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Higher Fresh Gas Flow Rates Decrease Tidal Volume During Pressure Control Ventilation

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Abstract

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BACKGROUND—We observed that increasing fresh gas flow (FGF) decreased exhaled tidal volume (V_T) during pressure control ventilation (PCV). A literature search produced no such description whereby unintended V_T changes occur with FGF changes during PCV.

METHODS—To model an infant's lungs, one lung of a mechanical lung model (Dual Adult TTL 1600, Michigan Instruments, Inc., Grand Rapids, MI) was set at a compliance of 0.0068 L/cm H_2O . An Rp50 resistor (27.2 cm H_2O /L/sec at 15 L/min) simulated normal bronchial resistance. The simulated lung was connected to a pediatric breathing circuit via a 3.5-mm cuffed endotracheal tube. A ventilator with PCV capability (Model 7900, Aestiva, GE Healthcare, Madison, WI) measured exhaled V_T , and a flow monitor (NICO, Respironics, Murrysville, PA) measured peak inspiratory flow, positive end-expiratory pressure (PEEP), and peak inspiratory pressure (PIP). In PCV mode, exhaled V_T displayed by the ventilator at FGF rates of 1, 6, 10, and 15 L/min was manually recorded across multiple ventilator settings. This protocol was repeated for the Avance CS2 anesthesia machine (GE Healthcare).

RESULTS—For the Aestiva, higher FGF rates in PCV mode decreased exhaled V_T . Exhaled V_T for FGFs of 1, 6, 10, 15 L/min were on average 48, 34.9, 16.5, and 10 mL, respectively, at ventilator settings of inspiratory pressure of 10 cm H_2O , PEEP of 0 cm H_2O , and respiratory rate of 20. This is a decrease by up to 27%, 68%, and 80% when FGFs of 6, 10, 15 L/min are compared to a FGF of 1 L/min, respectively. In the GE Avance CS2 at the same ventilator settings, the tidal volumes for the same settings and FGF rates of 1, 6, 10, and 15 L/min were on average 46, 43, 40.4, and 39.7 mL. The FGF effect on V_T was not as pronounced with the GE Avance CS2 as with the GE Aestiva.

CONCLUSIONS—FGF has a significant effect on V_T during PCV in the Aestiva bellows ventilator, suggesting caution when changing FGF during PCV in infants. Our hypothesis is that at higher FGF rates, an inadvertent PEEP is developed by the flow resistance of the ventilator relief valve that is not recognized by the ventilator. In turn, less change in pressure is needed to reach the set inspiratory pressure, resulting in lower V_T delivery at higher FGF rates. This underappreciated FGF- V_T interaction during PCV with a bellows ventilator may be clinically significant in pediatric patients; prospective data collection in patients is needed for further evaluation.

Introduction

Prior to the introduction of pressure control ventilation (PCV) in anesthesia ventilators, it was already known that fresh gas flow (FGF) rates had an effect on delivered tidal volume (V_T) during volume control ventilation.¹ At higher FGF rates, higher V_T , peak inspiratory pressure, and minute ventilation were delivered during volume control ventilation due to the pressure relief valve remaining closed during inspiration.² A simple formula can be used to determine the new V_T due to ventilator and FGF coupling in volume control ventilation.² Newer anesthesia machines have FGF compensation during volume control ventilation to help circumvent this problem. This compensation is not immediate, but happens after a few breaths. Inspiratory-to-expiratory time ratio and ventilatory frequency can also influence delivered V_T in volume control ventilation and PCV.^{1,3}

Clinically, we observed that during PCV in a child, a higher FGF appears to paradoxically decrease V_T instead of augmenting it, as in volume control ventilation. We were unable to

find any description in the literature of FGF coupling to V_T during PCV. If FGF rate adjustments can significantly and inadvertently affect the delivered V_T during PCV, then changes in V_T may go unnoticed and be detrimental to the operator's clinical intent and patient care.^{4,5} This is especially relevant for the neonatal patient population given the low V_T and low margin for V_T error, for this especially at-risk population.^{6,7}

