Use of High-Frequency Ventilation in the Pediatric Intensive Care Unit

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Abstract

Keywords

- ▶ acute lung injury
- ▶ acute respiratory failure
- ▶ high-frequency percussive ventilation
- ▶ high-frequency oscillatory ventilation
- ▶ high-frequency ventilation

Objective To evaluate the clinical characteristics, ventilator settings, and gas exchange indices of patients placed on high-frequency percussive ventilation (HFPV) and high-frequency oscillatory ventilation (HFOV).

Methods Retrospective observation of all consecutive patients aged 0 to 18 years with acute respiratory failure managed with high-frequency ventilation from the institution's introduction of HFPV on May 1, 2012, until July 10, 2013.

Measurements and Main Results Twenty-seven patients underwent HFPV as a first mode of high-frequency ventilation and 16 patients underwent HFOV first. HFPV was used more frequently in patients with acute respiratory illnesses ($p < 0.01$), lower Pediatric Index of Mortality 2 scores (rank-sum $p < 0.04$), higher $\text{SpO}_2/\text{FiO}_2$ (SF) ratios ($p < 0.01$), and lower oxygen saturation indices ($p < 0.01$). HFPV patients showed increased SF ratios ($p < 0.01$) and decreased Paco_2 levels ($p = 0.02$) 6 hours after initiation, and HFOV patients showed no significant differences. Peak inspiratory pressures (HFPV) and mean airway pressures (HFOV) remained at or below 30 cm H_2O at each time point. HFPV and HFOV patients had an average of 2.8 and 2.9 mode changes, respectively. Mortality was 15% in the HFPV group and 50% in the HFOV group.

Conclusions HFPV is associated with rapid improvement in oxygenation and ventilation at acceptable airway pressures in patients with acute respiratory failure of various etiologies, primarily for those with difficulties of ventilation or secretion management. In our institution, HFOV appears to be initiated first in children with higher severity of illness.

Introduction

Acute respiratory failure (ARF) in children occurs when the respiratory system is unable to meet the metabolic demands of the tissues, typically evidenced by acute hypoxemia, acute hypercarbia, or both.¹ It is the most common indication for

intensive care unit (ICU) admission in the pediatric population and results in significant resource utilization, morbidity, and mortality.² Acute respiratory infection is a common cause of ARF, in addition to neuromuscular disease, trauma, and septic shock.¹

Pediatric intensive care practitioners use a variety of ventilators and modes of mechanical ventilation for critically

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ill children in ARF. An increasing number of modes have been made available, many following the advent of microprocessor control in the early 1980s and the technological boom of the 1990s.³ Alternative modes of ventilation have increased in use with the recognition of the consequences of ventilator-induced lung injury.^{4,5} These modes include high-frequency oscillatory ventilation (HFOV) and high-frequency percussive ventilation (HFPV), among others.⁶⁻⁸ Currently, there is no consensus on the appropriate mode of ventilation for specific types of respiratory failure or lung injury. The Pediatric Acute Lung Injury Consensus Conference is attempting to arrive at expert consensus on this and other issues related to acute lung injury with initial results pending.⁹

HFOV is widely utilized in the neonatal and pediatric populations for lung-protective ventilation. It provides subdead space tidal volumes at a rapid rate, allowing for pulmonary gas exchange with minimal atelectrauma.¹⁰ A continuous high-frequency rate of 200 to 900 beats/minute is provided using an oscillating membrane, resulting in active inhalation and exhalation during each cycle. These oscillations are superimposed on a continuous distending pressure which maintains lung volume.¹¹ Although HFOV has been used and studied in the general pediatric critical care setting,^{12,13} there is no consensus on how to identify patients who would most benefit from its use.

