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

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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 ($F_{IO2}$) to the $F_{IO2}$ measured by the ventilator and the $F_{IO2}$ 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 $F_{IO2}$ delivery and monitoring. CONCLUSIONS: Both ventilators cycled consistently with heliox mixtures. In most cases, actual delivered $V_T$ can be reliably calculated if the $F_{IO2}$ 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. © 2005 Daedalus Enterprises]

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 asthma2–5 and airway obstruction6–9 to bronchiolitis10–12 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-
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., 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 $V_T = \text{respiratory-system compliance} \times \text{pressure}$ (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$_2$O; resistance was set at 5 cm H$_2$O/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.,

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$_2$O) 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$_2$O.

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$_2$O, 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$_2$O 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$_2$O, respiratory rate 12 breaths/min, inspiratory-expiratory ratio 1:1, and trigger sensitivity -2 cm H$_2$O. 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 FIO$_2$ 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 FIO$_2$ 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 FIO$_2$, 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 set VT and delivered VT (r$^2$), as well as between the exhaled VT and the delivered VT.

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 FIO$_2$ settings. The magnitude of that discrepancy is inversely related to the FIO$_2$: the lower the FIO$_2$ (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 FIO$_2$ of 0.5; by 12.0 ± 1.0% at an FIO$_2$ of 0.4; by 13.6 ± 0.57% at an FIO$_2$ of 0.3; and by 15.6 ± 1.1% at an FIO$_2$ of 0.21. For a given FIO$_2$ 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.

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$_2$O, with a maximum discrepancy of 1.0 cm H$_2$O. With the Servo-i the mean difference was 0.63 ± 0.25 cm H$_2$O, with a maximum discrepancy of 0.9 cm H$_2$O.

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$_2$O, with a maximum discrepancy of 0.5 cm H$_2$O. 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$_2$O, with a maximum discrepancy of 1.5 cm H$_2$O.

Accuracy of the Ventilators’ Oxygen Blenders and Oxygen Analyzers

With the Inspiration, the delivered FIO$_2$ was less than the set FIO$_2$, with a difference of 2.6 ± 2.2%. The discrepancy
was greatest at an $F_{I\text{O}_2}$ of 0.5, with a maximum difference of 7%. The ventilator’s oxygen-analyzer measurement was within $1.6 \pm 1.9\%$ of the set $F_{I\text{O}_2}$. The ventilator’s oxygen analyzer was accurate, as compared to the supplemental analyzer’s readings, with a difference of $1.8 \pm 1.1\%$; the maximum discrepancy was between set $F_{I\text{O}_2}$ of 0.5 and 0.7. The ventilator’s oxygen analyzer overestimated the analyzed $F_{I\text{O}_2}$ by 2% (Fig. 4).

With the Servo-i, the delivered $F_{I\text{O}_2}$ was greater than the set $F_{I\text{O}_2}$, with a discrepancy of $0.87 \pm 0.83\%$. The discrepancy was greatest between $F_{I\text{O}_2}$ values of 0.7 and 0.8, with a maximum difference of 2%. The ventilator’s oxygen-analyzer reading was within $2.1 \pm 1.3\%$ of the set $F_{I\text{O}_2}$. The ventilator’s oxygen analyzer, as compared to the supplemental analyzer, had a discrepancy of $1.5 \pm 1.1\%$. The maximum discrepancy occurred between set $F_{I\text{O}_2}$ of 0.3 and 0.4, and the ventilator’s oxygen analyzer overestimated the $F_{I\text{O}_2}$ by 3% (Fig. 5).

**Discussion**

This study corroborates previously documented research, which found that the use of helium as a driving gas affects ventilator performance. Although both ven-
Tidal Volume

The Inspiration’s VT output increased with increasing helium concentration, from 6.3% to a maximum of 15.6%. This is in contrast to the Servo-i VT output, which decreased 4.8% with all evaluated FIO2 levels except 100% oxygen. With the Inspiration, the increase in delivered VT versus set VT can be explained by the increase in flow caused by the lower gas density of helium. The Inspiration controls VT 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 VT will increase. With the Inspiration, as delivered VT increases with the addition of heliox, the exhaled VT decreases. The clinician needs to be aware of this monitoring discrepancy and make appropriate adjustments to the set VT to achieve the desired delivered VT.

The Servo-i VT 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 VT 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 VT-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 VT 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 VT 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 VT was 500 mL.

Because most flow sensors are not calibrated for heliox, we expected the differences between delivered VT and set VT and exhaled VT with both ventilators in volume-control mode. Our results permitted the development of correction factors to predict actual delivered VT during heliox use, by correcting either the set VT or the exhaled VT. The exception to this is the Servo-i at the highest helium concentrations (70–80%). The correction factors should be used only for set VT 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

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<tr>
<th>% Helium/% Oxygen</th>
<th>Inspiration</th>
<th>Servo-i</th>
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<tr>
<td></td>
<td>Set VT</td>
<td>Exhaled VT</td>
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<tr>
<td>80/20</td>
<td>1.15</td>
<td>1.6</td>
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<td>70/30</td>
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<tr>
<td>50/50</td>
<td>1.06</td>
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*Multiply the ventilator-measured tidal volume (VT) value by the correction factor to determine the actual delivered VT.

Set VT = tidal volume set on ventilator controls
Exhaled VT = 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

<table>
<thead>
<tr>
<th>Set PEEP (cm H2O)</th>
<th>Actual Delivered PEEP</th>
<th>Inspiration</th>
<th>Servo-i</th>
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<td>5</td>
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<td>10</td>
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PEEP = positive end-expiratory pressure

![Fig. 3. Measured peak inspiratory pressure (PIP) versus set PIP at 4 different fractions of inspired oxygen (FIO2) (balance helium).](image-url)
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 except with pressure-control of 15 cm H2O, during which, at all FIO2 levels, the Servo-i PIP was consistently 0.5 cm H2O 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 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 FIO2 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 FIO2 alarm. This high-priority alarm arises from internal alarm settings that are activated in the event of a discrepancy between the set FIO2 and the FIO2 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 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 FIO2 and the FIO2 measured by the ventilator. Clinicians are generally uncomfortable about physically disconnecting ventilator features, so strong performance of the ventilator blending system with heliox concentration other than 80/20 will almost always cause 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 always within 5% and no oxygen alarm conditions were encountered during testing. The Servo-i oxygen analyzer was 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 FIO2. 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 VT can be reliably calculated if the FiO2 and the set VT or the measured exhaled VT are known. With the Servo-i and high helium concentration, the exhaled VT 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.

ACKNOWLEDGMENTS

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REFERENCES