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High-frequency percussive ventilation in cardiac surgery patients failing mechanical conventional ventilation†

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Abstract

OBJECTIVES: Failure of mechanical conventional ventilation (MCV) after cardiac surgery portends a dismal prognosis, with extracorporeal membrane oxygenation frequently utilized as a salvage therapy. We describe our experience with high-frequency percussive ventilation (HFPV) as a rescue therapy for hypoxaemia refractory to MCV after cardiac surgery.

METHODS: In a 6-year retrospective analysis from 2009 to 2015, we identified 16 subjects who required HFPV after cardiac surgery. Data regarding demographics, intraoperative details, postoperative ventilatory settings including length of time on HFPV and postoperative outcomes were collected. The primary outcome was improvement in oxygenation as measured by pre- and post-HFPV partial pressures of oxygen (pO_2) and ratio of pO_2 to fraction of inspired oxygen (P/F ratio).

RESULTS: Sixteen patients required HFPV after cardiac surgery. Operative procedures included coronary artery bypass surgery ($n = 6$), aortic aneurysm or dissection repair ($n = 5$), valve with bypass surgery ($n = 2$), aortic valve replacement ($n = 2$) and extracorporeal membrane oxygenation ($n = 1$). Median pO_2 increased from 61 to 149.5 mmHg ($P < 0.001$) and the median P/F ratio improved from 62 to 169 ($P < 0.001$). The improvement in pO_2 and P/F ratio was durable at 24 h whether the patient was returned to MCV ($n = 4$) or remained on HFPV ($n = 12$) with pO_2 and P/F ratio increasing from 61 to 104 mmHg ($P < 0.001$) and from 62 to 193.5 ($P < 0.001$), respectively. Survival to discharge was 81%.

CONCLUSIONS: In our cohort of cardiac surgical patients, HFPV was successfully utilized as a rescue therapy, obviating the need for extracorporeal membrane oxygenation. Although further studies are warranted, HFPV should be considered in cardiac surgical patients failing MCV.

Keywords: Respiratory failure • Hypoxaemia • High-frequency percussive ventilation • Volumetric diffusive respiration • Cardiac surgery

INTRODUCTION

The prevalence of respiratory failure (RF) after cardiac surgery is 2–22% [1] and is associated with increased morbidity, mortality and hospital costs [1, 2]. It is commonly defined as the failure to wean from ventilation within 48–72 h or unplanned reintubation after surgery and can carry a mortality as high as 15.5% [1–3].

There are a number of strategies available to treat patients with postoperative RF, including, but not limited to, recruitment manoeuvres, increase in positive end-expiratory pressure (PEEP), paralysis, prone positioning, high-frequency oscillatory ventilation, airway pressure release ventilation and inhaled pulmonary vasodilators. Patients with severe RF who fail to respond to these manoeuvres are usually rescued by extracorporeal membrane oxygenation (ECMO) as a last resort. At our institution, we have accumulated significant experience with high-frequency percussive ventilation (HFPV), which, based on our RF treatment algorithm [4], is used in patients who fail mechanical conventional ventilation (MCV) and are being considered for ECMO.

High-frequency ventilation implies that ventilatory modality is capable of delivering 150 cycles/min or more of subphysiologic tidal volumes. There are 3 types of high-frequency ventilation: jet, oscillatory and percussive ventilation. High-frequency oscillatory ventilation oscillates the lung at a constant mean airway pressure allowing for maintenance of alveolar recruitment while avoiding low end-expiratory pressure and high peak

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pressures [5]. High-frequency oscillatory ventilation is a ventilation modality that has been used as a salvage or rescue modality for severe hypoxaemia refractory to MCV modality [6]. Although the modality has theoretical appeal, 2 recent randomized controlled trials in patients with the diagnosis of adult respiratory distress syndrome indicated no difference in outcome in one study [7], while the other showed an increase in inpatient hospital mortality [8].