The neonatal patient population is more vulnerable to lung injury from both ventilator-induced lung injury due to overdistention (volutrauma) and the repetitive opening and collapse of alveoli (atelectrauma),⁴ which can lead to bronchopulmonary dysplasia.⁴ A volume-targeted and low pressure setting ventilation approach is recommended for pre-term infants, but if FGF setting changes significantly alter V_T in PCV, they can possibly lead to alveolar over- or under-distention (depending on whether FGF is decreasing or increasing from the original setting, respectively).⁵

The preferred mode of ventilation for pediatric patients depends on what type of anesthesia machines are available.⁸ If older machines are being used, then PCV is a commonly used mode in neonates because it provides a lower peak inspiratory pressure, constant airway pressure, and compensation for any potential leaks around an uncuffed endotracheal tube.⁹ Volume control ventilation is less popular in infants because some of the preset V_T may be lost due to leaks around the uncuffed endotracheal tube. In addition, gas compression in the ventilator circuit and circuit compliance complicate accurate measurement of the actual delivered V_T .⁹ If more modern ventilators are available, then modes such as PCV with volume guarantee by GE or Autoflow by Draeger would deliver tidal volumes closer to the desired V_T because the set target is V_T , not a pressure target, while the inspiratory flow pattern is decelerating like in PCV.⁸

The purpose of this study was to determine if FGF rates have an effect on expiratory V_T during PCV. Because small changes in V_T are more impactful in neonates and infants, the study was designed to reflect an infant's lungs. We clinically observed and therefore hypothesized that there is a significant difference in V_T being delivered at varying FGF rates during PCV. We conducted additional bench model experiments by varying the respiratory rate, positive end-expiratory pressure (PEEP), and inspiratory pressure to compare effects on exhaled V_T .

Materials and Methods

All experiments were conducted in an environmentally controlled simulation lab using mechanical lung models and anesthesia machines. Patients were not part of the study, which was therefore exempt from IRB review.

Inclusion/Exclusion Criteria

Because the impact of small V_T changes would likely be more important in neonates and infants, the design of this study was focused on infants and neonates. The experimental design used compliance and airway resistance values similar to those of an infant.

We collected data using the two different anesthesia machine models used at our hospital (Aestiva 5 and Avance CS2, both with bellows, both GE Healthcare, Madison, WI) to determine if the unintended interaction is inherent to only an older bellows ventilator anesthesia machine design (Aestiva 5).

Study Design

All experiments were conducted at the University of Florida Center for Safety, Simulation & Advanced Learning Technologies. To obtain data for this study, a mechanical test lung, flow resistor, and a cuffed 3.5-mm endotracheal tube were used to simulate an infant's lungs and were connected to an anesthesia machine via a standard infant circle breathing system (Vital Signs Pediatric Breathing Circuit, GE Healthcare Company, Totowa, NJ). Each extensible limb of the breathing circuit was stretched to 90 cm. The GE Datex Ohmeda Aestiva 5 (Aestiva) with software, version 4.8, PSVPro and the GE Datex Ohmeda Avance CS2 with software, version 10.01, were the ventilators used in this study. Each anesthesia machine passed a complete pre-use check before use.

The lungs were simulated by using only one lung (bellows) of a Dual Adult TTL Model 1600 Training/Test Lung (Michigan Instruments, Inc. Grand Rapids, MI). The exhaled V_T that was captured and displayed by the integrated monitor for each ventilator was manually recorded.

A NICO Cardiopulmonary Monitor System (Respironics, Philips, Wallingford, CT) was used to collect peak inspiratory and expiratory flow and pressure as well as the end expiratory pressure at the Y-piece.

Modeling of Infant Lungs with a Mechanical Lung Model—Two major components when modeling infant lungs are compliance and airway resistance. Normal compliance for an infant lung is approximately 5 mL/cm H₂O.^{10,11} To approximate that compliance value, we only used one compartment of the mechanical lung. In addition, we placed two springs on the lung to reduce compliance to 6.8 mL/cm H₂O, which is the lowest (stiffest) possible value using this mechanical lung model, which could be considered as modeling an older infant.

