Inspiratory Limb Carbon Dioxide Entrainment During High-Frequency Oscillatory Ventilation: Characterization in a Mechanical Test Lung and Swine Model

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BACKGROUND: High-frequency oscillatory ventilation (HFOV) has been utilized as a rescue oxygenation therapy in adults with ARDS over the last decade. The HFOV oscillating piston can generate negative pressure during the exhalation cycle, which has been termed active exhalation. We hypothesized that this characteristic of HFOV entrains CO_2 into the inspiratory limb of the circuit and increases the total dead space. The purpose of this study was to determine if retrograde CO_2 entrainment occurs and how it is altered by HFOV parameter settings. METHODS: An HFOV was interfaced to a cuffed endotracheal tube and connected to a mechanical test lung. Negative pressure changes within the circuit's inspiratory limb were measured while HFOV settings were manipulated. Retrograde CO_2 entrainment was evaluated by insufflating CO_2 into the test lung to achieve 40 mm Hg at the carina. Inspiratory limb CO_2 entrainment was measured at incremental distances from the Y-piece. HFOV settings and cuff leak were varied to assess their effect on CO_2 entrainment. Control experiments were conducted using a conventional ventilator. Test lung results were validated on a large hypercapnic swine. RESULTS: Negative pressure was detectable within the inspiratory limb of the HFOV circuit and varied inversely with mean airway pressure ($\bar{P}_{aw}$) and directly with oscillatory pressure amplitude (ΔP). CO_2 was readily detectable within the inspiratory limb and was proportional to the negative pressure that was generated. Factors that decreased CO_2 entrainment in both the test lung and swine included low ΔP, high mean airway pressure, high oscillatory frequency (Hz), high bias flow, and endotracheal tube cuff leak placement. CO_2 entrainment was also reduced by utilizing a higher bias flow strategy at any targeted mean airway pressure. CONCLUSIONS: Retrograde CO_2 entrainment occurs during HFOV use and can be manipulated with the ventilator settings. This phenomenon may have clinical implications on the development or persistence of hypercapnia. *Key words: high-frequency oscillatory ventilation; retrograde carbon dioxide entrainment: carbon dioxide rebreathing; hypercapnia; acute respiratory distress syndrome; active exhalation.* [Respir Care 2012;57(11):1865–1872]

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Introduction

Over the last decade, high-frequency oscillatory ventilation (HFOV) has been utilized as a rescue oxygenation therapy for adults with severe ARDS.[1,2] The use of HFOV has consistently shown short-term improvement in oxygenation parameters, which is attributed to the use of higher mean airway pressure ($\bar{P}_{aw}$).[1,3-5] Furthermore, HFOV is associated with reduced rates of ventilator-induced lung injury in small and large animal models, when compared to conventional ventilation.[3,4,6]

Recommendations from an expert discussion group in 2007 addressed the issue of balancing acceptable blood gas values with lung-protective ventilation during the use of HFOV in adults.[7] The goal was to create a strategy that would provide adequate oxygenation and CO_2 clearance, while minimizing injurious stresses on the lung.

Specifically regarding CO_2 clearance, it was recommended that oscillatory pressure amplitude (ΔP) remain at 90 cm H_2O, and that an arterial pH of 7.25–7.35 be achieved by adjusting respiratory frequency in Hertz (Hz) alone. To promote lung protection by minimizing delivered tidal volume (V_T), it is suggested that respiratory frequency be increased to the highest feasible rate that would obtain the targeted pH. In contrast to conventional ventilation, V_T is altered during HFOV with changes in respiratory frequency.[8-10] At low respiratory frequency and high ΔP, V_T can exceed the volume of anatomical dead space in smaller patients, and may contribute to ventilator-induced lung injury. Of note, in patients requiring a respiratory frequency $\leq$ 7 Hz the placement of an endotracheal tube (ETT) cuff leak is recommended to facilitate CO_2 clearance, which might avoid further increases in delivered V_T. An observational study reported that 30% of patients on HFOV for the treatment of ARDS required a cuff leak to achieve the suggested pH target; however, this will vary between institutions based on their individual protocols.[11]

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During the exhalation cycle of the 3100B HFOV (SensorMedics/CareFusion, San Diego, California), the oscillating piston can generate negative pressure relative to the mean airway pressure. This property of HFOV is often referred to as "active exhalation"; however, its contribution to expiratory flow and gas exchange has not been well characterized. The 3100B HFOV utilizes bias flow in an attempt to direct all expired gases into the expiratory limb of the circuit. Its efficiency, however, to compensate for the negative pressures generated by the oscillating piston is unknown. Because of these characteristics, we hypothesized that negative pressure generated by the oscillating piston within the inspiratory limb of the 3100B HFOV circuit promotes the entrainment of expired CO_2. Retrograde CO_2 entrainment, if present, would increase the total dead space and could contribute to hypercapnia.

