RESEARCH ARTICLE

The use of high-frequency percussive ventilation after cardiac surgery significantly improves gas exchange without impairment of hemodynamics

Charles Oribabor, MD[1], Iosif Gulkarov, MD[2], Felix Khusid, RRT-NPS, ACCS, RPFT, FAARC, FCCM, FCCP, ATSF[3], Emma Fischer MS, RRT-NPS[3], Adebayo Esan, MD[4], Nancy Rizzuto, MSN, ANP, CCRN[5], Anthony Tortolani, MD[6], Paris Ayanna Dattilo, RN[7], Kaki Suen, PA-C[8], Justin Ugwu, MD[1], Brent Kenney, RRT, FAARC[9]

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Objective: Respiratory failure represents a significant source of morbidity and mortality for surgical patients. High-frequency percussive ventilation (HFPV) is emerging as a potentially effective rescue therapy in patients failing conventional mechanical ventilation (CMV). Use of HFPV is often limited by concerns for potential effects on hemodynamics, which is particularly tenuous in patients immediately after cardiac surgery. In this manuscript we evaluated the effects of HFPV on gas exchange and cardiac hemodynamics in the immediate postoperative period after cardiac surgery, in comparison with CMV.

Methods: Twenty-four consecutive cardiac surgery patients were ventilated in immediate postoperative period with HFPV for two to four hours, then they switched to a CMV using the adaptive support ventilation mode for weaning. Arterial blood gases were performed during the first and second hour on HFPV, and at 45 minutes after initiation of CMV. Respiratory settings and invasive hemodynamic data (mixed venous oxygen saturation, central venous pressure, systemic and pulmonary blood pressure, cardiac output and index) were collected utilizing right heart pulmonary catheter and arterial lines during HFPV and CMV. Primary outcome was improvement in the ratio between partial pressure of oxygen to fraction of inspired oxygen (P/F ratio) and changes in hemodynamics.

Results: Analysis of data for 24 patients revealed a significantly better P/F ratio during the first and second hour on HFPV, compared with a P/F ratio on CMV (420.0 ± 158.8, 459.2 ± 138.5, and 260.2 ± 98.5 respectively, $p < 0.05$), suggesting much better gas exchange on HFPV than on CMV. Hemodynamics were not affected by the mode of the ventilation.

Conclusions: Improvement in gas exchange, reflected in a significantly improved P/F ratio, wasn't accompanied by worsening in hemodynamic parameters. The significant gains in the P/F ratio were lost when patients were switched to conventional ventilation. This data suggest that HFPV provides significantly better gas exchange compared with CMV and can be safely utilized in postoperative cardiac patients without any significant effect on hemodynamics.

Key Words: *high-frequency percussive ventilation; cardiac surgery; gas exchange; hemodynamics*

INTRODUCTION

Postoperative respiratory failure is a significant source of morbidity and mortality in postoperative patients. Postoperative pulmonary alterations after cardiac surgery include increased minute ventilation, breathing frequency, CO_2 production and oxygen consumption, and decreased tidal volume [1]. Postoperative pulmonary complications in open-heart surgery also have an effect on gas exchange making it difficult to manage postoperative patients while on the mechanical ventilator and after extubation. Intrapulmonary shunting has been shown to be a large component of impaired gas exchange before, during, and after cardiac surgery [2]. Recruitment of lung tissue with increased lung volume may be beneficial in reducing intrapulmonary shunting and the resultant hypoxemia [3]. The methods employed for lung recruitment are widely varied, and there is considerable variance among methods in clinicians treating this patient population. Some of the recruitment maneuvers include high positive end expiratory pressure (PEEP), prone positioning, inhaled

[1]*Department of Medicine, New York Presbyterian Brooklyn Methodist Hospital, Brooklyn, NY, USA*
[2]*Department of Cardiothoracic Surgery, Staten Island University Hospital Staten Island, NY, USA*
[3]*Department of Respiratory Therapy, New York Presbyterian Brooklyn Methodist Hospital, Brooklyn, NY, USA*
[4]*Department of Medicine, Hanover Hospital, Hanover, PA, USA*
[5]*Department of Nursing, Brooklyn University Hospital and Medical Center, Brooklyn, NY, USA*
[6]*Department of Surgery, Brooklyn University Hospital and Medical Center, Brooklyn, NY, USA*
[7]*Department of Emergency Medicine, New York Presbyterian Brooklyn Methodist Hospital, Brooklyn, NY, USA*
[8]*Department of Cardiothoracic Surgery, New York Presbyterian Brooklyn Methodist Hospital, Brooklyn, NY, USA*
[9]*Department of Respiratory Therapy, Mercy Hospital Springfield, Springfield, MO, USA*
Correspondence: Iosif Gulkarov, MD, Staten Island University Hospital, 501 Seaview Avenue, Suite 202, Staten Island, New York 10305, USA. Tel.: (718) 226-6210, Fax: (718) 226-1563; E-mail: igulkarov@northwell.edu