Descriptions for modeling infant airway resistance are not consistent, varying from 26,¹² 29,¹³ and 70¹⁰ cm H₂O/L/sec, with Nunn elaborating that the majority of the airway resistance is caused by bronchial resistance. In preliminary experiments we determined that the flow rates of infant lungs during PCV range up to 15 L/min. Given these findings, we selected a nominal resistance of 30 cm H₂O/L/sec at a 15 L/min flow rate. Our protocol replaces the tracheal resistance with the resistance of a 3.5-mm internal diameter endotracheal tube. A lower simulated resistance value than the actual patient resistance will not amplify the effect of FGF on PCV given the basic flow equation. In the flow equation, resistance is directly related to pressure drop. Higher resistance leads to a higher pressure drop if the flow remains constant.

To include airway resistance, we used the Rp resistors supplied with the mechanical lung. For these resistors, the flow resistance curve on a pressure (y-axis) versus flow rate (x-axis)

plot is not linear (a straight line as in electrical circuits) but is actually a parabola. The slope of this curve is the flow resistance, which is dependent on the flow rate. The Rp50 resistor used in this study specifies a pressure drop of 6.8 cm H₂O and 27.2 cm H₂O at 15 and 30 L/min, respectively.¹⁴ The resistance of an Rp50 resistor is $(6.8 \text{ cm H}_2\text{O}/15 \text{ L/min}) \times 60 \text{ (sec/min)} = 27.2 \text{ cm H}_2\text{O/L/sec}$ at 15 L/min. At a flow of 30 L/min, the resistance of an Rp50 resistor is $(27.2 \text{ cm H}_2\text{O}/30 \text{ L/min}) \times 60 \text{ (sec/min)} = 54.4 \text{ cm H}_2\text{O/L/sec}$ at 30 L/min. The resistance values of 27.2 cm H₂O/L/sec at 15 L/min and 54.4 cm H₂O/L/sec at 30 L/min of an Rp50 resistor nicely approximate the range of 30 to 60 cm H₂O/L/sec recommended by the mechanical lung model manufacturer as well as the lower and upper resistance range described in the literature (26–70 cm H₂O/L/sec).^{10,12–14}

Pressure Control Ventilation Settings—Each ventilator used the same settings for each data collection trial. The ventilator was placed in PCV mode. The following parameters were changed with each trial: respiratory rate, inspiratory pressure, and PEEP. The inspiratory-to-expiratory ratio (1:2), FIO₂ (50%), and pressure limit (40 cm H₂O) were not changed during the entire experiment. Changing respiratory rate or inspiratory-to-expiratory ratio changes delivered V_T during volume control ventilation and PCV and therefore would become confounding variables in this PCV study if they were not kept constant.^{1,2}

Because 4 combinations of settings are used, one standard setting (Setting 1) was selected to compare to subsequent trials. The standard setting is a respiratory rate (RR) of 20 breaths/min, an inspiratory pressure (Pi) of 10 cm H₂O, and a PEEP of 0 cm H₂O. The settings are summarized in Table 1.

For each setting, the same data collection routine was used. The FGF rate was first set at 1 L/min, and the ventilator was allowed to equilibrate for 1 min before recording any data. The V_T delivered was recorded for up to 10 data points from the ventilator's integrated monitor. The V_T was also independently confirmed on the NICO monitor for consistency but was not recorded. Pressure at the Y-piece, peak inspiratory flow, and peak expiratory flow were recorded from the NICO monitor. The FGF rate was then changed to 6, 10, and 15 L/min, and the same data were recorded at each FGF. Between each FGF rate change, the ventilator was allowed to equilibrate.

Data Management and Statistical Analysis

Because this study was a bench model where we did not introduce any variability and set all the parameters (FGF, PEEP, inspiratory pressure, and respiratory rate), our statistical analysis consisted of mean, standard deviation, and coefficient of variation. In actual clinical settings, variability does exist due to patient and surgical differences. The 10 measurements at each combination of settings were averaged for each FGF rate. Standard deviation and coefficient of variation were also calculated. The percent difference of V_T was calculated between 1 and 6 L/min, between 1 and 10 L/min, and between 1 and 15 L/min.