The purpose of this research was to determine if retrograde CO_2 entrainment into the inspiratory limb of the 3100B HFOV occurs, and to characterize how CO_2 entrainment is effected by manipulations of the different ventilator parameters.

QUICK LOOK

Current knowledge

High-frequency oscillation is used to treat refractory hypoxemia across a range of patients, from neonates to adults. A unique characteristic of high-frequency oscillation is known as active exhalation, created by the negative displacement of a diaphragm or piston.

What this paper contributes to our knowledge

Retrograde carbon dioxide movement into the patient circuit is common during high-frequency oscillation and may exacerbate hypercarbia. Carbon dioxide rebreathing can be reduced by reducing ΔP; by using a higher mean airway pressure, higher oscillatory frequency, and higher bias flow; and by the presence of an endotracheal tube cuff leak.

Methods

HFOV Inspiratory Limb Pressure Measurements

A SensorMedics 3100B HFOV was interfaced to a cuffed 8.0 mm ETT positioned within an artificial trachea (Fig. 1). The artificial trachea was attached to a test lung (5600i, Michigan Instruments, Grand Rapids, Michigan) set with a compliance of 0.02 L/cm H_2O (approximating ARDS compliance). A pressure transducer (TruWave, Edwards Lifesciences, Irvine, California) with a maximum frequency response of 200 Hz was adapted to fit the temperature port on the inspiratory limb of the HFOV circuit, located 2.5 cm from the Y-piece. The pressure transducer was zeroed relative to atmospheric pressure. Pressure tracings were displayed on a hemodynamic monitor (Solar 8000i, General Electric, Fairfield, Connecticut). Peak positive and negative pressure values were identified with the pressure display cursor and recorded while adjusting $\bar{P}_{aw}$ or ΔP.

HFOV settings during the $\bar{P}_{aw}$ experiment were as follows: ΔP 90 cm H_2O, bias flow 30 L/min, inspiratory time (I-time) 33%, frequency 7 Hz. HFOV settings during the

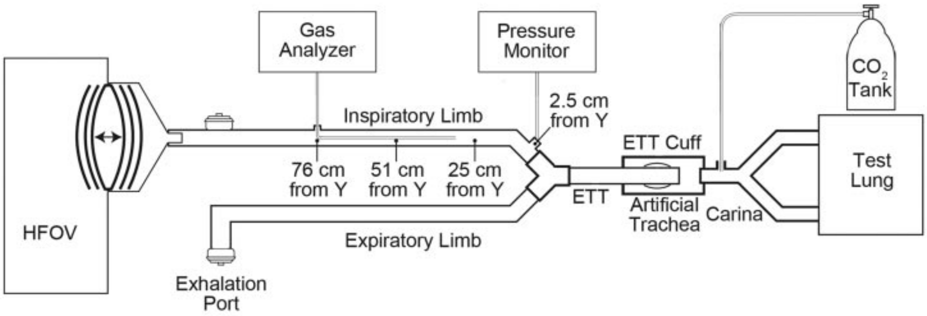

Fig. 1. Mechanical lung design. A pressure transducer was fitted 2.5 cm from the Y-piece during pressure measurements. During retrograde CO_2 entrainment measurements, the pressure transducer was removed and the gas analyzing line was inserted at 76 cm from the Y-piece, and positioned at locations of interest during the different experiments. Y = Y-piece. ETT = endotracheal tube.

ΔP experiment were as follows: $\bar{P}_{aw}$ 34 cm H_2O, bias flow 30 L/min, I-time 33%, frequency 7 Hz.