HFPV was introduced in 1986 and employs a combination of conventional pressure-controlled breaths and an oscillatory rate, delivered via the Volumetric Diffusive Respirator-4 (VDR-4) (Percussionaire Corporation, Sagle, Idaho, United States).¹⁴ The VDR-4 is a pneumatically powered and time-cycled ventilator that maintains inspiratory and expiratory oscillation during conventional pressure-limited breaths followed by passive exhalation to a set end-expiratory pressure. Oscillatory (percussive) rates are typically set at 200 to 900 beats/minute, and the conventional (convective) rate is typically set at 10 to 25 breaths/minute (→Fig. 1). Percussive breaths are generated by a sliding venturi valve, creating a cone-shaped oscillatory pulse which is believed to travel centrally and result in a countercurrent around the periphery of the airways.⁶ It is possible that this countercurrent effect facilitates ventilation and removal of airway debris more effectively than HFOV or conventional ventilation. HFPV has been used in the adult and pediatric burn populations, showing benefit at mobilizing retained airway debris using lower pressures than conventional ventilation.¹⁵⁻¹⁷ Its use has also been described in neonatal respiratory failure^{18,19} and general adult critical care settings.²⁰⁻²² However, description of use of HFPV in the general pediatric critical care setting is limited to a case report of salvage therapy following hydrocarbon ingestion²³ and one retrospective case series.²⁴

Fig. 1 VDR-4 ventilator screen image showing the high-frequency percussive ventilation pressure scalar. Used with permission.

In this study, we describe our initial experience with HFPV in pediatric patients with ARF compared with our concurrent usage of HFOV. We sought to evaluate the clinical characteristics and respiratory dynamics of patients placed on HFPV and HFOV. We also evaluated the clinical and ventilator courses of each patient. We hypothesized that there would be sustained improvement in oxygenation and ventilation at lower peak inspiratory pressures (PIPs) and mean airway pressures (MAPs) with each mode of alternative ventilation.

Materials and Methods

Patient Selection and Design

This was a retrospective observational study of patients undergoing HFPV and HFOV in the pediatric intensive care unit (PICU) and cardiac intensive care unit at Primary Children's Hospital in Salt Lake City, UT, comprising a total of 44 beds in a tertiary referral center that serves the Intermountain West. We evaluated the VDR-4 for use in our institution during 2011 and early 2012, and training was completed on May 1, 2012. A query of the Intermountain Healthcare respiratory database was conducted to identify eligible patients. All consecutive patients aged 0 to 18 years who underwent HFPV or HFOV between May 1, 2012, and July 10, 2013, were eligible for inclusion, which yielded 60 records. One record represented HFPV initiated following brain death in anticipation of organ donation, and this record was excluded. The remaining 59 records represented 43 unique patients, 10 of whom had multiple courses of one or both modes of high-frequency ventilation (HFV). Records of the nine patients with multiple HFV courses during the same hospitalization were combined, and the single patient with two hospitalizations including HFV courses during the study period was analyzed as one record for demographic variables and as two records for hospital course and outcome variables. Patients were stratified into those who underwent HFPV as their first form of HFV and those who underwent HFOV as their first form of HFV.

Ventilation Strategy

Ventilator selection and management were left to the discretion of the ICU attending physicians, who were neither directed by a ventilator management protocol nor informed that their management decisions would be the subject of chart review. Conventional ventilation was provided using the Evita XL (Dräger Medical, Lübeck, Germany) in a pressure-regulated volume control mode, pressure-controlled mode, airway ressure release ventilation, or a combination of these. In our institution, HFOV and HFPV have been primarily reserved as rescue modes of ventilation for patients not adequately supported by conventional ventilation. HFPV was provided using the VDR-4 and HFOV was provided using the SensorMedics 3100-A and 3100-B (Cardinal Health, Dublin, Ohio, United States). All devices have been approved by the U.S. Food and Drug Administration.

Data Collection

Manual chart review of the identified patients was conducted to extract demographic variables, underlying illnesses,

admission diagnoses, causes of respiratory failure, Pediatric Index of Mortality 2 (PIM2) scores at admission, hospital courses, and outcomes. Ventilator courses, daily ventilator settings, daily blood gas values, and additional blood gas values surrounding each ventilator mode change were recorded. Adjunctive medications and therapies were also extracted, including vasoactive medications, albuterol, inhaled nitric oxide, corticosteroids, chest percussive therapy, and thoracostomy tubes.