Results

For Setting 1 with the GE Aestiva anesthesia machine, the average delivered V_T for FGF rates of 1, 6, 10, and 15 L/min were 48, 34.9, 16.5, and 10 mL, respectively, with a standard

deviation of 0, 0.32, 0.52, and 0, and coefficient of variation of 0%, 0.9%, 3.1%, and 0%, respectively (Table 2). Similar results were found for the other settings (Table 2). For Setting 1 in the GE Avance CS2 anesthesia machine, the average delivered V_T for FGFs of 1, 6, 10, and 15 L/min were 46, 43, 40.4, and 39.7 mL, respectively, with a standard deviation of 0, 0, 0.52, and 0.48 and coefficient of variation of 0%, 0%, 1.3%, and 1.2%, respectively (Table 2). The observed V_T decrease, with higher FGF rates was not as large with the GE Avance CS2 as the GE Aestiva. Minimal delivered V_T changes were noted once a PEEP of 5 cm H_2O was added (Setting 2) or when inspiratory pressure was increased to 20 cm H_2O (Setting 3) (Table 2).

The same data were regraphed to show the results in percentages. In a GE Aestiva anesthesia machine at Setting 1, the percent decrease of V_T comparing the 1 L/min FGF rate to 6, 10, and 15 L/min rates was 27%, 65%, and 79%, respectively (Table 3). At Setting 4, where the respiratory rate was decreased to 10 breaths/min, the percent decrease for the same FGF rates was 23%, 68%, and 80%, respectively. Setting 2 (the addition of PEEP) and 3 (an increase of inspiratory pressure) also had decreased V_T up to 33% (Table 3).

In a GE Avance CS2 anesthesia machine on Setting 1, the percent decrease of V_T comparing a 1 L/min FGF rate to 6, 10, and 15 L/min was 6.5%, 12%, and 13.7%, respectively (Table 3). The results for the other settings are in Table 3.

The GE Avance CS2 data also showed a decrease in exhaled V_T as the FGF rate increased for Settings 1 and 4, but not as pronounced as with the Aestiva. In Settings 2 and 3, the delivered V_T change was closer to zero. Across the multiple ventilatory settings in the Avance CS2 when comparing FGF rates of 1 to 6 L/min, 10 and 15 L/min, exhaled V_T decreased by up to 12%, 16%, and 17%, respectively.

An airway pressure versus time plot from the NICO system for the GE Aestiva reveals that as the FGF rate increased, inadvertent PEEP also increased (Figure 1). The inadvertent FGF-related extra pressure before a breath is given diminishes the ventilator pressure delivery (ΔP , P) so that to reach the set inspiratory pressure of 20 cm H_2O , it is now delivering a P of 18, 17, 16, and 15 cm H_2O (instead of a P of 20 cm H_2O) for FGF rates of 1, 6, 10, and 15 L/min, respectively.

Discussion

For the GE Aestiva 5, with infant PCV ventilator settings, there was a marked decrease in V_T delivered as the FGF rate increased across all the ventilator settings. The NICO airway pressure versus time graph in Figure 1 illustrates why this occurs. At a set inspiratory pressure, an inadvertent PEEP is generated with higher FGF rates, which leads to a smaller P , which in turn decreases delivered tidal volumes. We hypothesize that there is inadvertent PEEP generated by the FGF as it flows past the ventilator pressure relief valve within the ventilator. Unlike when PEEP is explicitly set by the user to a non-zero value such as 5 cm H_2O , the software does not seem to account for the unintended (not explicitly set) FGF-related PEEP from increased FGF when delivering gas to the lungs during the inspiratory phase to reach the inspiratory pressure target (e.g., 20 cm H_2O). The machine only delivered

enough gas to create an increase in pressure (P) equal to the (smaller) difference between the inspiratory pressure target and the inadvertent PEEP. We suspect that this decrease in delivered P is the likely cause of the difference in exhaled V_T that was originally noted. Figure 2 uses the same pressure data from Figure 1 but looks more closely at the pressure during the end expiratory period. This clearly shows an elevated pressure at baseline before the next breath is given.