Unlike high-frequency oscillatory ventilation, HFPV results in stepwise inflation and deflation of the lung based on lung compliance and airway resistance. In comparison with MCV, HFPV improves oxygen exchange but at lower peak airway pressures than MCV further reducing lung injury while inducing alveolar recruitment and mobilizing secretions from the lung periphery to the central airways [9, 10]. Therefore, compared with MCV, HFPV is less likely to cause barotrauma as the air flow in HFPV does not take the path of least resistance as it does with MCV. Barotrauma or pneumothorax that is not decompressed would preclude the use of HFPV [11]. Otherwise, in the hands of experienced operators, HFPV does not have any other contraindications.

The literature describing the use of HFPV in cardiac surgery patients is limited [12]. It has been suggested that HFPV may improve oxygenation and ventilation at lower peak inspiratory pressures with minimal effect on haemodynamics [12]. The mechanism by which HPFV carries out gas exchange is poorly understood; however, 6 theories have been postulated including (i) direct bulk flow; (ii) longitudinal dispersion of gas molecules at the terminal airways and alveoli; (iii) pendelluft air flow between neighbouring lung regions, thereby increasing dead space ventilation; (iv) laminar flow; (v) cardiogenic mixing and (vi) molecular diffusion [4].

Because of our accumulated experience with this unique patient population, we thus describe our experience with HFPV in postoperative patients to better define the role of HFPV in patients with severe RF after cardiac surgery.

METHODS

This study was approved by our local institutional review board. Informed consent was waived due to the observational retrospective design of the study. Our institutional electronic medical records were queried using the term HFPV from January 2009 to December 2015. Forty-two patients were identified, of whom 16 underwent cardiac surgery and required HFPV postoperatively in the setting of hypoxaemic RF despite maximal support with MCV. HFPV was initiated at the discretion of intensive care unit team after partial pressure of oxygen (pO_2)/fraction of inspired oxygen ratio (P/F ratio) of 60 on maximally tolerated PEEP. HFPV was delivered via volumetric diffusive respirator (VDR-4; Percussionaire Corp., Sandpoint, ID, USA). Basic initial settings include high-frequency rate of 500–600 percussions/min, convective rate of 15 breaths/min, the lowest pulsatile flow rate leading to the rise of the chest, oscillatory CPAP of 10–15 cmH_2O, fraction of inspired oxygen of 100% and titrated down to avoid hyperoxia, inspiratory/expiratory ratio of 1:1 on both convective and percussive rate. Humidification is provided by humidifier (MR 850, Fisher & Paykel, Auckland, New Zealand) setup at 39°C.

Data collected included demographics, preoperative and intraoperative variables and postoperative outcomes. Data regarding respiratory support included time from surgery to initiation of HFPV, duration of HFPV support and pre-HFPV ventilator settings (tidal volume, fraction of inspired oxygen and PEEP). Lung mechanics (peak inspiratory pressure) and chest radiography were reviewed to calculate lung compliance and determine each patient's Murray score prior to HFPV initiation. Pre- and post-HFPV pO_2 and P/F ratio at 2 and 24 h after the initiation of HFPV were collected.

Statistical analysis

Categorical variables were presented as frequencies (%) and analysed using Pearson's χ^2 test. Continuous variables were expressed as median (interquartile range). We used Wilcoxon rank-sum test to analyse continuous variables. Main outcome data were plotted on box-and-whisker diagram. Simple linear regression was used to investigate relationships between time from surgery to the initiation of HFPV and the percent change in P/F ratio. A *P*-value of <0.05 was considered statistically significant. Analysis was performed using Stata 14.1 (StataCorp, College Station, TX, USA).

Patients

A total of 1283 patients underwent cardiac surgery at our institution between January 2009 and December 2015. Of the 80 patients who developed postoperative RF, 16 patients were refractory to MCV and were transitioned to HFPV. Median patient age was 66 years, and 11 (69%) patients had preoperative evidence of pulmonary disease. Preoperative demographics and comorbidities are listed in Table 1. Six patients had undergone isolated on-pump coronary artery bypass grafting, 2 had on-pump coronary artery bypass grafting along with valve surgery, 5 had on-pump aortic aneurysm/dissection repair, 2 had on-pump valve surgery and 1 was placed on ECMO for cardiopulmonary arrest (Table 1). Intraoperative data and postoperative complications are listed in Table 2.