PIM2 score was calculated as per Slater et al²⁵ based on data from the time of admission to the critical care unit. As not all patients had frequent arterial blood gas values, primary measurements of oxygenation included SpO₂/Fio₂ ratio (SF ratio) and oxygenation saturation index (OSI), calculated as MAP × Fio₂ × 100/SpO₂. PaO₂/Fio₂ ratio (PF ratio) was also calculated for those with arterial blood gas values available. Parameter values closest in time to HFV initiation and 6, 12, 24, 48, and 72 hours after HFV initiation were selected. Although documentation of ventilation parameters and blood gases was entirely decided by the clinical team, the difference between actual time and each time standard (e.g., 6 hours after initiation of HFV) was small (►Table 1).

Statistical Analysis

We used the chi-square test or Fisher exact test, where appropriate, for categorical variables and a Student *t*-test or the Wilcoxon rank-sum test, where appropriate, for bivariate analyses of continuous variables. A paired *t*-test was used for within-group comparisons. Linear regression with robust standard errors was used to test the slopes of the relationships between OSI, SF ratio, MAP, and Paco₂ and time. Statistical significance was defined as *p* < 0.05, and analyses were performed using STATA (StataCorp LP, College Station, Texas, United States) and the R environment (version 3.1.1). This study was reviewed and approved with waiver of informed consent by the University of Utah School of Medicine Institutional Review Board.

Results

Patient Characteristics at Time of Initiation of HFV

During the 14-month study period, HFPV was used as the first form of HFV in 27 patients aged 1 month to 18 years old

Table 1 Actual time (hours) after initiation of high-frequency ventilation versus standardized time

Standardized time (h)	Actual time, median (interquartile range) (h)
6	5.8 (5.2–6.6)
12	11.6 (10.9–12.8)
24	24.5 (22.6–26)
48	47.9 (46.8–49.1)
72	70.5 (69.2– 73.3)
96	95.9 (93.25–97)

(► **Table 2**), with HFOV used as a subsequent mode in 4 of these patients (► **Fig. 2**). HFOV was used as the first form of HFV in 16 patients with ages from 0 months to 16 years old, 5 of whom underwent HFPV as a subsequent mode. Four patients (three HFPV first) had pre-existing tracheostomies without ventilator dependence. Twenty-two patients (nine HFPV first) had arterial lines. All of the patients except one (HFPV first) met SF ratio criteria (<221) for acute respiratory distress syndrome (ARDS).²⁶

More patients undergoing HFPV first were admitted for acute respiratory infections (21/27; 78%) compared with patients undergoing HFOV first (5/16; 31%; exact $p = 0.004$). Patients placed on HFPV first were admitted to the PICU with a lower mean PIM2 probability of death than patients placed on HFOV first (5 vs. 23%; rank-sum $p < 0.04$). Patients placed on HFPV first were more likely than those placed on HFOV first to have received albuterol prior to HFV initiation (37 vs. 6%; exact $p < 0.03$) and equally likely to have received an inotrope or vasopressor (19 vs. 44%; exact $p = 0.09$). Patients placed on HFPV first did not have a different amount of time on conventional ventilation before transitioning to HFV, or number of ventilator days prior to HFV (2 vs. 1; rank-sum $p = 0.18$). Patients placed on HFPV first had less severe lung injury at the time of HFV initiation (mean SF ratio 160 vs. 106; t -test $p < 0.001$; mean OSI 11 vs. 19; t -test $p < 0.001$). Clinical documentation indicated that patients were more often placed on HFPV first for secretion management or ventilation (22/27, 81% vs. 1/16, 6%; exact $p < 0.001$) and more often placed on HFOV first for problems with oxygenation (14/16, 88% vs. 4/27, 15%; exact $p < 0.001$). Two patients were started on HFPV at the time of intubation, and an additional two were transitioned to HFPV immediately upon arrival from another facility.