vasodilators, high-frequency oscillatory ventilation, and high-frequency percussive ventilation (HFPV) [4]. Although, these maneuvers can be effective, they are not without significant practical difficulties when utilized in postoperative cardiac surgery patients. The often-fragile hemodynamic status of postoperative cardiac surgery patients requiring vasopressors and inotropes would benefit from methods that maximize lung recruitment and improve gas exchange without hemodynamic embarrassment. In this manuscript we compare gas exchange with hemodynamic performance of conventional mechanical ventilation (CMV) and HFPV.

HFPV was delivered via volumetric diffusive respirator (VDR-4; Percussionaire Corporation, Sandpoint Idaho USA). The VDR is classified as a pneumatically driven, time-cycled, high-frequency flow interrupter, intermittent mandatory ventilation [5]. It uses a sliding venturi to inject sub-tidal volumes at high frequencies. Settings include pulsatile flow rate, oscillatory continuous positive airway pressure (CPAP), PEEP, inspiratory time, expiratory time, pulse frequency, and pulse inspiratory and expiratory (I:E) ratio. The sliding venturi precisely stacks the injected sub tidal volumes at the high-frequency rate set, for the inspiratory time selected. The inspiratory time is time cycled off, allowing a drop to oscillatory CPAP/PEEP for the selected expiratory time. High-frequency rates may be varied from 80 to 1000 cycles per minute with the VDR-4.

HFPV has been used to improve gas exchange in patients with adult respiratory distress syndrome (ARDS) failing conventional ventilation, while increasing mean airway pressure and decreasing peak airway pressure without affecting hemodynamics [6, 7]. Previous studies have shown HFPV to be effective in reducing intracranial pressure in traumatic brain injury [8, 9], treating lung injury associated with burns and inhalational injury [10–13], reducing time on extra-corporeal membrane oxygenation [14, 15], recruiting lung volume and improving hypoxemia in pulmonary resection [16], and improving oxygenation and providing lung protective ventilation in pediatric acute respiratory failure [17]. HFPV was also used as salvage therapy in patients after cardiac surgery [18] and in morbidly obese patients [19]. To date, there have been no studies demonstrating improvement in oxygenation in the immediate postoperative period in cardiac surgery patients and its effects on hemodynamics.

METHODS

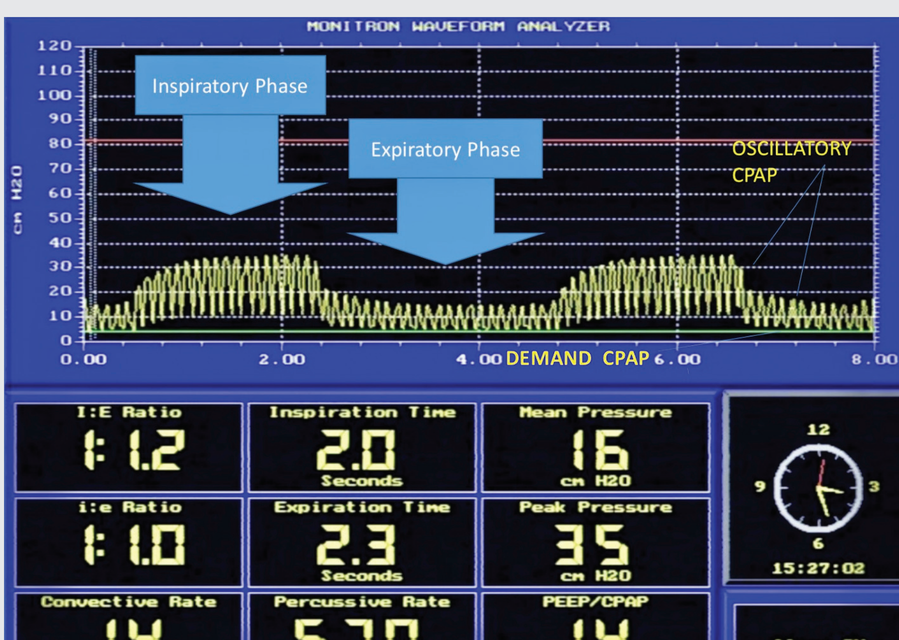
This study was approved by the New York Methodist Hospital Institutional Review Board for scientific and ethical merit. Twenty-four consecutive cardiac surgery patients undergoing elective cardiac surgery were recruited from February 2012 to April 2012. After arrival from the operating room the patients were transferred from the conventional ventilator used in the operating room to HFPV mode. HFPV mode was utilized for ventilation until initial hemodynamic and respiratory stability was achieved, followed by transitioning to CMV in two to four hours. Hemodynamic and respiratory stability was defined as stable vital signs, pressor, and inotrope requirements and stable acid base status of the patient.