CO_2 Entrainment During HFOV in Mechanical Lung Model

The 3100B HFOV and mechanical test lung were set up as previously described (with the exception of the pressure transducer). A gas analyzer (RGM 5250, Datex-Ohmeda, Madison, Wisconsin) with a sample flow rate of 190 ± 40 mL/min, response time $\leq$ 400 ms at a flow of 200 mL/min) was utilized to measure inspiratory limb CO_2 entrainment. The gas analyzing line was inserted at a point 76 cm from the Y-piece within the inspiratory limb of the HFOV circuit, and then positioned at the carina. CO_2 was insufflated (7% CO_2 from a size H tank) into the test lung at a flow of 0.5 L/min to attain 40 mm Hg CO_2 at the carina. The CO_2 insertion point into the system was located between the artificial trachea and the carina. The settings of the 3100B HFOV during this calibration period were: $\bar{P}_{aw}$ 34 cm H_2O, bias flow 30 L/min, I-time 33%, frequency 7 Hz, ΔP 90 cm H_2O, F_{IO_2} 0.21. The settings used to calibrate CO_2 insufflation also served as the baseline settings for each of the subsequent experiments. Gas sampling at the carina was performed prior to initiation of all experiments to confirm that carinal CO_2 was 40 mm Hg. Insufflated CO_2 flow did not require adjustment between experiments and was not altered during experiments in order to mimic steady state CO_2 production.

The gas analyzer was withdrawn back from the carina, into the inspiratory limb of the HFOV circuit, to a maximum of 89 cm from the Y-piece, confirming the presence of retrograde CO_2 entrainment. After confirming CO_2 was detectable within the inspiratory limb, the gas analyzer was placed at 51 cm from the Y-piece position and the different parameters ($\bar{P}_{aw}$, bias flow, respiratory frequency, ΔP) of the 3100B HFOV were independently manipulated to assess each setting's effect on CO_2 entrainment. Evaluation of CO_2 entrainment was also performed while simultaneously increasing bias flow and manipulating the mean pressure adjustment to maintain a constant $\bar{P}_{aw}$ of 34 cm H_2O. All experiments were performed with and without a 5 cm H_2O cuff leak. Cuff leaks were created by increasing bias flow to raise $\bar{P}_{aw}$ by 5 cm H_2O, followed by removal of air from the ETT pilot balloon until the original $\bar{P}_{aw}$ was achieved.

CO_2 Entrainment During Conventional Ventilation in Mechanical Lung Model

Conventional ventilator experiments with a ventilator (Servo-i, Maquet, Bridgewater, New Jersey) were performed to validate the experimental design. Two modes were utilized: volume control continuous mandatory ventilation (VC-CMV) and Bi-Vent (pressure controlled ventilation on 2 independently adjustable levels allowing unrestricted spontaneous breathing on both levels). CO_2 insufflation was performed during these control experiments by 2 different methods: 40 mm Hg CO_2 (measured at end-exhalation) was attained at the carina prior to manipulating the ventilator parameters (CO_2 flow of 0.1 L/min); and CO_2 flow of 0.5 L/min to match the same flow as used during the HFOV experiments (producing a carinal CO_2 of > 107 mm Hg, which is above the limit of the gas analyzer). Test lung compliance was set at 0.02 L/cm H_2O.

The VC-CMV settings during CO_2 insufflation were as follows: V_T 420 mL (simulating 6 mL/kg/ideal body weight in a patient with an ideal body weight of 70 kg), PEEP 10 cm H_2O, respiratory rate 15 breaths/min, F_{IO_2} 0.4, inspiratory/expiratory ratio 1:3. Once carinal CO_2 was established, the gas analyzer was withdrawn back into the inspiratory limb and measurements of CO_2 entrainment were obtained at incremental distances. The analyzer was then positioned 8 cm from the Y-piece to assess the effect on CO_2 entrainment, while independently manipulating