Oxygenation

After placement on HFPV, patients showed rapidly improving oxygenation as reflected by a higher SF ratio at 6 hours than at initiation (paired t -test $p = 0.009$), although patients placed on HFOV first did not (paired t -test $p = 0.06$). Neither group showed an overall improving SF ratio over 96 hours (both slopes $p > 0.05$). The HFPV group showed a steadily decreasing OSI (► **Fig. 3**; slope $p = 0.02$) but the HFOV group did not (slope $p = 0.15$).

Ventilation

Although patients placed initially on HFPV showed a rapid decrease in $Paco_2$ (► **Fig. 4**; initiation vs. 6 hours after, paired t -test $p = 0.02$), neither group showed an overall decrease in $Paco_2$ at 96 hours (► **Fig. 4**; both slopes $p > 0.05$).

Airway Pressure

Both HFPV and HFOV were associated with rapid increases in MAP (initiation vs. 6 hours after; paired t -test $p = 0.04$ for both groups). Neither group showed an overall change in MAP over time (► **Fig. 5**; both slopes $p > 0.05$). The mean PIP for the HFPV group was below 30 cm H_2O at every time point, and PIP steadily decreased over time (slope $p = 0.01$). Although PIP is not measured on HFOV, the

mean MAP in the HFOV group was at or below 30 cm H_2O at each time point.

Complications

One patient had hypotension attributed to HFPV use, which resolved upon return to conventional ventilation. One patient sustained a new pneumothorax on HFPV requiring tube thoracostomy following HFPV course, and another who required tube thoracostomy during HFPV for pleural effusion died while on HFPV. Four HFPV patients required bronchoscopy for secretion removal. One patient started on HFOV first sustained a new pneumothorax and three others required tube thoracostomy for pleural effusions.

Ventilator Course and Outcomes

Patients started on HFPV stayed on it longer than patients begun on HFOV. For patients begun on HFPV, the mean duration of HFPV use was 3.7 days, with four patients (15%) on HFPV for less than 12 hours and six patients (22%) on HFPV for less than 24 hours. Four (67%) of these short-course patients died, accounting for all deaths of those started on HFPV first. For patients begun on HFOV, the mean duration of HFOV use was 3.4 days, with 7 patients (44%) on HFOV for less than 12 hours and 11 patients (69%) on HFOV for less than 24 hours. Six (55%) of these short-course patients died. Patients begun on HFPV experienced an average of 2.8 ± 1.5 ventilator mode changes, compared with 2.9 ± 2 mode changes in the HFOV group. Patients started on HFPV first had similar rates of neuromuscular blockade infusions as patients started on HFOV first (16/27, 59% vs. 11/16, 69%; exact $p = 0.75$).

Four patients were rescued from HFV to extracorporeal membrane oxygenation (ECMO) for refractory hypoxemia. One patient was rescued from HFPV to a 10-day course of venovenous ECMO and survived to hospital discharge. Two patients were rescued from HFOV to venovenous ECMO and survived to hospital discharge, although one required home ventilation via tracheostomy. One patient was rescued from HFOV to a 3-day course of venoarterial ECMO for refractory hypoxemia with impaired cardiac systolic function and died while on ECMO.

Four patients (of 27, 15%) in the HFPV group died prior to hospital discharge (one of primary respiratory causes, two nonrespiratory, and one withdrawal of care), compared with half (8/16, 50%, exact $p = 0.03$) in the HFOV group (four of primary respiratory causes and four nonrespiratory). All four of the HFOV patients who developed pneumothorax or required tube thoracostomy survived to hospital discharge.

