A Laboratory Evaluation of 2 Mechanical Ventilators in the Presence of Helium-Oxygen Mixtures

Melissa K Brown RRT-NPS and David C Willms MD

BACKGROUND: Helium-oxygen (heliox) mixtures are being used more frequently with mechanical ventilators. Newer ventilators continue to be developed that have not yet been evaluated for safety and efficacy of heliox delivery. We studied the performance of 2 previously untested ventilators (Servo-i and Inspiration) during heliox administration. METHODS: We measured tidal volume (V_T) delivery, gas blending, gas analyzing, and pressure stability in the presence of heliox. A heliox (80% helium/20% oxygen) tank was attached to the 50-psi air inlet. We compared the set V_T (ie, set on the ventilator) and the exhaled V_T (measured by the ventilator) to the delivered V_T (measured with a lung model). Pressure measurements were also evaluated. We also compared the ventilator-setting fraction of inspired oxygen (F_{IO_2}) to the F_{IO_2} measured by the ventilator and the F_{IO_2} measured with a supplemental oxygen analyzer. RESULTS: Heliox significantly affected both the exhaled V_T measurement and the actual delivered V_T ($p < 0.001$) with both the Servo-i and the Inspiration. Neither peak inspiratory pressure (in the pressure-controlled ventilation mode) nor positive end-expiratory pressure were adversely affected by heliox with either ventilator. Introducing heliox into the gas-blending systems caused only a small error in F_{IO_2} delivery and monitoring. CONCLUSIONS: Both ventilators cycled consistently with heliox mixtures. In most cases, actual delivered V_T can be reliably calculated if the F_{IO_2} and the set V_T or the measured exhaled V_T is known. With the Servo-i, at high helium concentrations the exhaled V_T measurement was unreliable and caused a high-priority alarm condition that couldn't be disabled. A supplemental oxygen analyzer is not necessary with either device for heliox applications. *Key words: helium, heliox, tidal volume, mechanical ventilation.* [Respir Care 2005;50(3):354–360.

Introduction

The medical use of helium-oxygen mixture (heliox) was first described by Barach in 1935, to treat asthma and airway obstruction.[1] Recently, heliox applications have expanded from asthma[2–5] and airway obstruction[6–9] to bronchiolitis[10–12] and chronic obstructive pulmonary disease.[13–15] The advantage of heliox is primarily its lower density than either air or oxygen. The lower density reduces airway resistance and thus reduces patient work of breathing and the driving pressure required to achieve adequate ventilation. The mechanisms of improved ventilation efficiency may be by conversion of turbulent flow to laminar flow and, perhaps, improved gas mixing in distal airways.

With the recent increased interest in heliox for critically ill patients, heliox delivery methods have evolved from masks to mechanical ventilators. Because of its low den-

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eVent Medical Ltd supplied heliox for this study.

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sity and high thermal conductivity, heliox can interfere with normal ventilator function and monitoring. For example, with heliox, a screen pneumotachometer may underestimate flow (and thus volume), because of the lower resistance across the screen. Hot-wire type pneumotachometers will grossly malfunction, because heliox's thermal conductivity is markedly higher than that of air. Accurate measurement of flow is essential for mechanical ventilators to control tidal volume (V_T) delivery, monitor inspiratory and expiratory volumes, and blend and analyze gas mixtures. Accurate information is clinically valuable and necessary to ensure patient safety.

There are few published studies of the effect of heliox on specific mechanical ventilators. The most comprehensive review, by Tassaux et al,[16] does not address ventilators more recently introduced. The present study was designed to determine how 2 newer ventilators (the Servo-i and the Inspiration) function in the presence of heliox. We were interested in testing these ventilators' performance during heliox administration, to determine whether they could deliver gas accurately during volume-controlled and pressure-controlled ventilation. We also sought to determine (1) correction factors for measured volumes, (2) whether the set positive end-expiratory pressure (PEEP) is maintained, and (3) if the delivered fraction of inspired oxygen (F_{IO_2}) was within the normal error range during heliox administration.