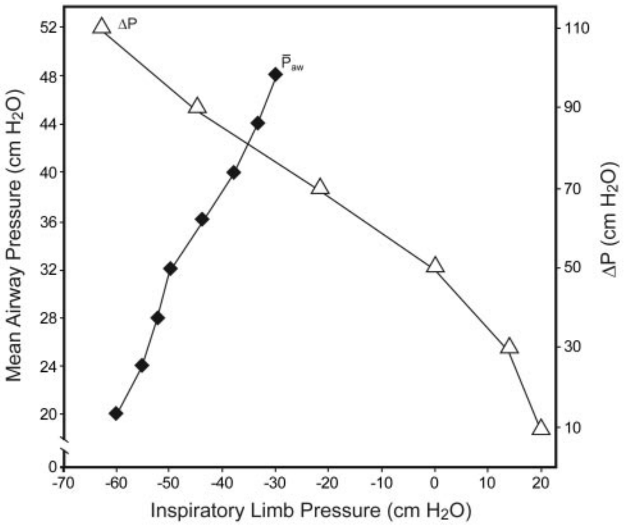

Fig. 2. Inverse effects of mean airway pressure ($\bar{P}_{aw}$) and ΔP on inspiratory limb negative pressure. Increasing $\bar{P}_{aw}$ reduces negative pressure (other settings: ΔP 90 cm H_2O, frequency 7 Hz, bias flow 30 L/min, inspiratory time 33%). Raising ΔP increases negative pressure (other settings: $\bar{P}_{aw}$ 34 cm H_2O, frequency 7 Hz, bias flow 30 L/min, inspiratory time 33%).

the different ventilator parameters as follows: PEEP 5–25 cm H_2O, respiratory rate 10–30 breaths/min, V_T 100–700 mL.

The Servo-i ventilator was then placed in Bi-Vent mode with baseline settings as follows: P_{high} 30 cm H_2O, P_{low} 5 cm H_2O, inspiratory/expiratory ratio = 4:1, F_{IO_2} 0.4. The gas analyzer was placed 8 cm from the Y-piece and effects on CO_2 entrainment were assessed as was done during the VC-CMV experiment. The ventilator parameters were independently manipulated as follows: P_{high} 20–34 cm H_2O, P_{low} 0–20 cm H_2O, inspiratory/expiratory ratio 1:5–5:1.

CO_2 Entrainment During HFOV in Swine Model

Once retrograde CO_2 entrainment during HFOV was characterized with the mechanical lung model, a feasibility study was performed on a 75 kg swine (*Sus scrofa*). The use of this swine was approved by the Wilford Hall Medical Center Institutional Animal Care and Use Committee (IACUC) board and was performed during an ongoing training protocol. The swine utilized for this experiment did not receive artificial lung injury as directed by the training protocol. The swine was anesthetized with isoflurane and intubated with a 7.0 mm ETT. A fentanyl infusion was then used to continue analgesia-sedation as the swine was transitioned to a 3100B HFOV. In a similar fashion to the test lung HFOV experiment, the gas analyzing line was inserted into the inspiratory limb of the circuit and CO_2 was measured at incremental distances from the Y-piece. The initial HFOV settings were identical to the baseline settings used during the mechanical test lung experiment (with the exception of F_{IO_2} of 1.0 during the swine experiment, as directed by the IACUC training protocol). The swine was briefly hypoventilated between experiments by increasing respiratory frequency for 10 seconds to achieve mild hypercapnia (P_{aCO_2} 52.5–63.8 mm Hg). Once retrograde CO_2 entrainment was confirmed within the inspiratory limb, the gas analyzing line was placed 25 cm from the Y-piece position and the HFOV parameters were independently manipulated ($\bar{P}_{aw}$, bias flow, respiratory frequency, ΔP) to assess their effects on CO_2 entrainment. Despite maximal ETT cuff inflation, there was 10 mm Hg CO_2 detectable within the swine's oropharynx. The effect of an additional 5 cm H_2O ETT cuff leak was also assessed.

Statistical Analysis

All retrograde CO_2 entrainment measurements were performed in duplicate for both the 3100B HFOV and conventional ventilator experiments on the test lung. Data were averaged and rounded to the nearest whole number. Retrograde CO_2 entrainment results were identical during the HFOV test lung experiments ($\leq$ 1 mm Hg). Due to restrictions of the swine training protocol, only one set of data for retrograde CO_2 entrainment in the swine model was collected. All inspiratory limb negative pressure measurements were performed in triplicate.

Results

HFOV Inspiratory Limb Pressure Measurements

Negative pressure was readily measured within the inspiratory limb of the HFOV circuit and varied inversely with $\bar{P}_{aw}$ and directly with ΔP. Representative data from a single experiment are depicted in Figure 2. Retrograde CO_2 entrainment increased when more negative pressure was generated within the inspiratory limb of the circuit (Fig. 3).

