Carbon Dioxide Elimination and Gas Displacement Vary With Piston Position During High-Frequency Oscillatory Ventilation

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INTRODUCTION: Alterations in gas displacement in pediatric patients ventilated with the SensorMedics 3100A high-frequency oscillator are most commonly manipulated by adjusting the amplitude, frequency, and percent inspiratory time. The piston-position-and-displacement indicator is commonly centered and subsequently not adjusted. That practice may limit the clinician's ability to optimize carbon dioxide elimination. We hypothesized that varying the piston position would alter gas displacement and carbon dioxide elimination. METHODS: We conducted an observational study in a tertiary pediatric intensive care unit and a correlated bench study. In the clinical study, 24 patients were ventilated with a SensorMedics 3100A high-frequency oscillator. Transcutaneously measured carbon dioxide (P_{tCO_2}) values were documented with the piston-position-and-displacement indicator in left, center, and right positions. In the bench study the oscillator was set and maintained at: mean airway pressure 15 cm H_2O, inspiratory time 33% of respiratory-cycle time, bias flow 20 L/min. A pneumotachometer attached to a respiratory mechanics monitor was placed between the ventilator circuit and a test lung. Data were collected with the piston-position-and-displacement indicator at the left, center, and right positions with frequencies of 4–14 Hz and amplitudes of 25–55 cm H_2O. Data were collected over a 3-minute time period for each combination of frequency, amplitude, and piston-position-and-displacement-indicator position. We compared the data with repeated-measures analysis of variance. Pairwise comparisons were performed with a 2-tailed Student's *t* test with Bonferroni correction. RESULTS: Among the 24 patients P_{tCO_2} was significantly associated with the position of the piston ($p < 0.007$). In the bench study, gas displacement was higher when the piston-position-and-displacement indicator was positioned to the left (than when at the center position) 91.7% of the time ($p < 0.0001$). When the piston-position-and-displacement indicator was positioned to the right (as compared to the center position), gas displacement was lower 75% of the time ($p < 0.0001$). CONCLUSION: Adjusting the oscillator piston alters the volume of gas displaced and provides an additional means for titrating carbon dioxide elimination. *Key words: high-frequency ventilation, acute lung injury, acute respiratory distress syndrome, pediatric, neonatal, mechanical ventilation, carbon dioxide, tidal volume*. [Respir Care 2005; 50(3):361–366. © 2005 Daedalus Enterprises]

Introduction

In the early 1990s, studies by Arnold et al[1] and Clark[2] demonstrated the potential benefits of high-frequency oscillatory ventilation (HFOV). In patients who require an elevated mean airway pressure for adequate oxygenation

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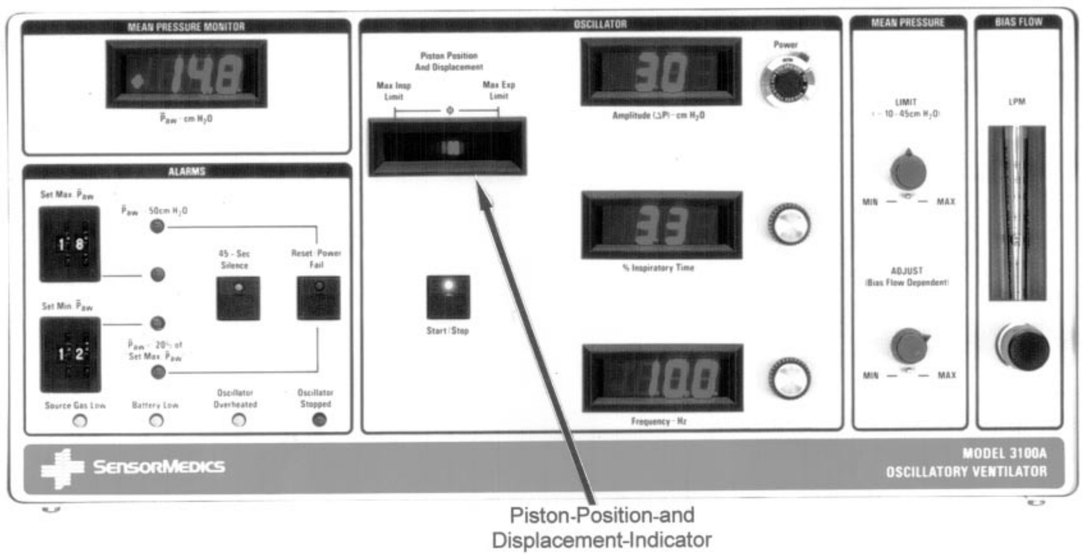

Fig. 1. The SensorMedics 3100A high-frequency oscillator.