RESULTS

Arterial blood gas and ventilatory settings just before the institution of HFPV demonstrated severe hypoxaemia with a median P/F ratio of 62 (57–70) with a median PEEP of 11 (8–15) mmHg. The median Murray score was 2.75 (2–3.3), consistent with the presence of severe lung injury. The median pO_2 increased from 61 to 149.5 mmHg 2 h after initiation of HFPV ($P < 0.001$) and the median P/F ratio improved from 62 to 169 ($P < 0.001$). The median pO_2 increased nearly by 70% 24 h after initiation of HFPV from 61 to 104 mmHg ($P < 0.001$) and the median P/F ratio increased more than 3-fold from 62 to 193.5 ($P < 0.001$), despite 25% of patients having been weaned back to MCV by this time point (Table 3, Figs 1 and 2). Median time on MCV prior to initiation of HFPV was 4.5 (interquartile range 1.5–12) days. Median time on HFPV was 5 (1.5–12) days. Survival to discharge was 81%. Three patients expired due to multiorgan failure. Patient 8 expired from septic shock due to pneumonia refractory to multiple vasopressors and family opted for comfort measures. Patient 10 expired from right heart failure a day after separation from ECMO, despite 14 days of biventricular support with ECMO. Patient 14 expired due to severe hypoxaemia from septic shock from pneumonia and renal failure.

Analysis of the relationship between timing of institution of HFPV and improvement in oxygenation and P/F ratio revealed

Table 1: Patient demographics and baseline characteristics

	HFPV	Non-HFPV
Number of patients (*n*)	16	1267
Demographics		
Age	72 (62–77)	66 (58–74)
Male gender	10 (62.5%)	822 (64.1%)
Body mass index (kg/m^2)	29 (23–34)	27.6 (24–31)
Risk factors (*n*, %)		
Coronary artery disease	11 (69)	827 (65)
Diabetes mellitus	7 (44)	547 (42.7)
Congestive heart failure	6 (38)	334 (26.1)
Left ventricular ejection fraction (%)	55 (35–65)	55 (40–60)
End-stage renal disease	1 (6)	56 (4.4)
Chronic kidney disease	3 (9)	473 (36.9)
Peripheral vascular disease	5 (31)	211 (16.5)
Cerebrovascular disease	2 (13)	243 (19)
Pulmonary disease	11 (69)	887 (69.1)
Type of surgical intervention (*n*, %)		
Elective procedures	2 (12.5)	484 (37.7)
Emergent procedures	5 (31)	49 (3.8)
Isolated CABG	6 (38)	688 (53.7)
Isolated valve	2 (13)	371 (29)
Valve/CABG	2 (13)	139 (10.9)
Other (including ECMO and aortic surgery)	6 (37)	85 (6.6)
STS risk, *n* (%)		
Patients with calculated STS risk	10 (62.5)	736 (57.4)
STS risk of mortality	2.5 (1.7–5.2)	1.4 (0.7–3.1)
STS risk of mortality and morbidity	20 (13.3–38.2)	14 (8.6–23.5)
STS risk of prolonged ventilation	14 (9.5–29)	8.8 (5.2–15.9)

Chronic kidney disease is defined as estimated glomerular filtration rate below 60 ml/min/1.73 m^2. Pulmonary disease includes patients from mild-to-severe degree of chronic obstructive pulmonary disease based on Gold criteria [20]. All continuous data are presented as median (interquartile range).

CABG: coronary artery bypass grafting; ECMO: extracorporeal membrane oxygenation; STS: Society of Thoracic Surgery; HFPV: high-frequency percussive ventilation.

Table 2: Intraoperative and postoperative variables

Cardiopulmonary bypass time (min)	126 (92–222)
Aortic cross-clamp time (min)	70 (49–135)
Deep hypothermic circulatory arrest (*n*, %)	4 (25%)
Mechanical circulatory support (*n*, %)	
Intra-aortic balloon pump	2 (13%)
Extracorporeal membrane oxygenation	2 (13%)
Postoperative complications (*n*, %)	
Reoperation for bleeding	1 (6%)
Transfusions	8 (50%)
Sepsis	3 (19%)
Renal failure	5 (31%)
Days to HFPV initiation	4.5 (1.5–12)
Pre-HFPV pO_2 (mmHg)	61 (57–70)
Pre-HFPV pO_2/FiO_2 ratio	62 (57–70)
Pre-HFPV pCO_2 (mmHg)	39 (37–42.5)
Conventional ventilatory settings	
PEEP (cmH_2O)	11 (8–15)
PIP (cmH_2O)	28.5 (24–31)
Tidal volume (ml/kg)	7.48 (6.7–8.3)
Lung compliance[a] (ml/cmH_2O)	31 (27–34)
Murray Score	2.75 (2–3.25)

All continuous data presented as median (interquartile range).