Taking Settings 3 in the GE Aestiva 5 as an example, let us suppose that the patient (an infant weighing 5 kg) had ventilator settings with a respiratory rate of 20 breaths/min, a PEEP of 0 cm H₂O, and an inspiratory pressure of 10 cm H₂O. The FGF rate might be 1 L/min to conserve volatile anesthetic. The patient's tidal volumes are about 48 to 50 mL per breath (about 10 mL/kg). Toward the end of the case, the FGF is increased to 10 L/min to speed emergence. At the same ventilator settings, the patient is now only receiving a tidal volume of 17 mL, which is about only 3.4 mL/kg. The reverse is true if the FGF rate was decreased from a high setting after induction to a lower setting during maintenance, potentially leading to a much higher tidal volume than intended. Additionally, the inadvertent PEEP generated by high FGF, regardless of tidal volume changes, can also be detrimental in some patient populations, e.g., patient status post-Fontan or Glenn procedure.

We believe the cause of the FGF-dependent variable PEEP and therefore also V_T is higher FGF rates generating an inadvertent PEEP. The pressure relief valve still opens at the nominal intrinsic PEEP of 3 cm H₂O associated with an upright bellows ventilator (based on a bias weight on the ventilator relief valve diaphragm). In addition, the FGF through the flow resistance of the open ventilator pressure relief valve adds a resistive component of pressure, effectively increasing the total (intrinsic + resistive) PEEP. The higher the FGF, the higher the resistive component of the PEEP, the lower the P for a given inspiratory pressure target, and thus, the lower the exhaled V_T . Although once a user sets the PEEP to be higher than 5 cm H₂O, the interaction between FGF and exhaled tidal volume is less apparent. The manufacturer, GE Healthcare, has also agreed to the same conclusion. (Personal email communication from GE Healthcare, February 13, 2015).

To understand the mechanism, the manufacturer of the Avance and Aestiva (GE Healthcare) was made aware of our experimental results. We explored reasons why the Avance exhaled V_T during PCV was less sensitive to FGF changes than the Aestiva. At first, we explored the circuit compliance compensation, which is present in the Avance but not in the Aestiva. However, the manufacturer indicated that circuit compliance compensation is not used during the inspiration part of PCV, but rather for reducing the exhaled V_T . In other words, if the exhaled V_T during PCV was 60 mL, and the Avance software calculates 10 mL was sequestered by the breathing circuit, then the reported exhaled V_T on the ventilator monitor would be 10 mL less (50 mL). Thus, circuit compliance compensation does not explain why varying FGF changes the exhaled V_T more in the Aestiva compared to the Avance, during PCV. Further discussion has not provided us any clarification. The anesthesia machine schematic diagrams for the GE Aestiva, GE Avance, and a virtual anesthesia machine are available for reference in Appendix A, B, and C, respectively (Supplemental Data Appendices A–C).^{15–17}

Conclusions

In the GE Aestiva 5, higher FGF rates significantly decreased delivered V_T . The P being delivered to the patient is decreased or increased by up to 5 cm H_2O , depending on whether the FGF rate is being significantly increased or decreased, respectively. This finding is potentially clinically relevant in the pediatric population because a delivered V_T difference of up to 40 mL is much more significant in an infant. The difference of approximately 40 mL was the maximum difference in V_T found in our settings for the different FGFs. We also noted that the interaction between FGF and tidal volumes is almost completely eliminated once the PEEP is set to 5 cm H_2O or higher. We share our observation and the results of our bench experiments to raise awareness of this previously unappreciated FGF- V_T interaction during PCV in the bellows ventilators we investigated. It is likely that other bellows ventilators beyond the two we evaluated also have a FGF- V_T interaction during PCV. Anesthesiologists and anesthesia providers should pay extra attention to monitoring exhaled V_T as well as inadvertent PEEP during PCV whenever the FGF rate is significantly changed, particularly in the infant population where unintended V_T change makes the most difference.

In this study, we only compared two ventilators, but other ventilators should be tested as well to determine if they also have the same FGF- V_T interaction during PCV.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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Figure 1.

Airway pressure versus time plot for the GE Aestiva anesthesia machine for different fresh gas flow rates is shown here. Settings 3 was used in this particular data collection.