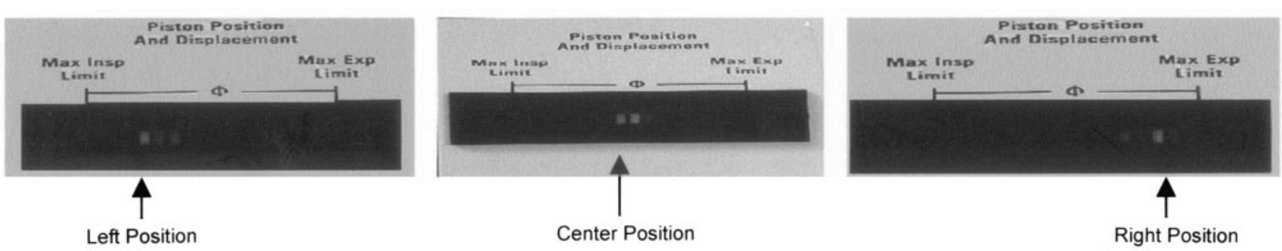

Fig. 2. The piston-position-and-displacement indicator in the left, center, and right positions.

and/or a large tidal volume (V_T) for adequate carbon dioxide elimination, HFOV offers an attractive alternative to conventional mechanical ventilation. Theoretically, HFOV minimizes the adverse effects of volutrauma, barotrauma, and stretch injury associated with conventional ventilation.[3–6] HFOV with the SensorMedics 3100A high-frequency oscillator (Viasys Healthcare, Yorba Linda, California) has become an acceptable treatment for the respiratory management of critically ill infants and children with severe acute lung injury.[7]

As the use of HFOV has increased, the titration of mean airway pressure, ventilation frequency, and amplitude has become commonplace. However, despite the increasing use of the 3100A oscillator, confusion persists as to what role, if any, the position of the oscillation piston plays in achieving maximum carbon dioxide elimination.

The 3100A oscillator actively exchanges gas in and out of the lungs with an electromechanically controlled piston. The movement of the piston and, thus, the volume of gas displaced and carbon dioxide eliminated are controlled by the ventilation settings.[8,9] During HFOV, V_T is traditionally adjusted by altering amplitude, frequency, and/or percent inspiratory time.[10–12] However, with the 3100A oscillator, as the ventilatory support is increased, the piston may become misaligned from its optimal position. Theoretically, nonoptimal piston alignment can decrease gas displacement and thus decrease carbon dioxide elimination. In our clinical experience, this effect is more likely with patients who have severe lung injury and in larger pediatric patients ($>$ 35 kg), who typically require relatively high ventilation settings.

Inadequate carbon dioxide elimination is a potentially important limitation of HFOV.[13] Although there is increasing use of permissive hypercapnia,[8,14] it may be possible to improve carbon dioxide elimination by more optimally aligning the oscillation piston.

Theoretically, a potential approach to improve ventilation during HFOV is to alter the piston-position-and-displacement indicator (Fig. 1) from the commonly used center position. Most clinicians place the piston-position-and-displacement indicator in the center position (Fig. 2), where it remains throughout the course of HFOV. However, clinical observations in our pediatric intensive care unit revealed that centering the piston-position-and-displacement indicator does not necessarily correlate with increased carbon dioxide elimination. Thus, we hypothesized that the "traditional" and recommended practice of centering the piston-position-and-displacement indicator may limit the clinician's ability to improve carbon dioxide elimination because V_T might not be optimized. We further hypothesized that altering the display of the piston-position-and-displacement indicator from the center position would vary the amount of gas displaced, and therefore allow us to propose a mechanism to improve carbon dioxide elimination.

Methods

To assess the effect of altering the piston-position-and-displacement indicator from its traditional center position, we performed a clinical observational study with a heterogeneous population of pediatric intensive-care patients (ages 0–14 years) who required HFOV for acute respiratory failure. To investigate the mechanism of the observed clinical change in carbon dioxide elimination, we performed a bench study with a test lung to assess the volume of gas displaced in various piston positions.

Clinical Study

To determine the effect of piston position on carbon dioxide removal, we collected data during an 11-month period from all patients ventilated with the 3100A oscillator. The need for informed consent was waived by our institutional review board. All procedures were performed in accordance with Duke University Medical Center's committee on human experimentation.