Methods

Two ventilators were tested: the Inspiration (eVent Medical Ltd, Galway, Ireland) and the Servo-i (Maquet Critical Care, Solna, Sweden). The devices were calibrated according to the manufacturers' specifications. An 80% helium/20% oxygen mixture, in an H-size tank, was connected via the 50-psi air inlet of the ventilator. The ventilator was connected to a test lung (Michigan Instruments, Grand Rapids, Michigan) that was cross-calibrated independently from the manufacturer.

The test lung is built around a chamber, and the compliance and "airway" resistance of the chamber are determined by precision spring-loading and variable cross-section resistors. The delivered V_T is determined as V_T = respiratory-system compliance × pressure (measured at zero flow). The calculated V_T is verified against a calibrated volume scale attached to the device. Test-lung compliance was set at 0.05 L/cm H_2O; resistance was set at 5 cm H_2O/L/s with room-air temperature, barometric pressure, and humidity (ie, ambient temperature and pressure saturated). In this lung model, flow and V_T measurements are independent of gas density, as described by Tassaux et al.[16]

A pulmonary mechanics monitor (PF-300, IMT Medical, Vaduz, Liechtenstein) was calibrated according to the manufacturer's specifications and inserted into the inspiratory limb of the ventilator circuit to verify V_T on 100% oxygen, determine overall system static compliance, and independently verify the F_{IO_2}, peak inspiratory pressure (PIP), and PEEP. A pressure monitor (Magnehelic, Dwyer Instruments, Michigan City, Indiana) (which has a bellows flat spring dial gauge with an operating range of 0–80 cm H_2O) was calibrated according to the manufacturer's specifications and placed proximal to the test lung to measure plateau pressure. System static compliance was measured on 100% oxygen for V_T of 300–1,000 mL, in 100-mL increments, during volume-controlled ventilation, constant flow, with a 0.5-s inspiratory pause. Measured compliance was linear over the tested range of V_T.

Measurement of V_T and PEEP

The following variables were compared: set V_T (ie, the V_T ventilator setting), exhaled V_T (measured by the ventilator's pneumotachometer), and delivered V_T (measured by the lung model). Measurements were taken at measured F_{IO_2} values of 0.21, 0.30, 0.40, 0.50, and 1.0. With F_{IO_2} values < 1.0, helium constituted the balance of the gas mixture (eg, with F_{IO_2} 0.21, helium constituted 79% of the gas mixture).

If there was a discrepancy between the set F_{IO_2} and the measured F_{IO_2}, the blender was adjusted to deliver the desired F_{IO_2}. Smaller intervals were selected in the lower F_{IO_2} range, to focus data collection on the concentrations most widely used in clinical practice. The ventilation mode was volume-control. We studied V_T settings of 500, 750, and 1,000 mL. For each F_{IO_2}, the same preset V_T was used, regardless of actual delivered V_T, with the following ventilator settings: PEEP zero, respiratory rate 12 breaths/min, peak flow 40 L/min, inspiratory-expiratory ratio 1:1, trigger sensitivity −2 cm H_2O.

Six successive breaths were measured and analyzed for each V_T, with 2 min allowed after each change for system equilibration. We collected data on actual PEEP levels (measured by the pulmonary mechanics monitor) at PEEP of 5, 10, and 15 cm H_2O, at the settings used for the 750-mL V_T, to determine PEEP stability with a heliox mixture. Set PEEP was compared to measured PEEP in the lung model chamber at F_{IO_2} of 0.21 (balance helium) and 1.0.