Basic initial VDR settings include high-frequency rate of 500–600 percussions per minute, convective rate of 12 to 16 breaths per minute, oscillatory CPAP of 5 cm H_20, the lowest pulsatile flow rate leading to the rise of the chest, fraction of inspired oxygen (FiO_2) of 70%, and I:E ratio of 1:1 on both convective and percussive rate (Figure 1). Humidification was provided by humidifier (MR 850, Fisher & Paykel, Auckland, New Zealand) set up at 37° C. Arterial blood gases (ABGs) were recorded at 15–30 minutes during the first and second hour HFPV, and 45 minutes after transition to CMV from HFPV. When hemodynamic and respiratory stability was achieved after two to four hours of HFPV, the patients were transferred to CMV for weaning and extubation (Hamilton G5, Hamilton Medical AG, Bonaduz, Switzerland). The mode used on the Hamilton G5 for weaning and extubation was adaptive support ventilation (ASV), which is classified as pressure-controlled intermittent mandatory ventilation.

ASV is a closed-loop mode of ventilation that provides ventilatory support based on the patient's work of breathing. ASV uses Otis' equation to predict a tidal volume and respiratory rate that minimizes the patient's work of breathing [20]. The operator enters the patient height, gender, and percent minute volume (%MV), PEEP, FIO_2,

FIGURE 1

Screenshot of the waveform display on volumetric diffusive respirator (VDR-4; Percussionaire Corporation, Sandpoint Idaho USA).



expiratory trigger sensitivity, trigger, ramp speed, and ASV pressure limit. The Hamilton G5 in ASV mode continuously monitors the work of breathing relative to the selected %MV, adjusting peak pressure, tidal volume, and breathing frequency accordingly [21]. The range of %MV used in ASV mode was 130–160%, with FiO_2 of 0.70, and PEEP of 5 cm H_2O.

Ventilatory and hemodynamic parameters and values recorded were FiO_2, mean airway pressure (MAP), peak inspiratory pressures (PIP), respiratory rate, PEEP, tidal volume, I:E ratio, partial pressure of oxygen (PaO_2) to FiO_2 (P/F ratio), mixed venous oxygen saturation, central venous pressure, systemic and pulmonary blood pressure, cardiac output, and index.

ANALYSIS

Statistical analysis was performed using SPSS statistical package software. Continuous data were expressed as a mean ± standard deviation. A paired *t*-test was used in a side-by-side comparison of the mean of the first and second hour P/F ratios on HFPV with the corresponding values on ASV. Assessment of the effect of two ventilatory modes on hemodynamic parameters was made using an ANOVA test, to compare the first and second hours on HFPV to the first hour on ASV. All statistical tests were two sided and alpha was set at $p < 0.05$.

RESULTS

The mean age for these open-heart surgery patients was 61.2 ± 14.7 years (range 29–80 years). There were 12 males (50%), and 12 females (50%) included in this study analysis (Table 1). The mean P/F ratio was significantly higher when utilizing HFPV during the first and second hour as compared with ASV (420.0 ± 158.8, 459.2 ± 138.5, and 260.2 ± 98.5, $p < 0.05$, respectively). The mean MAPin HFPV group was similar to MAP in CMV group (11.0 ± 1.8 cm H_20 vs. 10.4 ± 2.1 cm H_20). Additionally, there were no statistical differences in hemodynamic parameters observed between both modes of ventilation (Table 2).

TABLE 1

Demographic and perioperative data of the cohort

Male, *n* (%)	12 (50%)
Age, years (range)	61.2 ± 14.7 (30–80)
Procedure (*n*)	
CABG	13
Valve (AVR, MV procedure)	7
Valve/CABG	2
Other (atrial myxoma, ASD repair)	2
FEV1 (%)	83 ± 16.6
Preoperative LVEF (%)	49 ± 14

CABG, coronary artery bypass grafting; AVR, aortic valve replacement; MV, mitral valve; ASD, atrial septal defect; FEV1, forced expiratory volume at 1 second; LVEF, left ventricular ejection fraction. Continuous data are expressed as a mean ± standard deviation.

DISCUSSION

This study is the first descriptive analysis of the applicability of HFPV in comparison with CMV in cardiac surgery patients with close monitoring of their hemodynamics. The mean P/F ratio was significantly higher when utilizing HFPV during the first and second hour as compared with ASV (420.0 ± 158.8, 459.2 ± 138.5 and 260.2 ± 98.5, $p < 0.05$, respectively). The mechanism by which HFPV carries out gas exchange is suggested by various theories, including direct bulk flow, longitudinal dispersion of gas molecules at terminal airways and alveoli, Pendelluft air flow between neighboring lung regions thereby increasing dead space ventilation, laminar flow, cardiogenic mixing, and molecular diffusion [22].