CO_2 Entrainment During HFOV in Mechanical Lung Model

With the 3100B HFOV on baseline settings, retrograde CO_2 entrainment was detectable as far back as 89 cm from the Y-piece. Entrained CO_2 steadily decreased 1 mm Hg for every 2.5–5.0 cm from the Y-piece and dissipated to 0 mm Hg at 89 cm from the Y-piece (Fig. 4).

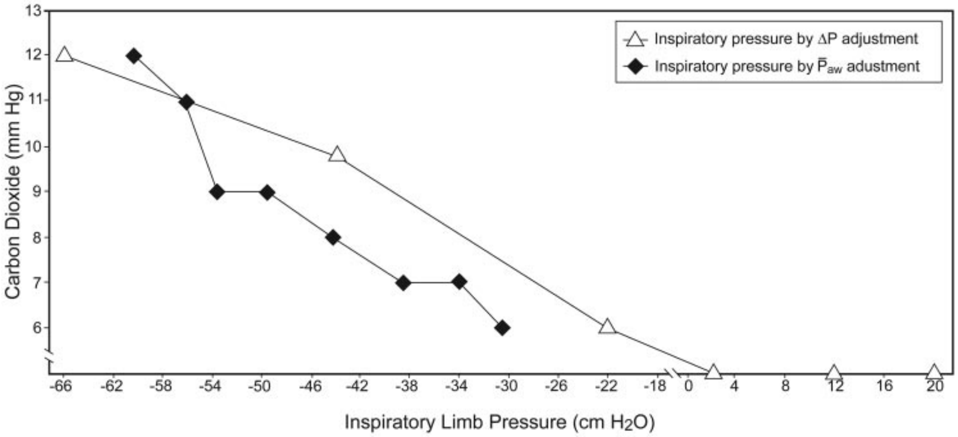

Fig. 3. Effect of inspiratory limb negative pressure on retrograde CO_2 entrainment. Retrograde CO_2 entrainment increases (at 51 cm from the Y-piece) when more negative pressure is generated by either reducing mean airway pressure ($\bar{P}_{aw}$) or raising ΔP. The data points represent the means of duplicate experiments (measurements varied ≤ 1 mm Hg).

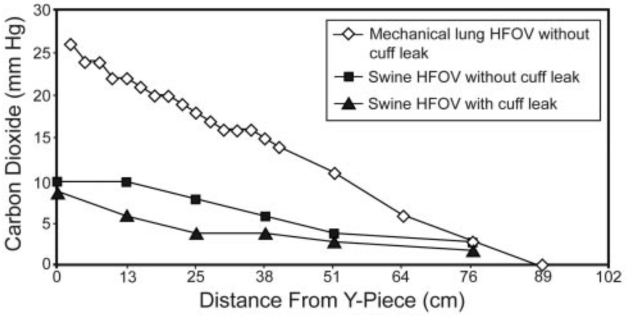

Fig. 4. Inspiratory limb CO_2 pressure and distance of CO_2 entrainment at baseline settings in the mechanical lung and swine models. The high-frequency oscillatory ventilation (HFOV) settings were: mean airway pressure $\bar{P}_{aw}$ 34 cm H_2O, ΔP 90 cm H_2O, frequency 7 Hz, bias flow 30 L/min (without cuff leak), inspiratory time 33%. Despite maximal cuff inflation, there was a persistent 10 mm Hg CO_2 leak within the swine's oropharynx.

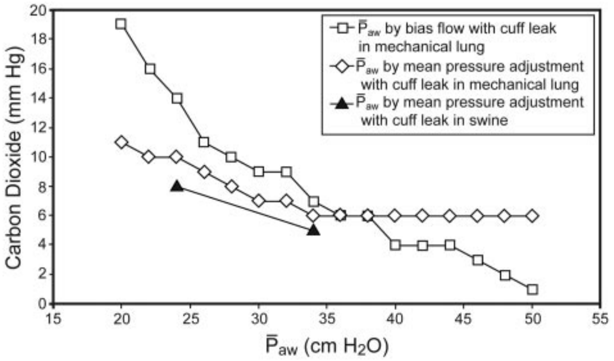

Fig. 5. Effect of mean airway pressure ($\bar{P}_{aw}$) adjustments on retrograde CO_2 entrainment. The $\bar{P}_{aw}$ was manipulated by either the mean pressure adjustment or by bias flow (17–60 L/min). Adjustments were made relative to baseline settings: $\bar{P}_{aw}$ 34 cm H_2O, ΔP 90 cm H_2O, frequency 7 Hz, bias flow 30 L/min, inspiratory time 33%. Mechanical lung data were obtained at 51 cm from the Y-piece, and swine data at 25 cm from the Y-piece.