[a]Lung compliance is measured by tidal volume/peak inspiratory pressure–positive end-expiratory pressure.

HFPV: high-frequency percussive ventilation; pO_2: partial pressure of oxygen; FiO_2: fraction of inspired oxygen; pCO_2: partial pressure of carbon dioxide; PEEP: positive end-expiratory pressure; PIP: peak inspiratory pressure.

that earlier institution of HFPV had a trend towards greater initial improvement in oxygenation and P/F ratio (Fig. 3).

DISCUSSION

In this descriptive analysis, we present our experience with HFPV as a rescue therapy in patients suffering from RF refractory to MCV after cardiac surgery. HFPV delivers pneumatically powered, time-cycled, pressure-limited, flow-interrupted breaths. The diffusive and convective effects of the percussive air flow create biphasic oscillations that generate a countercurrent flow of gas, facilitating removal of intrapulmonary secretions and displacement of trapped gas, and recruitment of the lung is achieved through improved intrapulmonary diffusion [3].

There are limited data supporting the use of HFPV in neonatal, paediatric and adult respiratory distress syndrome and burn patients. HFPV has been a mainstay in the management of burn patients with smoke inhalation injury for more than 20 years. Based on its superior performance in burn patients, HFPV became a primary ventilatory modality at the US Army Institute of Surgical Research/US Army Burn Center for patients with smoke inhalation injury [13]. In a randomized controlled study by Chung *et al.* [14], a low-tidal volume MCV strategy was compared with HFPV in severely burned adult patients. Although ventilation was similar in both study groups, oxygenation (pO_2 and P/F ratio) was significantly better in the HFPV arm, with HFPV serving as a rescue therapy for those patients failing MCV. A similar study performed in children with severe burns by Carman *et al.* [15] had comparable findings with higher pO_2 and P/F ratios in HFPV group compared with pressure-controlled ventilation.

The available literature is scarce on the use of HFPV after cardiac surgery. A report by Forti *et al.* [12] describes the use of HFPV in a patient that failed MCV 10 days after valve surgery, with subsequent extubation of the patient 2 days later. Our observations echo this report with regard to the dramatic increase in pO_2 and P/F ratio with initiation of HFPV in cardiac surgery patients (Table 3). As evidenced by their Murray scores (>2.5), the patients in our study cohort were critically ill patients with severe lung injury requiring rescue therapy. Through the use of HFPV, improvements in pO_2 and P/F ratio were achieved at 2 h and sustained up to 24 h (Table 3, Figs 1 and 2), even after discontinuation of HFPV in a quarter of the patients. The improvement in pO_2 and P/F ratio was more robust with earlier institution of HFPV, specifically in the acute phase of their RF [<14 days of mechanical ventilation (Fig. 3)]. We achieved an 81% survival rate in a cohort of critically ill patients and obviated the need for ECMO and the associated morbidity secondary to significant bleeding and thrombotic complication rates [15]. We also felt that HFPV mediated improvement in oxygenation and ventilation early on in postoperative course after cardiac surgery led to better overall haemodynamics in our cohort of cardiac patients who otherwise would not always tolerate high-pressure ventilation.