Measurement of PIP in Pressure-Controlled Ventilation

Pressure-control levels of 15, 20, and 30 cm H_2O were studied to determine if heliox affected the ventilator's control of PIP in the pressure-control mode. Measurements were taken at F_{IO_2} of 0.21, 0.30, 0.50 (balance helium), and 1.0. We used the fastest available rise time, and the following settings: PEEP 5 cm H_2O, respiratory rate 12 breaths/min, inspiratory-expiratory ratio 1:1, and trigger sensitivity −2 cm H_2O. We collected data on PIP (measured by the supplemental monitors), inspiratory V_T (measured by the pulmonary mechanics monitor), and exhaled V_T (measured by and displayed on the mechanical ventilator).

Accuracy of the Ventilator Oxygen Blender and Oxygen Analyzer

The ventilator oxygen blender was evaluated at set F_{IO_2} of 0.21, 0.30, 0.40, 0.50, 0.60, 0.70, 0.80, 0.90 (balance helium), and 1.0. The volume control ventilator settings for the evaluation of PEEP of 5 were utilized to determine oxygen blender accuracy. The set F_{IO_2} was compared to single measurements from both the ventilator's oxygen analyzer and the pulmonary mechanics monitor. Sufficient time was allotted to allow the analyzers to stabilize.

Data Analysis

Data are expressed as mean ± SD. For each F_{IO_2}, the differences between set V_T and delivered V_T and between exhaled V_T and delivered V_T were compared and analyzed with the paired Student's *t* test. Differences were considered statistically significant when $p < 0.05$. Data were stored in a spreadsheet (Excel, Microsoft, Redmond, Washington) and analyzed with statistics software (Analyze-it for Excel, Leeds, England). We conducted multiple regression analysis with statistics software (Minitab, State College, Pennsylvania) to determine whether there was a linear relationship between F_{IO_2}, set V_T, and delivered V_T, as well as between the exhaled V_T and the delivered V_T.

Results

Both ventilators cycled consistently with all heliox mixtures in both volume-control and pressure-control ventilation. The triggering function was not tested.

Set V_T, Exhaled V_T, and Delivered V_T in the Volume-Control Mode

With the Inspiration ventilator the delivered V_T was significantly higher than set V_T ($p < 0.001$) at all V_T and F_{IO_2} settings. The magnitude of that discrepancy is inversely related to the F_{IO_2}: the lower the F_{IO_2} (balance helium), the more the delivered V_T exceeded the set V_T (Fig. 1). Thus, delivered V_T exceeded set V_T by 6.3 ± 1.5% at an F_{IO_2} of 0.5; by 12.0 ± 1.0% at an F_{IO_2} of 0.4; by 13.6 ± 0.57% at an F_{IO_2} of 0.3; and by 15.6 ± 1.1% at an F_{IO_2} of 0.21. For a given F_{IO_2} there was a linear relationship between the set V_T and the delivered V_T ($r^2 = 0.99$, $p < 0.001$). Delivered V_T was also higher than the exhaled V_T measured by the ventilator's pneumotachometer. The magnitude of the delivered-versus-exhaled V_T discrepancy was significant ($p < 0.001$), inversely related to F_{IO_2}, and linear ($r^2 = 0.99$, $p < 0.001$). Thus, delivered V_T exceeded exhaled V_T (Fig. 2) by 24.3 ± 4% at an F_{IO_2} of 0.5; by 36.6 ± 2.5% at an F_{IO_2} of 0.4; by 48.3 ± 1.1% at an F_{IO_2} of 0.3; and by 60 ± 4.6% at an F_{IO_2} of 0.21.

With the Servo-i, delivered V_T was lower than set V_T. That discrepancy was significant ($p < 0.001$) but within 4.8 ± 2.4%. The discrepancy was constant across all F_{IO_2} values (see Fig. 1). There was a linear relationship between set V_T and delivered V_T ($r^2 = 1$, $p < 0.001$). Exhaled V_T was significantly lower than delivered V_T ($p < 0.001$), by 1.6 ± 1.5% at F_{IO_2} of 0.4 and 0.5 (see Fig. 2). At F_{IO_2} of 0.3 the relationship between exhaled V_T and delivered V_T became less linear; the exhaled V_T underestimated the delivered V_T by 37.6 ± 31.6%.