All patients were monitored with a transcutaneous monitor (model 850, Novametrix Medical Systems, Wallingford, Connecticut). Standard arterial blood gas analysis was performed to confirm correlation between the P_{aCO_2} and the carbon dioxide value displayed by the transcutaneous monitor (P_{tCO_2}). The transcutaneous monitor was considered to correlate if the displayed value was within 3% of the P_{aCO_2} value.

Piston positioning was determined by the piston-position-and-displacement indicator display on the front of the oscillator (see Fig. 1). The piston was considered to be in the center position when the indicator bars were equally positioned to either side of the center of the display area (see Fig. 2). The piston was considered to be in the left position when the indicator bars were all to the left of center, with the end indicator bar touching center. The piston was considered to be in the right position when the bars were all right of center, with the end bar touching center. Following the manufacturer's recommendations, at no time did the piston reach the mechanical limit of its potential positioning. This was assured by (1) visual inspection of the piston-position-and-displacement indicator and (2) evaluation of the auditory change that occurs when the piston reaches its mechanical stroke limit. Adjusting the piston position can result in changes in other HFOV settings, so adjustments were made to return the amplitude and mean airway pressure to the level set prior to the piston adjustment. Fraction of inspired oxygen (F_{IO_2}), frequency, bias flow, and percent inspiratory time were held constant.

For each patient, the initial P_{tCO_2} value was recorded after 20 minutes with the piston in the position chosen by the patient care team. The piston was then moved (in a random order) to one of the other positions, and after a 20-minute stabilization period, a second data set was collected. Then the piston was moved to the remaining position, and after another 20-minute stabilization period, a third data set was collected. Following data collection, the piston was placed and maintained in the position that most improved carbon dioxide elimination for that patient.

We used repeated-measures analysis of variance, followed by a 2-tailed Student's *t* test with Bonferroni correction, to compare the P_{tCO_2} values of the 3 piston positions. Differences were considered statistically significant when $p < 0.05$. Data are reported as mean $\pm$ standard deviation.

Bench Study

To determine the effect of piston position on the volume of gas displaced, we used a 3100A oscillator with a rigid circuit. HFOV was set and maintained at: F_{IO_2} 0.21, mean airway pressure 15 cm H_2O, inspiratory time 33%, bias flow 20 L/min. A pneumotachometer connected to a pulmonary mechanics monitor (CO_2SMO Plus Respiratory Profile Monitor, Respironics, Wallingford, Connecticut) was placed between the ventilator circuit and a test lung (IngMar Medical, Pittsburgh, Pennsylvania). To minimize the confounding variable of changes in condensation in the patient circuit, a heater and humidifier were not used.

Data were collected with the piston-position-and-displacement indicator placed in the left, center, and right positions over a clinically relevant range of frequencies and amplitudes. Piston position was defined as in the clinical portion of the study. Again, the piston was not allowed to reach its mechanical limit. The frequency was varied from 4 Hz to 14 Hz, in increments of 2 Hz. The amplitude was varied from 25 cm H_2O to 55 cm H_2O, in increments of 10 cm H_2O. Continuous V_T data were collected over a 3-min period to allow the flow within the ventilator circuit to stabilize.

Fifty consecutive breath cycles were used for each combination of piston position, frequency, and amplitude. The effects of piston position, frequency, and amplitude on V_T were determined with analysis of variance, followed by pairwise *t* tests between the position means at each amplitude and frequency. Differences were considered statis-

Table 1. Clinical Relationship of Carbon-Dioxide Elimination to Piston Position

Patient #	P_{tCO_2} (mm Hg)		
	Left*	Center*	Right*
1	65	78	86
2	61	40	50
3	70	82	122
4	35	37	39
5	67	45	57
6	48	45	57
7	84	82	132
8	30	36	39
9	65	78	86
10	40	45	62
11	42	52	64
12	48	45	53
13	73	70	81
14	84	82	132
15	36	35	35
16	59	58	55
17	44	47	45
18	55	58	55
19	39	47	46
20	46	48	48
21	36	30	39
22	54	64	63
23	57	42	64
24	39	47	46

P_{tCO_2} = transcutaneously measured carbon dioxide pressure
*"Left", "center", and "right" refer to the piston-position-and-displacement indicator (see Fig. 2).

tically significant when $p < 0.05$ after Bonferroni correction for type-1 error. The reliability of the bench-study volume measurement was assessed by calculating the intra-class correlation coefficient. A total of 72 data sets were compared. Data are reported as mean ± standard deviation.