The effect of increasing $\bar{P}_{aw}$ using either bias flow or the mean pressure adjustment, with a 5 cm H_2O cuff leak in place, is depicted in Figure 5. In both cases, increasing $\bar{P}_{aw}$ reduced retrograde CO_2 entrainment. Increasing $\bar{P}_{aw}$ by adjusting bias flow had a greater effect on reducing CO_2 entrainment, when compared to utilizing the mean pressure adjustment. Removal of the 5 cm H_2O cuff leak increased the amount of CO_2 entrainment in both cases, and the trends were comparable to those seen with a cuff leak (data not shown).

The effect on retrograde CO_2 entrainment when increasing bias flow at a constant $\bar{P}_{aw}$ of 34 cm H_2O is shown in Figure 6. Retrograde CO_2 entrainment was reduced with a higher bias flow strategy. A 5 cm H_2O cuff leak further reduced CO_2 entrainment once bias flow was increased above 30 L/min.

The effect of increasing ΔP is depicted in Figure 7. In the absence of a cuff leak, CO_2 entrainment became detectable once ΔP reached 70 cm H_2O, and continued to rise as ΔP was increased. A 5 cm H_2O cuff leak reduced CO_2 entrainment yet maintained a similar trend.

The effect of increasing respiratory frequency is depicted in Figure 8. CO_2 entrainment was decreased as respiratory frequency was increased. In the presence of a cuff leak, retrograde CO_2 entrainment was further reduced at respiratory frequencies less than 10 Hz.

CO_2 Entrainment During Conventional Ventilation in Mechanical Lung Model

In both the VC-CMV and Bi-Vent modes, no retrograde CO_2 entrainment was detectable beyond 8 cm from the Y-piece while insufflating CO_2 at either 0.1 L/min or 0.5 L/min. The absence of inspiratory limb CO_2 entrainment

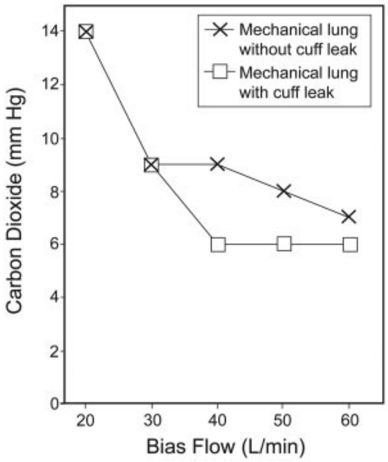

Fig. 6. Effect of bias flow manipulations at constant mean airway pressure $\bar{P}_{aw}$ on retrograde CO_2 entrainment. Data were obtained at 51 cm from the Y-piece. Other high-frequency oscillatory ventilation settings remained at baseline: mean airway pressure $\bar{P}_{aw}$ 34 cm H_2O, ΔP 90 cm H_2O, frequency 7 Hz, inspiratory time 33%.

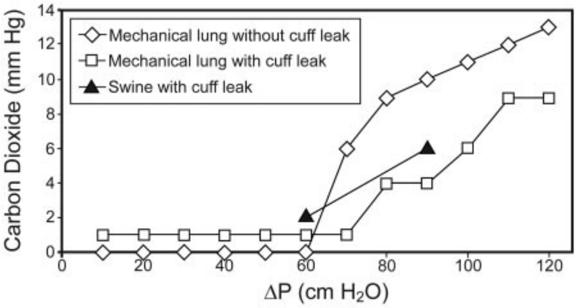

Fig. 7. Effect of ΔP manipulations on retrograde CO_2 entrainment. Data were obtained 51 cm from the Y-piece in the mechanical lung model and 25 cm from the Y-piece in the swine model. Other HFOV settings remained at baseline: mean airway pressure 34 cm H_2O, bias flow 30 L/min, frequency 7 Hz, inspiratory time 33%.

during this experiment confirmed that this phenomenon is unique to HFOV and validated the mechanical test lung design. Further validation of the experimental design was that no CO_2 entrainment was detectable during HFOV when the piston was turned off.