With the Servo-i, as the V_T was increased, the discrepancy became greater, with resulting overall less linearity between the exhaled V_T and delivered V_T ($r^2 = 0.76$, $p < 0.001$). At an F_{IO_2} of 0.21 the V_T reading became increasingly erratic, displaying V_T of < 100 mL at all V_T values. At an F_{IO_2} of 0.21 and test V_T of 500 mL, the high-priority, low-minute-volume alarm sounded and could not be disabled, causing a constant-alarm condition.

For both ventilators, a volume-correction factor can be applied to determine actual delivered V_T, if F_{IO_2} and set V_T or exhaled V_T are known (Table 1). However, with the Servo-i no exhaled-V_T correction factors are possible for F_{IO_2} of ≤ 0.3.

Positive End-Expiratory Pressure

Measured PEEP was in good agreement with set PEEP (Table 2). With the Inspiration ventilator the mean difference between measured and set PEEP was 0.9 ± 0.17 cm H_2O, with a maximum discrepancy of 1.0 cm H_2O. With the Servo-i the mean difference was 0.63 ± 0.25 cm H_2O, with a maximum discrepancy of 0.9 cm H_2O.

Peak Inspiratory Pressure

Measured PIP was in agreement with set PIP on most settings with the Inspiration (Fig. 3); the mean difference was 0.11 cm ± 0.22 cm H_2O, with a maximum discrepancy of 0.5 cm H_2O. With the Servo-i the discrepancy between measured and set PIP was consistently larger (see Figure 3); the mean difference was 1.31 ± 0.11 cm H_2O, with a maximum discrepancy of 1.5 cm H_2O.

Accuracy of the Ventilators' Oxygen Blenders and Oxygen Analyzers

With the Inspiration, the delivered F_{IO_2} was less than the set F_{IO_2}, with a difference of 2.6 ± 2.2%. The discrepancy

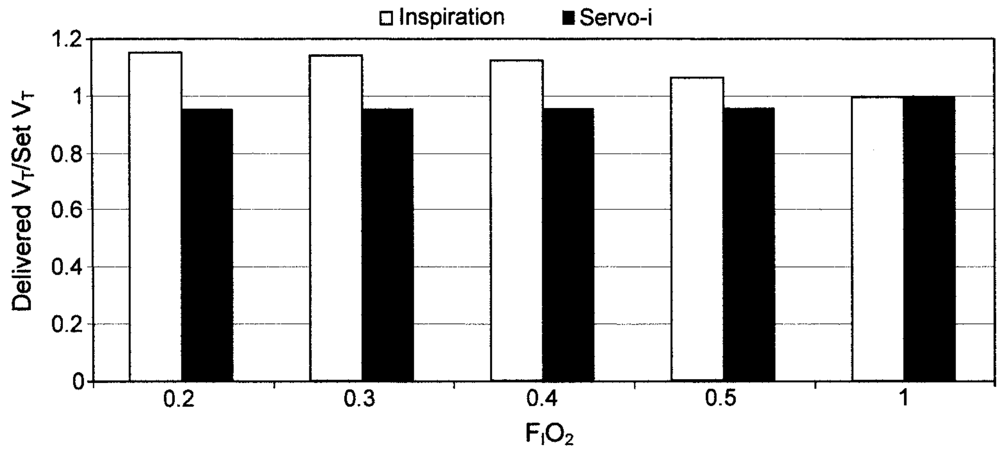

Fig. 1. Effect of heliox on the ratio of delivered tidal volume (V_T measured by the lung model) to set V_T (the V_T setting on the ventilator) with the Inspiration ventilator (white bars) and the Servo-i ventilator (black bars). The bars indicate the mean of the ratio of the delivered V_T to the set V_T at each fraction of inspired oxygen (F_{IO_2}) (balance helium) for the 3 V_T tested.

