated at the airway.

We used an *in vitro* model to manipulate experimental conditions while controlling for all other variables. Accurate measurement of V_T is essential when a low-V_T strategy is used to protect injured lungs as is recommended by the recent ARDS Network study [4]. In the adult lung model, we manipulated the compliance to simulate the lung compliance quartiles reported in the ARDSNet study [4]. Our findings have clinical implications. In agreement with other investigators [1-3], we found that unadjusted V_T measured at the ventilator is highly inaccurate. We found this inaccuracy to increase markedly when lung compliance was abnormal. This means that dual-control automated ventilator modes (for example volume support or pressure-regulated volume control) that make adjustments based on V_T measured at the ventilator might ineffectively ventilate patients with poor lung compliance. Automated ventilator modes should be used with care in critically ill children.

We support the current recommendations of previous investigators [1-3] that V_T should be measured at the ETT in critically ill children receiving mechanical ventilator support. These investigators emphasized the need to measure V_T at the ETT for all children; they did not control for the presence of uncuffed ETTs in their studies or evaluate the effect of leakage. Significant loss of V_T occurs when both ETT leakage and poor lung compliance are present. Although the V_T measured at the ETT may underestimate the actual V_T being delivered in this situation, it is still the best estimation of the tidal volume delivered to the lung. Use of cuffed ETTs to minimize ETT leakage may lead to more accurate measurement of V_T when lung compliance is poor [7]. When ETT leakage is 20% or greater, Main and colleagues [8] reported inconsistent tidal volume delivery and gross overestimation of respiratory compliance and resistance in children.

When ETT leakage is minimal, it seems from our simulated lung models that calculation of effective V_T would give similar readings to V_T measured at the airway, even in small patients. This could potentially negate the need for the addition of sensors at the airway and their associated increase in airway resistance for small ETTs [2]. Unfortunately, ETT leakage is dynamic and dependent on head position. Unless a simple, accurate and continuous means of measuring ETT leakage is available, it is safest to measure V_T at the airway in all mechanically ventilated children. Future studies of V_T measurement accuracy in mechanically ventilated children should control for the degree of ETT leakage.

Key messages

- Previous investigators have emphasized the need to measure tidal volume at the endotracheal tube for all mechanically ventilated children.
- When endotracheal leakage is minimal, it would appear from this study using simulated lung models that calculation of effective tidal volume would give similar readings to tidal volume measured at the airway, even in small patients.
- Future studies of tidal volume measurement accuracy in mechanically ventilated children should control for the degree of endotracheal tube leakage.

Competing interests

None declared.

Acknowledegments

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