Figure 2.

Airway pressure versus time plot for the GE Aestiva anesthesia machine for different fresh gas flow rates is shown here. Settings 3 was used in this particular data collection. This figure looks more closely at the pressure being delivered to the patient during the end expiratory period.

Table 1.

Ventilator Settings Used During Pressure Control Ventilation

	Setting 1	Setting 2	Setting 3	Setting 4
Set inspiratory pressure (cm H ₂ O)	10	10	20	10
Respiratory rate (breaths/min)	20	20	20	10
Positive end-expiratory pressure (cm H ₂ O)	0	5	0	0

Table 2.

Average Tidal Volume (milliliters), Standard Deviation, and Coefficient of Variation for Each Setting at Varying Fresh Gas Flow Rates for GE Aestiva and Avance CS2.

FGF ^a (L/min)	1	6	10	15
GE Aestiva	Mean ± Standard Deviation (Coefficient of Variation %)			
Settings 1 ^a Standard (mL)	48 ± 0 (0)	34.9 ± 0.3 (0.9)	16.5 ± 0.5 (3.2)	10 ± 0 (0)
Settings 2 (PEEP 5 cm H ₂ O; mL)	62 ± 0 (0)	57.3 ± 0.5 (0.8)	45 ± 0 (0)	41 ± 0 (0)
Settings 3 (Pi 20 cm H ₂ O; mL)	108 ± 0 (0)	85.8 ± 0.4 (0.5)	78.9 ± 0.6 (0.7)	72.4 ± 0.5 (0.7)
Settings 4 (RR 10; mL)	48 ± 0 (0)	37 ± 0 (0)	15.1 ± 0.3 (2.1)	9.6 ± 0.5 (5.4)
GE Avance CS2	Mean ± Standard Deviation (Coefficient of Variation %)			
Settings 1 Standard (mL)	46 ± 0 (0)	43 ± 0 (0)	40.4 ± 0.5 (1.2)	39.7 ± 0.49 (1.3)
Settings 2 (PEEP 5 cm H ₂ O; mL)	65 ± 0 (0)	68.5 ± 2.6 (3.8)	64.2 ± 3.7 (5.8)	65.3 ± 0.5 (0.7)
Settings 3 (Pi 20 cm H ₂ O; mL)	105 ± 0 (0)	102.7 ± 0.7 (0.6)	106.1 ± 0.6 (0.5)	98 ± 1.4 (1.4)
Settings 4 (RR 10; mL)	50.1 ± 1 (1.9)	44.1 ± 0.6 (1.3)	42 ± 0 (0)	41.2 ± 1.8 (4.2)

Abbreviations: FGF, fresh gas flow; PEEP, positive end-expiratory pressure; Pi, inspired pressure; RR, respiratory rate.

^a Settings 1 is the standard parameters (Pi 10 cm H₂O, RR 20, PEEP 0 cm H₂O). Settings 2 had PEEP (5 cm H₂O) added, Settings 3 had inspired pressure increased (Pi 20 cm H₂O), and Settings 4 had RR decreased (RR 10) when compared to Settings 1.

Table 3.

Percent Decrease of Tidal Volume Compared to 1 L/min Fresh Gas Flow Rate for GE Aestiva and GE Avance CS2.

FGF^a (L/min)	6	10	15
GE Aestiva			
Settings 1 Standard (%)	-27.3	-65.6	-79.2
Settings 2 (PEEP 5 cm H ₂ O; %)	-7.6	-27.4	-33.9
Settings 3 (Pi 20 cm H ₂ O; %)	-20.6	-26.9	-33
Settings 4 (RR 10; %)	-22.9	-68.5	-80
GE Avance CS2			
Settings 1 Standard (%)	-6.5	-12.2	-13.7
Settings 2 (PEEP 5 cm H ₂ O; %)	5.4	-1.2	0.5
Settings 3 (Pi 20 cm H ₂ O; %)	-2.2	1	6.7
Settings 4 (RR 10; %)	-12	-16.2	-17.8

Abbreviations: FGF, fresh gas flow; PEEP, positive end-expiratory pressure; Pi, inspired pressure; RR, respiratory rate.