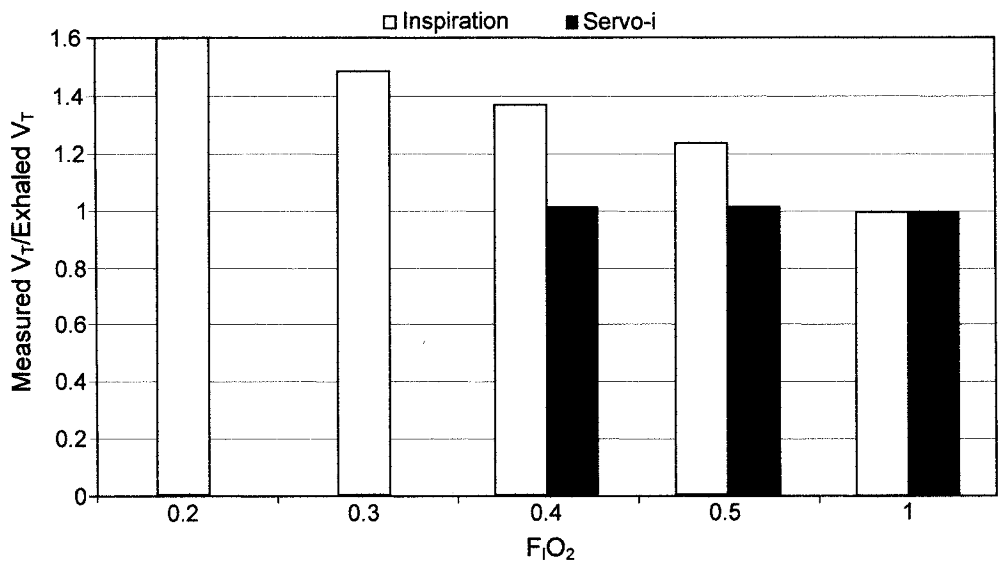

Fig. 2. Effect of helium on the ratio of delivered tidal volume (V_T measured by the lung model) to exhaled V_T (V_T measured by the ventilator's pneumotachometer) with the Inspiration ventilator (white bars) and the Servo-i ventilator (black bars). The bars indicate the mean of the ratio of the delivered V_T to the exhaled V_T at each fraction of inspired oxygen (F_{IO_2}) (balance helium) for the 3 tidal volumes tested. Exhaled V_T from the Servo-i was erratic on F_{IO_2} 0.3 and 0.2.

was greatest at an F_{IO_2} of 0.5, with a maximum difference of 7%. The ventilator's oxygen-analyzer measurement was within 1.6 ± 1.9% of the set F_{IO_2}. The ventilator's oxygen analyzer was accurate, as compared to the supplemental analyzer's readings, with regard to heliox mixtures, with a difference of 1.8 ± 1.1%; the maximum discrepancy was between set F_{IO_2} of 0.5 and 0.7. The ventilator's oxygen analyzer overestimated the analyzed F_{IO_2} by 2% (Fig. 4).

With the Servo-i, the delivered F_{IO_2} was greater than the set F_{IO_2}, with a discrepancy of 0.87 ± 0.83%. The discrepancy was greatest between F_{IO_2} values of 0.7 and 0.8, with a maximum difference of 2%. The ventilator's oxygen-analyzer reading was within 2.1 ± 1.3% of the set F_{IO_2}. The ventilator's oxygen analyzer, as compared to the supplemental analyzer, had a discrepancy of 1.5 ± 1.1%. The maximum discrepancy occurred between set F_{IO_2} of 0.3 and 0.4, and the ventilator's oxygen analyzer overestimated the F_{IO_2} by 3% (Fig. 5).