Our institution is the only centre in New York State that employs HFPV as an alternate ventilation strategy in adults and is

Table 3: Individual patient-level data

Patient	Operation	Murray Score	Cause of respiratory failure	Days to HFPV	Pre-HFPV pO_2 (mmHg)	2 h/24 h post-HFPV pO_2 (mmHg)	Pre-HFPV P/F ratio	2 h/24 h post-HFPV P/F ratio	Days on HFPV	Outcome
1	CABG	3.8	CPO + PNA	39	71	118/102	101	169/340	4	Alive
2	CABG	2.8	CPO	6	74	229/104	74	352/231	3	Alive
3	AVR	1.8	CPO + PNA	27	89	147/123	223	490/410	2	Alive
4	CABG/AVR	3.3	CPO	2	64	354/92	64	590/167	3	Alive
5	CABG	2.0	CPO	1	63	432/137	63	617/391	1	Alive
6	Aortic repair	3.0	CPO + PNA	1	60	441/88	60	441/98	2	Alive
7	Aortic repair	3.5	CPO + PNA	6	58	152/83	58	169/138	5	Alive
8	CABG/AVR	2.8	CPO + PNA	3	33	77/104	33	77/173	7	Expired
9	ECMO	3.3	CPO	1	61	481/221	61	481/221	6	Alive
10	CABG	1.8	CPO + PNA	15	28	158/55	28	158/55	2	Expired
11	Aortic repair	3.3	CPO + PNA	7	70	112/113	70	112/251	3	Alive
12	Aortic repair	2.0	CPO + PNA	3	56	195/107	56	325/214	1	Alive
13	CABG	2.0	CPO	2	70	108/96	70	108/96	7	Alive
14	Aortic repair	2.5	CPO + PNA	9	37	112/102	37	112/102	18	Expired
15	CABG	2.8	CPO	15	61	85/195	61	85/217	8	Alive
16	AVR	3.3	CPO + PNA	1	61	129/112	67	130/113	4	Alive

CABG: coronary artery bypass graft; AVR: aortic valve repair; ECMO: extracorporeal membrane oxygenation; CPO: cardiogenic pulmonary oedema; PNA: pneumonia; HFPV: high-frequency percussive ventilation; P/F: partial pressure of oxygen/fraction of inspired oxygen.

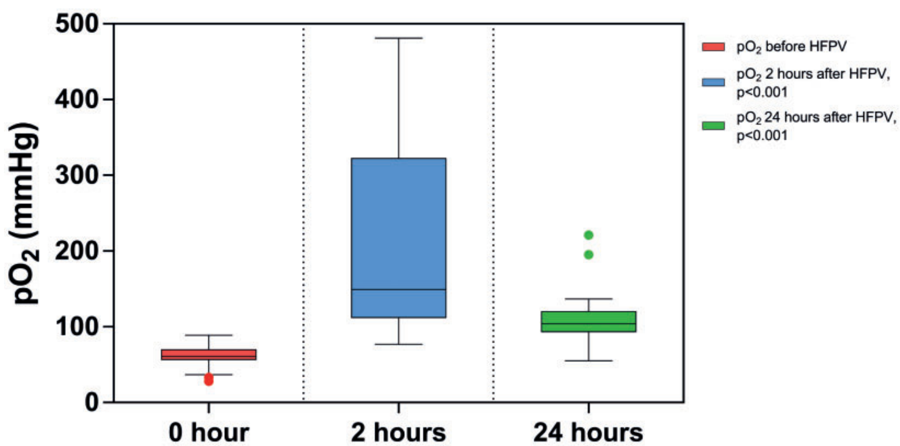

Figure 1: Changes in pO_2 with initiation of HFPV. Box-and-whisker plot. Line through box indicating median and closed circles as outliers (×1.5 above the maximum or minimum). HFPV: high-frequency percussive ventilation; pO_2: partial pressure of oxygen.