Results

Clinical Study

Twenty-four patients, ranging in age from 1 day to 14 years, were studied (mean age 9.0 ± 47.8 months, mean weight 8.0 ± 7.8 kg). All patients had a < 3% disparity between P_{tCO_2} and P_{aCO_2} measured via blood gas analysis, so no patients were excluded from the data analysis (Table 1). Changes in P_{tCO_2} were associated with piston position to a degree that was highly unlikely to be due to chance ($p < 0.007$). For these 24 patients as a group, there was no statistically significant difference in P_{tCO_2} between the left position to the center position. However, a subgroup of 8 patients (33% of the population studied) had a > 15% decrease in P_{tCO_2}, which may be clinically important. With the piston positioned to the right, P_{tCO_2} was significantly higher than with the piston in the left ($p < 0.003$) or center ($p < 0.002$) position (Table 2).

Table 2. Difference in Carbon Dioxide Elimination Between Left and Center Piston Position Among Patients Who Had Better Clearance in the Left Position

Patient #	P_{tCO_2} (mm Hg)		Difference (%)†
	Left*	Center*	
1	65	78	17
3	70	82	15
8	30	36	17
9	65	78	17
11	42	52	19
19	39	47	17
22	54	64	16
24	39	47	17

P_{tCO_2} = transcutaneously measured carbon dioxide pressure
*"Left" and "center" refer to the piston-position-and-displacement indicator (see Fig. 2).
†The mean difference is 9.4 ± 2.9 mm Hg. The median difference is 10 mm Hg.

Bench Study

Seventy-two data sets were collected, consisting of 50 data points per set of ventilation settings. The volume of gas displaced was significantly different in the center, left, and right positions for each combination of frequency and amplitude (Table 3). The reliability of the volume measurement over the range of amplitudes, frequencies, and positions was high, with an intra-class correlation coefficient of 0.91.

Varying the piston position altered the volume of gas displaced over a clinically relevant range of amplitudes and frequencies. With no other manipulations in ventilation settings, gas displacement was greater in the left position than in the center position in 91.7% (22/24) of the setting combinations. Gas displacement was less in the right position than in the center position in 75% (18/24) of the setting combinations.

Discussion

Although HFOV improves oxygenation in patients with acute lung injury, neonatal respiratory distress syndrome, and acute respiratory distress syndrome,[1,8] HFOV's ability to adequately ventilate certain subgroups of patients may be limited. This limitation is generally seen in pediatric and adult patients (ie, > 35 kg) with severe lung injury. The objectives of this study were: (1) to determine the effect of altering the 3100A oscillator piston position on

Table 3. Gas Displacement in the Left, Center, and Right Piston Positions*

Amplitude (cm H_2O)	Frequency (Hz)	Gas Displacement (mL/oscillation)		
		Left	Center	Right
25	4	52 ± 0.97†	42 ± 0.45	35 ± 0.31†
25	6	35 ± 0.35†	28 ± 0.14	26 ± 0†
25	8	27 ± 0.44†	24 ± 0.20	24 ± 0.14
25	10	21 ± 0.37†	18 ± 0.38	19 ± 0.51†
25	12	16 ± 0.54†	14 ± 0.53	15 ± 0.50†
25	14	15 ± 1.13†	14 ± 1.09	14 ± 1.91
35	4	68 ± 0.91†	52 ± 0.49	45 ± 0.65†
35	6	46 ± 0.44†	37 ± 0.42	33 ± 0.42†
35	8	35 ± 0.40†	30 ± 0.49	30 ± 0.50
35	10	27 ± 0.50†	26 ± 0.40	24 ± 0.61†
35	12	20 ± 0.98	20 ± 1.28	19 ± 0.79†
35	14	18 ± 1.0	19 ± 1.5	15 ± 3.02†
45	4	86 ± 0.73†	70 ± 0.38	66 ± 0.61†
45	6	60 ± 0.50†	49 ± 0.5	36 ± 0.50†
45	8	46 ± 0.60†	39 ± 0.47	37 ± 0.55†
45	10	41 ± 0.60†	36 ± 0.68	29 ± 1.83†
45	12	28 ± 0.77†	27 ± 0.35	25 ± 0†
45	14	21 ± 0.46†	17 ± 0.38	17 ± 0
55	4	103 ± 0.50†	86 ± 0.64	57 ± 0.64†
55	6	71 ± 0.53†	59 ± 0.42	42 ± 0.52†
55	8	54 ± 1.14†	46 ± 0.52	31 ± 0.65†
55	10	41 ± 0.60†	36 ± 0.68	23 ± 0.65†
55	12	31 ± 0.64†	29 ± 1.9	12 ± 0.50†
55	14	25 ± 0.34†	20 ± 0	8 ± 0.50†

*"Left", "center", and "right" refer to the piston-position-and-displacement indicator (see Fig. 2).
†$p < 0.05$ versus center position

carbon dioxide elimination in a heterogeneous group of pediatric intensive-care patients who required HFOV, and (2) to assess gas displacement in a bench study with a test lung.