Discussion

This study corroborates previously documented research,[16–20] which found that the use of helium as a driving gas affects ventilator performance. Although both ven-

Table 1. Tidal Volume Correction Factors With the Inspiration and Servo-i Ventilators*

% Helium/% Oxygen	Tidal Volume Correction Factor			
	Inspiration		Servo-i	
	Set V_T	Exhaled V_T	Set V_T	Exhaled V_T
80/20	1.15	1.6	0.95	NA†
70/30	1.14	1.48	0.95	NA†
60/40	1.12	1.37	0.95	1.02
50/50	1.06	1.24	0.95	1.02

*Multiply the ventilator-measured tidal volume (V_T) value by the correction factor to determine the actual delivered V_T.
set V_T = tidal volume set on ventilator controls
exhaled V_T = tidal volume measured by the ventilator's pneumotachometer
†Not applicable, because no correction factor is possible (see text)

Table 2. Set PEEP Versus Actual Delivered PEEP With a Mixture of 80% Helium and 20% Oxygen, With the Inspiration and Servo-i Ventilators

Set PEEP (cm H_2O)	Actual Delivered PEEP	
	Inspiration	Servo-i
5	4.0	4.1
10	9.0	9.4
15	14.3	14.6

PEEP = positive end-expiratory pressure

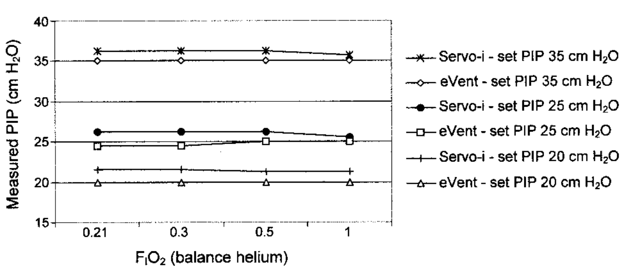

Fig. 3. Measured peak inspiratory pressure (PIP) versus set PIP at 4 different fractions of inspired oxygen (F_{IO_2}) (balance helium).

tilators we tested functioned during both volume-control and pressure-control, their V_T output, F_{IO_2} control, and monitoring capabilities were distorted to different degrees. As far as we know, this is the first study to evaluate the capability of the Servo-i and Inspiration ventilators for heliox delivery and to document correction factors that can be applied to V_T monitoring during heliox application with these ventilators.

Tidal Volume

The Inspiration's V_T output increased with increasing helium concentration, from 6.3% to a maximum of 15.6%. This is in contrast to the Servo-i V_T output, which decreased 4.8% with all evaluated F_{IO_2} levels except 100% oxygen. With the Inspiration, the increase in delivered V_T versus set V_T can be explained by the increase in flow caused by the lower gas density of helium. The Inspiration controls V_T delivery by feedback from a screen-type differential-pressure pneumotachometer to a proportional solenoid. The pneumotachometer underestimates heliox flow proportional to the helium percentage. If inspiratory time and inspiratory valve-opening stay constant, then the delivered V_T will increase. With the Inspiration, as delivered V_T increases with the addition of heliox, the exhaled V_T decreases. The clinician needs to be aware of this monitoring discrepancy and make appropriate adjustments to the set V_T to achieve the desired delivered V_T.

The Servo-i V_T output decreased with the addition of heliox but remained within the manufacturer's specifications. The Servo-i uses an inspiratory flow transducer similar to that in the Inspiration (differential flow transducer across a fixed resistance). The likely reason the Servo-i V_T stayed within specifications is the design of the inspiratory section of the ventilator. The air and oxygen gas modules are separate and do not have a common blending chamber. Each gas module has a temperature sensor and a supply pressure transducer. The increase of flow through the module caused by the addition of heliox would cause an increase in pressure and a feedback mechanism, prematurely terminating flow and preventing V_T-overshoot. The Servo-i uses an ultrasonic transducer to measure expiratory flow. The equation the ultrasonic transducer uses to calculate flow is based on the transit time between pulses transmitted in the direction of or against flow. The gas density acts as a known constant "K" in the equation. The low-density heliox confounds this flow-measurement technique, leading to erratic behavior at high concentrations. Not only did this preclude the calculation of correction factors for exhaled V_T with the Servo-i and 70/30 heliox, the device would not display an expiratory volume greater than 2 digits with 80/20 heliox, at all V_T values tested. The ultrasonic transducer's inability to measure the flow of 80/20 heliox led to a continuous low-minute-volume alarm when the set V_T was 500 mL.