Discussion

In this cohort, providers tended to use HFOV in patients with more severe hypoxemia, and to use HFPV in patients with secretion clearance and ventilation challenges. Both ventilation modes were used with what are thought to be lung-protective MAPs and PIPs (30 cm H_2O or less). Following transition to HFPV, there was a subjective improvement in secretion clearance similar to the effect reported in inhalational injuries,^{15–17} although no objective data were

Table 2 Patient demographics, baseline characteristics, admission diagnoses, gas exchange parameters, and outcomes. Number of patients with percentage or mean $\pm$ standard deviation (SD)

	HFPV first	HFOV first
	<i>n</i> = 27	<i>n</i> = 16
	<i>n</i> (%) or mean ($\pm$ SD)	<i>n</i> (%) or mean ($\pm$ SD)
Demographics		
Age (mo)	57 ($\pm$ 79)	52 ($\pm$ 59)
Weight (kg)	19 ($\pm$ 24)	17 ($\pm$ 15)
Male	12 (44%)	9 (56%)
Baseline characteristics		
Probability of death (PIM2)	11% ($\pm$ 20%)	32% ($\pm$ 30%)
Immunocompromised	4 (15%)	6 (38%)
Prematurity	10 (37%)	3 (19%)
Chronic lung disease	8 (30%)	2 (13%)
Acute respiratory illness	21 (78%)	5 (31%)
Sepsis	4 (15%)	3 (19%)
Prior ancillary therapies		
Inhaled nitric oxide	1 (4%)	2 (13%)
Albuterol	10 (37%)	1 (6%)
DNAse	5 (19%)	1 (6%)
Corticosteroids	2 (7%)	5 (31%)
Chest percussive therapy	8 (30%)	1 (6%)
Inotrope/vasopressor	5 (19%)	7 (44%)
ECMO	1 (4%)	0 (0%)
Reason for HFV initiation		
Oxygenation	4 (15%)	14 (88%)
Ventilation	8 (30%)	1 (6%)
Secretion management	14 (52%)	0
Not documented	1 (4%)	1 (6%)
Oxygenation/Ventilation impairment		
Oxygenation index	14 ($\pm$ 7.4) (<i>n</i> = 9)	25 ($\pm$ 11) (<i>n</i> = 10)
Oxygen saturation index	11 ($\pm$ 4.7) (<i>n</i> = 23)	19 ($\pm$ 5.2) (<i>n</i> = 13)
Mean airway pressure	16 ($\pm$ 2.9) (<i>n</i> = 23)	19 ($\pm$ 3.5) (<i>n</i> = 13)
FiO ₂	0.65 ($\pm$ 0.2) (<i>n</i> = 23)	0.90 ($\pm$ 0.14) (<i>n</i> = 13)
PF ratio	151 ($\pm$ 68) (<i>n</i> = 9)	120 ($\pm$ 120) (<i>n</i> = 10)
SF ratio	160 ($\pm$ 46) (<i>n</i> = 23)	106 ($\pm$ 24) (<i>n</i> = 13)
paCO ₂	60 ($\pm$ 19) (<i>n</i> = 20)	56 ($\pm$ 13) (<i>n</i> = 11)
Outcomes		
Total HFPV days	3.7 ($\pm$ 3.2)	0.7 ($\pm$ 1.4)
Total HFOV days	0.6 ($\pm$ 2.9)	3.4 ($\pm$ 4.8)
Total ventilator days	11 ($\pm$ 7.7)	11 ($\pm$ 11)
Total ICU days	15 ($\pm$ 11)	12 ($\pm$ 12)
Mortality	4 (15%)	8 (50%)

Abbreviations: DNAse, deoxyribonuclease; ECMO, extracorporeal membrane oxygenation; HFOV, high-frequency oscillatory ventilation; HFPV, high-frequency percussive ventilation; HFV, high-frequency ventilation; ICU, intensive care unit; PF ratio, PaO₂/FIO₂ ratio; PIM2, Pediatric Index of Mortality 2.

Fig. 2 Progression of study patients through modes of ventilation.

available. Outcomes were much worse in the HFOV group, although this correlates with the large selection bias which resulted in the more critically ill children being placed on HFOV.