CO_2 Entrainment During HFOV in Swine Model

With the swine on baseline HFOV settings and the ETT cuff maximally inflated, 10 mm Hg of CO_2 was detectable within the Y-piece. Due to the ETT size used during the swine experiment, there was a 10 mm Hg CO_2 leak detectable within the swine's oropharynx, despite maximal cuff inflation. Despite this persistent leak, inspiratory limb CO_2 entrainment was identified as far back as 89 cm from the Y-piece (see Fig. 4). A 5 cm H_2O cuff leak (in addition to the persistent leak) was then placed, which reduced but did not eliminate retrograde CO_2 entrainment.

The effect of manipulating $\bar{P}_{aw}$, ΔP, and respiratory frequency are shown in Figures 5, 7, and 8. As observed during test lung experiments, CO_2 entrainment during the swine experiment was directly proportional to ΔP and inversely proportional to $\bar{P}_{aw}$ and respiratory frequency.

Discussion

Our findings demonstrate that carbon dioxide is readily detectable within the inspiratory limb of the SensorMedics 3100B HFOV in both mechanical lung and swine models. Retrograde CO_2 entrainment was identified as far back as 76 cm from the Y-piece in both models, suggesting that total dead space may extend well into the inspiratory limb of the circuit. We speculate that an increase in total dead space by this phenomenon may contribute to clinical hypercapnia under some circumstances. This is a unique characteristic of the 3100B HFOV that, to our knowledge, has not previously been reported. In contrast, CO_2 rebreathing has been identified during noninvasive ventilation and has prompted modifications to the circuit (eg, single circuit bi-level positive airway pressure systems).[12,13]

The phenomenon of retrograde CO_2 entrainment is complex and has not been fully explored. Our experimental model was designed to verify that retrograde CO_2 entrainment does occur and to show the effect of ventilator parameter changes on the degree of CO_2 entrainment. We have also shown that inspiratory limb negative pressure correlates directly with the degree of CO_2 entrainment; however, this does not imply that inspiratory limb pressure must be negative for this phenomenon to occur. There are most likely other HFOV characteristics that contribute to inspiratory limb CO_2 entrainment, such as pressure differentials between the ETT and the inspiratory and expiratory limbs of the circuit during oscillatory piston cycles. In addition, our data demonstrated frequency dependence of CO_2 entrainment, which suggests that variable expiratory phase time constants may contribute.

These data indicate that retrograde CO_2 entrainment during HFOV is proportional to the negative pressure generated within the inspiratory limb of the circuit. During HFOV, retrograde CO_2 entrainment is reduced (not eliminated) by increasing $\bar{P}_{aw}$, decreasing ΔP, placement of a cuff leak, increasing respiratory frequency, and increasing bias flow at any targeted $\bar{P}_{aw}$. Whether retrograde CO_2 entrainment has a physiologic effect is still unknown. The presence of this phenomenon suggests that ventilator parameter changes that alter V_T alone may not always result in the anticipated P_{aCO_2} response. There is an equilibrium between minute ventilation and total dead space (induced by HFOV settings) that ultimately determines CO_2 clear-

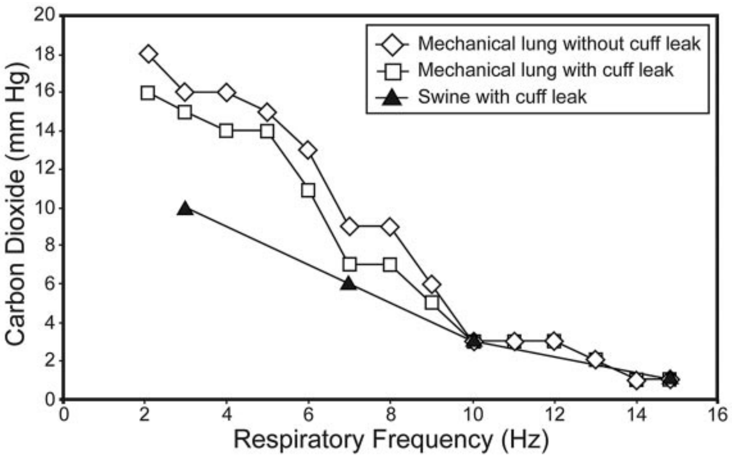

Fig. 8. Effect of respiratory frequency manipulations on retrograde CO_2 entrainment. Data were obtained at 51 cm from the Y-piece in the mechanical lung model and at 25 cm from the Y-piece in the swine model. Other HFOV settings remained at baseline: mean airway pressure 34 cm H_2O, ΔP 90 cm H_2O, bias flow 30 L/min, inspiratory time 33%.