Because most flow sensors are not calibrated for heliox, we expected the differences between delivered V_T and set V_T and exhaled V_T with both ventilators in volume-control mode. Our results permitted the development of correction factors to predict actual delivered V_T during heliox use, by correcting either the set V_T or the exhaled V_T. The exception to this is the Servo-i at the highest helium concentrations (70–80%). The correction factors should be used only for set V_T values of 500–1,000 mL. Further testing is required to determine ventilator performance and correction factors in the neonatal and pediatric range. Our testing was also limited to one ventilator of each type. Although

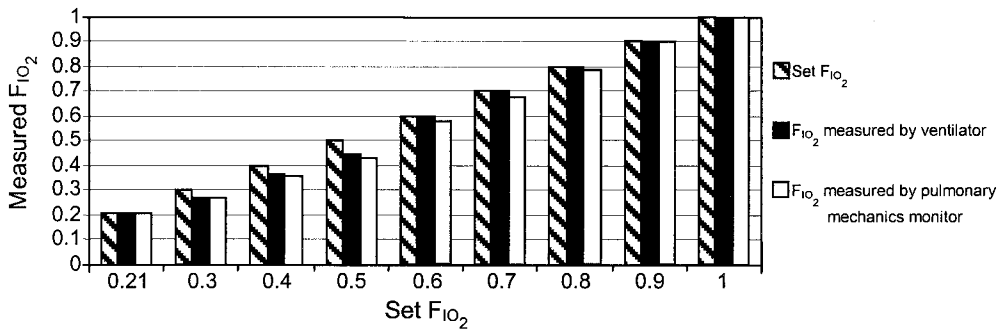

Fig. 4. Measured fraction of inspired oxygen (F_{IO_2}) versus set F_{IO_2} with the Inspiration ventilator. The measurements were made with the ventilator's oxygen analyzer and a pulmonary mechanics monitor at each F_{IO_2} from 0.21 to 1.0 (balance helium).

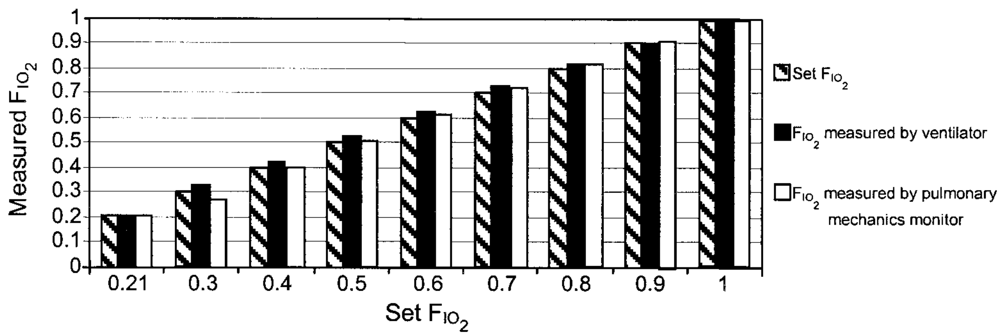

Fig. 5. Measured fraction of inspired oxygen (F_{IO_2}) versus set F_{IO_2} with the Servo-i ventilator. The measurements were made with the ventilator's oxygen analyzer and a pulmonary mechanics monitor at each F_{IO_2} from 0.21 to 1.0 (balance helium).

each unit was calibrated according to the manufacturer's specifications, a larger sample might have given slightly different results.

Pressure Stability

The expiratory valves on both the Inspiration and the Servo-i are flat diaphragm valves. On the Inspiration the valve is controlled by a proportional solenoid, and on the Servo-i by a magnetic coil actuator. The performance of these valves does not have a resistive component and should not be affected by gas density. To help prevent pressure-overshoot and to maintain set PEEP, the valves are dynamically controlled by monitoring circuit pressure. According to the Boyle law, pressure measurements are independent of gas density, so pressure measurements should not be influenced by the use of a lower-density gas such as heliox. PEEP measurements in all the tested conditions, with both ventilators, were within the manufacturer's operating specifications.