With the use of HFPV, we noticed significant improvement in the P/F ratio without any effect on hemodynamics. HFPV was shown to improve gas exchange at lower PIP, yet higher MAP [11, 12, 17]. Higher MAP theoretically can compromise cardiac function, especially in the setting right after cardiac surgery, therefore raising concerns for possible worsening of hemodynamics with HFPV. Several previous reports didn't detect any major effects of HFPV on hemodynamics in burn and adult respiratory distress syndrome patients [23, 24]. Reper and his colleagues [23] compared hemodynamics, blood oxygenation, and ventilatory parameters in eight stable ICU burn patients. Hemodynamic data were not significantly affected, PIPs were significantly lower with HFPV, but MAPs were unchanged. Oxygenation and CO_2 removal were significantly better. Gallagher and his colleagues [24] compared HFPV with CMV. PaO_2 on HFPV improved significantly ($p < 0.01$) compared with PaO_2 on CMV at the same level of FIO_2. Cardiac output was unaffected by the change to HFPV.

This study is unique in that it directly compares oxygenation in two vastly different ventilation modes after cardiac surgery within the same patient. Heretofore, HFPV has only been used and studied as a salvage therapy for patients failing CMV. In our study, the striking difference in the P/F ratio in the first and second hour on HFPV, compared with conventional ventilation, at a comparable MAP (Table 2), may represent a more effective method of augmenting lung recruitment and improving ventilation/perfusion (V/Q) matching. The potential benefits of HFPV in postoperative open-heart cardiac surgery patients are promising. Further studies comparing HFPV to conventional ventilation in the immediately postoperative cardiac surgery patient are therefore warranted.

TABLE 2

Cardiopulmonary data (mean ± standard deviation) during high-frequency percussive ventilation (HFPV) and conventional mechanical ventilation (CMV)

	First hour HFPV	Second hour HFPV	CMV
FiO_2, %	69.6 ± 0.02	68.1 ± 0.04	68.3 ± 0.04
Mean airway pressure, cm H_2O	11.0 ± 1.8	10.8 ± 1.9	10.4 ± 2.1
pH	7.4 ± 0.1	7.4 ± 0.09	7.4 ± 0.07
$PaCO_2$, mm Hg	34.6 ± 8.2	34.1 ± 8.8	36.8 ± 6.4
PaO_2, mm Hg	293.3 ± 112.3*	313.2 ± 95.9*	178.5 ± 70.4*
P/F ratio	420.0 ± 158.8*	459.2 ± 138.5*	260.2 ± 98.5*
Cardiac output, L/min	5.1 ± 1.1		5.2 ± 1.0
Cardiac index, L/min/m^2	2.6 ± 0.6		2.6 ± 0.5
Mixed venous PaO_2, %	73.5 ± 6.2		73.9 ± 6.0
PAS, mm Hg	31.9 ± 7.1		31.6 ± 6.5
PAD, mm Hg	16.9 ± 4.7		16.7 ± 3.9
CVP, mm Hg	11.9 ± 3.7		12.1 ± 2.6
Mean Arterial Pressure, mm Hg	83.5 ± 10.8		84.5 ± 10.3

Data are expressed as a mean ± standard deviation. FiO_2, fraction of inspired oxygen; $PaCO_2$, arterial carbon dioxide tension; PaO_2, arterial oxygen tension; P/F ratio, ratio between PaO_2 and FiO_2; PAS, systolic pulmonary arterial pressure; PAD, diastolic pulmonary arterial pressure; CVP, central venous pressure.
$^*P < 0.05$.

The limitations of the study are related to dynamic improvement in pulmonary function in cardiac surgery patients as time progresses. Improvement in P/F ratio may be partially related to improvement in V/Q mismatch as the pulmonary function "settles" and effects of cardiopulmonary bypass taper off. We also didn't incorporate pressor requirements into the study, they may be affected by higher mean airway pressures and mask some of subtle hemodynamic effects of HFPV.

CONCLUSIONS

In this population of postoperative open-heart cardiac surgery patients, HFPV was able to significantly improve gas exchange as reflected by a better P/F ratio without hemodynamic consequence.

DISCLOSURE

All authors contributed to the conception or design of the work, the acquisition, analysis, or interpretation of the data. All authors were involved in drafting and commenting on the paper and have approved the final version. This work was performed at New York Methodist Hospital, Brooklyn, New York, USA, now known as New York-Presbyterian Brooklyn Methodist Hospital.

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