ance. This may explain why increasing ΔP or lowering respiratory frequency (ie, increasing V_T) does not always result in the expected P_{aCO_2} reduction. To our knowledge, there are no studies available that have directly measured P_{aCO_2} during 3100B HFOV setting changes while simultaneously examining for retrograde CO_2 entrainment. We are now in the process of doing such a study. A majority of the current HFOV guidelines are based on the assumption that increasing V_T will consistently reduce P_{aCO_2}, yet there are no studies that directly measure P_{aCO_2} to corroborate this assumption. Previous work has looked at endotracheal tube CO_2 levels as a surrogate of P_{aCO_2} and related them to CO_2 removal; however, the high-frequency oscillator used during that study is not similar to the 3100B HFOV.[14,15]

If retrograde CO_2 entrainment is physiologically important, then reducing contamination of inspired gas may improve the effectiveness of CO_2 clearance. This could be achieved to some degree by altering HFOV strategies; however, more efficient reductions might be obtained with simple modifications to the circuit.

Limitations

A limitation to our mechanical lung model experiments was assuring CO_2 insufflation was comparable between the HFOV and conventional ventilator control experiments. We reconciled this by insufflating CO_2 during conventional ventilation at 0.1 L/min to achieve 40 mm Hg at the carina (identical partial pressure as during the HFOV experiment), as well as insufflating at 0.5 L/min (identical flow as during HFOV experiment). CO_2 at the carina was above the limit of the RGM 5250 gas analyzer (> 107 mm Hg) when insufflating at 0.5 L/min. In neither case was retrograde CO_2 entrainment detected beyond 8 cm from the Y-piece. Furthermore, no CO_2 was detected within the inspiratory limb of the 3100B HFOV circuit when the piston was inactivated (eg, no negative pressure within the inspiratory limb of the circuit).

There were also quantitative differences in the amount of CO_2 entrainment between the mechanical lung model and swine. We attribute this finding to a persistent cuff leak during the swine experiment, despite maximal ETT cuff inflation (oropharyngeal CO_2 of 10 mm Hg). Additionally, there are inherent differences in CO_2 production with a live animal. Despite the lower levels of entrained CO_2 measured during the swine experiment, the trends in CO_2 entrainment with manipulations of HFOV parameters were similar when compared to the mechanical test lung.

A further limitation of our experimental design was that the compliance of the test lung and the swine lung were different. The test lung was set to a compliance of 0.02 L/cm H_2O to simulate ARDS. The swine lung was un-injured and presumed to have normal compliance, as directed by the training protocol. The differing compliances between the test lung and swine lung may have contributed to the variation of CO_2 entrainment seen in our experiment. The effect of varying compliance on CO_2 entrainment is not known.

Our study was not designed to correlate carinal CO_2 changes or in vivo effects on P_{aCO_2} with ventilator parameter manipulations of retrograde CO_2 entrainment. Because of this limitation, we urge caution in extrapolating this information to a clinical setting. At our institution we routinely use an RGM 5250 gas analyzer during HFOV to document the adequacy of ETT cuff leaks, and now monitor for the presence of inspiratory limb CO_2 entrainment. In support of our experimental findings, we have recently observed retrograde CO_2 entrainment in a hypercapnic patient during HFOV.

Our findings have potential clinical implications during use of HFOV. For example, raising $\bar{P}_{aw}$ by increasing bias flow, as opposed to the mean pressure adjustment, will result in less CO_2 entrainment. In contrast, lowering $\bar{P}_{aw}$ using the mean pressure adjustment will result in a smaller increase in CO_2 entrainment, when compared to using bias flow. Furthermore, at any targeted $\bar{P}_{aw}$, entrained CO_2 is minimized by using a higher bias flow strategy. Additionally, retrograde CO_2 entrainment could be clinically important during $\bar{P}_{aw}$ weaning, particularly when using a high fixed ΔP (eg, 90 cm H_2O).

Conclusions

In summary, this research confirms that retrograde CO_2 entrainment does occur within the inspiratory limb of the 3100B HFOV circuit, and can be altered by manipulating HFOV parameters. Future research should address the incidence of this phenomenon in patients and its clinical implications.

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