The delivery of PIP in the pressure-control mode was not affected in a clinically important way with either ventilator tested by the addition of a heliox mixture. The Inspiration stayed well within its operating specifications at all pressures tested. The Servo-i stayed within its operating specifications at all pressures except with pressure-control of 15 cm H_2O, during which, at all F_{IO_2} levels, the Servo-i PIP was consistently 0.5 cm H_2O outside of its operating specifications. Previous studies on pressure functions and heliox use have also shown that heliox does not significantly affect pressure functions.[16,18,20] We did not, however, evaluate heliox's effect on flow or the pressure trigger function.

Accuracy of the Ventilators' Oxygen Blenders and Oxygen Analyzers

Our results are similar to other published reports that describe a ventilator-specific effect of heliox on gas blending.[16–18] Perhaps most important to the clinician is the degree of agreement between the ventilator F_{IO_2} setting and the oxygen analyzer's reading in the presence of heliox. For practical reasons, the accuracy of this device can be of utmost importance. One of the most typical alarm conditions triggered with the introduction of heliox to the gas-blending system in a mechanical ventilator is a low or high F_{IO_2} alarm. This high-priority alarm arises from internal alarm settings that are activated in the event of a discrepancy between the set F_{IO_2} and the F_{IO_2} measured by the ventilator. Using an 80/20 heliox tank mixture as a source gas necessarily introduces a small error into the system, but it is usually small enough that an alarm condition is not activated unless the blending system is greatly affected by the introduction of the heliox, or the manufacturer has preset the alarm parameters very tight. A heliox concentration other than 80/20 will almost always cause this alarm condition, and for that reason and others, the 80/20 tank concentration should always be used if possible. In some ventilators the oxygen analyzer can be disconnected and the oxygen alarm thus disabled. For the ventilator to be safely used in this manner, a supplemental oxygen analyzer with audible alarms must be used. With some ventilators it is not physically possible or safe to disconnect the oxygen analyzer, in which case it may be impossible to use the ventilator with heliox tank concentrations other than 80/20, or at all if there is a wide discrepancy between set F_{IO_2} and the F_{IO_2} measured by the ventilator. Clinicians are generally uncomfortable about physically disconnecting ventilator features, so strong performance of the ventilator blending system with heliox source gas is greatly preferred.

The Inspiration's oxygen blender and analyzer were always within 5%, and no oxygen alarm conditions were encountered during testing. The Servo-i oxygen blender and analyzer were always within 3% and no oxygen alarm conditions were encountered during testing. From a clinical standpoint there may be value in having specific knowledge of the actual delivered F_{IO_2}. This is possible only if the analyzer's heliox performance has been tested and documented. If no oxygen alarm conditions have been encountered and there is no clinically important difference in the performance of the ventilator's oxygen analyzer, then introduction of a supplemental oxygen analyzer is not necessary. In our tests, the Inspiration's oxygen analyzer was within 2% of the supplemental oxygen analyzer's readings, and the Servo-i was within 3%. An external oxygen analyzer is not necessary during heliox use with either the Inspiration or Servo-i.

Conclusions

Both the Inspiration and Servo-i cycled consistently with heliox mixtures during volume-controlled and pressure-controlled ventilation. In most cases, actual delivered V_T can be reliably calculated if the F_{IO_2} and the set V_T or the measured exhaled V_T are known. With the Servo-i and high helium concentration, the exhaled V_T display was unreliable and caused a high-priority alarm condition that could not be disabled. That alarm may preclude the use of the Servo-i with heliox in some clinical situations.

It is not necessary to use a supplemental oxygen analyzer with either the Inspiration or Servo-i for heliox applications.

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