The bench portion of our study found statistically significant differences in the volume of gas displaced in the 3 different piston positions. V_T was higher in the left position. Though there were a limited number of patients in the clinical part of the study, the clinical results were consistent with the bench-study findings. Carbon dioxide elimination was better in the left position with 33% of the patients, presumably because of the higher V_T in the left position, for a given amplitude, frequency, and inspiratory time.

In certain situations it appears that the center position may not correlate with an optimally aligned piston. This suggests the increase in gas displacement and associated improvement in carbon dioxide elimination is related to an improvement in the piston alignment. The potential explanations for this finding remain speculative. One possibility is that the piston-position-and-displacement indicator and the actual piston position are correlated, and V_T delivery varies with piston positioning. A second possibility is that as the temperature of the oscillator increases over time, the electronics of the piston-position-and-displacement indicator falsely shift despite an optimally aligned piston (ie, there is dissociation between the display and the actual piston position). In the common clinical practice of centering the display, the clinician might actually be misaligning the piston. It remains unclear whether our findings are a mechanical effect or a function of heat artifact.

Our data (especially the data from the bench portion of the study) indicate that the piston appears to be more often optimally aligned when the piston-position-and-displacement indicator is shifted left of center. However, there were no factors that predicted which piston position would better ventilate an individual patient. Thus, for each patient ventilated with the 3100A oscillator who develops undesirable hypercapnia, the clinician should alter the piston position to optimize carbon dioxide elimination, based on transcutaneous monitoring and/or standard arterial blood gas monitoring. The 3100A user manual indicates that, "operating the 3100A with the piston off center will not interfere with its performance, except in those rare occasions requiring maximum oscillatory displacement to generate maximum oscillatory pressures."[15] However, the piston must not be allowed to reach its mechanical limit (as determined by the bars on the piston-position-and-displacement indicator and by the auditory change that occurs when the piston reaches its mechanical limit), which could increase the mechanical fatigue on the ventilator.[15]

Regardless of the explanation for the change in carbon dioxide elimination with change in piston position, the mechanism for improved gas exchange is, most probably, increased V_T. The relative physiologic effects of increasing V_T (and, thus, carbon dioxide elimination) by altering the piston position, increasing the set amplitude, decreasing the ventilation frequency, or increasing the inspiratory time are unknown. However, patients ventilated with the 3100A who develop unacceptable hypercapnia despite maximum ventilation settings may substantially benefit from changing the piston position.

It is important to note the limitations of this study. Our clinical study was limited by small sample size; however; the results of our bench study lend support to our clinical findings. Additionally, the pulmonary mechanics monitor we used, which samples at 100 Hz, is not designed for use during HFOV. However, when comparing data at the same frequency, it is reasonable to expect comparable data regarding V_T. In the bench study, we tested only one model 3100A oscillator, so we cannot predict the behavior of any other such device. To minimize the confounding variable of changes in condensation in the patient circuit, we did not heat or humidify the ventilator circuit. However, all the measurements were obtained with the same circuit setup, so the lack of heating and humidification should not have adversely affected our findings. Additionally, only one inspiratory time (33%) was studied. Depending on the mechanism of improved gas displacement with piston positioning, altering the inspiratory time may yield different results.

Conclusion

Though it is common clinical practice to adjust the amplitude, frequency, and inspiratory time during HFOV when increased gas displacement and improved carbon dioxide elimination are clinically desired, repositioning the oscillation piston may also be an effective option. Our study demonstrates that changes in piston position affect V_T delivery and, thus, gas exchange. Although piston position adjustments should not take precedence over the more routine adjustments of amplitude, frequency, and percent inspiratory time, piston-position adjustments can be viewed as an additional tool in the management of pediatric patients requiring HFOV. More optimal placement of the piston may allow for increased carbon dioxide elimination during HFOV.

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