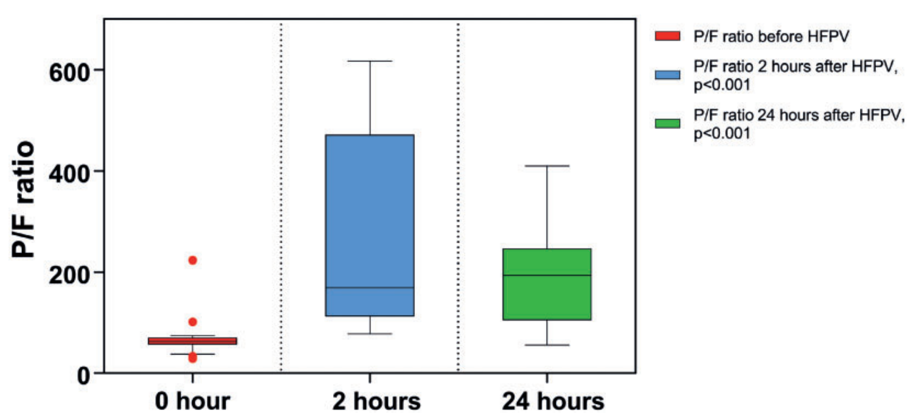

Figure 2: Changes in P/F ratio with initiation of HFPV. Box-and-whisker plot. Line through box indicating median and closed circles as outliers (×1.5 above the maximum or minimum). P/F: partial pressure of oxygen/fraction of inspired oxygen; HFPV: high-frequency percussive ventilation.

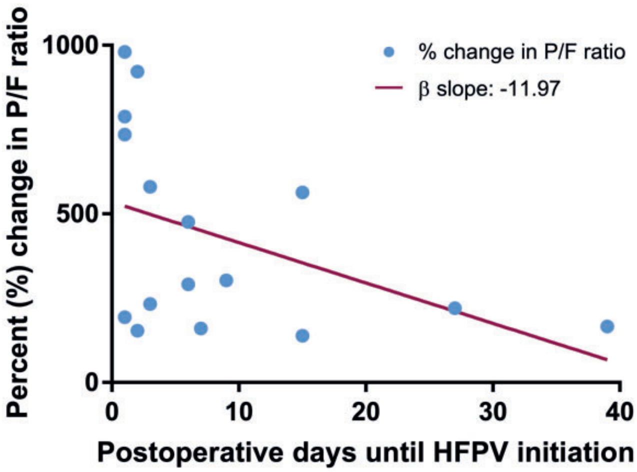

Figure 3: Days to HFPV initiation in relation to change in P/F ratio at 2 h. P/F: partial pressure of oxygen/fraction of inspired oxygen; HFPV: high-frequency percussive ventilation.

only applied to patients who failed MCV. Restricted use of HFPV is driven by the need for a dedicated adequately trained respiratory therapist assigned to a patient for the duration of HFPV and a limited number of HFPV ventilators available. It is not driven by the cost of the HFPV ventilator (VDR-4), which is about 25% higher than the price of conventional ventilator. Taking into account economics of HFPV, and our positive experience with this mode of ventilation, we believe that HFPV should be considered in patients failing MCV prior to initiation of ECMO.

Interestingly, HFPV may not only obviate the need for ECMO but also rescue patients who are already on ECMO. There were 3 recently published reports [16–18] in which HFPV was used as either a rescue modality or a weaning modality in patients with acute respiratory distress syndrome on ECMO. Blondonnet *et al.* [16] described a case of a 17-year-old male patient with severe adult respiratory distress syndrome from aspiration pneumonia who was placed on ECMO after failure to improve gas exchange with non-ventilatory strategies including paralysis, prone positioning and recruitment manoeuvres. Despite ECMO support, oxygenation did not improve and the patient was subsequently placed on HFPV with a 5-fold increase in pO_2 after 30 min. He was weaned off ECMO the following day. Boscolo *et al.* [17] described a 48-year-old woman with septic shock and hypoxaemic RF from pneumonia placed on ECMO after failure of MCV. On Day 18 of hospitalization, the patient was placed on HFPV due to inadequate oxygenation on MCV while on ECMO due to thick bronchial and peripheral secretions. Within 20 min of a 4-h HFPV trial, there was improvement in P/F ratio and mobilization of secretions. By the next day, the patient was separated from ECMO. A protocolized use of HFPV for adults with RF on ECMO was studied by Michaels *et al.* [18] and demonstrated reduced duration of ECMO support and a comparable survival to discharge rate to the CESAR trial [19].

Limitations

In addition to the small sample size, limitations of this study include those inherent in a retrospective analysis utilizing chart review including incomplete data and potential inaccuracies in data.

CONCLUSION

Although further studies are warranted, based on the presented patient cohort, HFPV should be considered as a rescue modality in patients after cardiac surgery failing MCV.

Conflict of interest: none declared.

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