Rizkalla et al recently reported their experience ventilating a cohort of children using HFPV at their institution.²⁴ Similar to their findings, we noted a rapid improvement in oxygenation (SF ratio) and CO₂ clearance upon transition to HFPV, regardless of the indication for HFPV initiation. Our mortality rate of 15% was also very similar to the 16% mortality they found. One benefit of our analysis relative to theirs was much longer follow-up (96 vs. 24 hours). They reported continued improvement in both oxygenation and ventilation over 24 hours after initiation of HFPV, but we did not find an overall trend over 96 hours. Those patients still on HFPV at 96 hours may be those who started with more severe lung disease, as patients who showed significant improve-

ment prior to this time point were likely transitioned back to conventional ventilation earlier.

Although airway pressures did not decrease upon transition to HFPV as we hypothesized, we did observe acceptable levels of permissive hypercapnea at airway pressures that would still be considered lung-protective. A ventilation strategy that includes permissive hypercapnea may contribute to limiting peak airway pressures. Other studies have also shown significant improvements in gas exchange with lower airway pressures in adults^{27,28} and children.²¹

Different from Rizkalla et al, we found significant variation in the length of time spent on HFPV, with over one-fifth of patients in our study on HFPV for less than 24 hours. Interestingly, 69% of those begun on HFOV died or were changed to a different mode within 24 hours. We found the use of HFPV as the initial mode of ventilation in four patients in our series, suggesting a perceived role for the mode beyond that of inhalation injury or salvage after failure of conventional ventilation.

A significant advantage of our analysis relative to Rizkalla et al is our inclusion of children who were initially treated on HFOV rather than HFPV. In many PICUs, HFOV is the other ventilator mode that providers may consider when children are failing conventional ventilation. Children who received HFOV first in our study tended to have more severe illness and impairment of gas exchange at HFV initiation. Half of the patients who received HFOV first died, as predicted by the much higher PIM2 scores observed for that group. It is possible that a tendency to use HFOV as salvage therapy resulted in its initiation at or near the peak of illness. Although we did not observe significant changes in oxygenation or ventilation after initiation of HFOV, MAPs were able to be maintained within a lung-protective range while achieving acceptable mean gas exchange values. It is possible that these patients would have required higher pressures to maintain these values if they had continued on conventional ventilation, although a matched control group was not available. Due to the lack of randomization in this study design, it is not possible to determine from these data any effect of HFOV on mortality, although recent studies have suggested HFOV results in similar²⁹ or even increased mortality³⁰ in adults with ARDS.

We observed a significant number of ventilator and mode changes. Because these transitions can expose patients to serious risks including atelectasis, severe hypoxemia with associated hemodynamic compromise, and barotrauma, more research is needed to optimize ventilation pathways and protocols and limit the number of risky mode and ventilator changes.

Limitations to the use of these modes of ventilation likely include attending physician, nursing, and respiratory therapist comfort levels with each mode. Furthermore, both modes of HFV suffer from inability to accurately measure tidal volumes, and they require frequent monitoring as they can be susceptible to drifting from the set parameters.

This study is limited by its single-center, retrospective observational nature, as clinicians were not provided specific protocols for ventilator management or limited in the

Fig. 3 Mean oxygenation saturation indices with 95% confidence intervals and linear regressions from prior to initiation (time 0) and throughout course of high-frequency percussive ventilation (HFPV) and high-frequency oscillatory ventilation (HFOV).

Fig. 4 Mean partial pressure of carbon dioxide in mm Hg with 95% confidence intervals and linear regressions from prior to initiation (time 0) and throughout course of high-frequency percussive ventilation (HFPV) and high-frequency oscillatory ventilation (HFOV).

ancillary therapies provided. Furthermore, as the study period began with the first patient placed on the VDR-4 in our institution, clinician management of HFPV may have changed during the study period in unmeasurable ways as experience with the ventilator increased. In addition, selection bias prevents comparison of outcomes between HFPV and HFOV patients, as baseline characteristics

showed a higher degree of illness in HFOV patients. Patients were placed on HFPV and HFOV at differing and uncontrolled times in their clinical course, and some may have been placed on the alternative modes of ventilation just prior to a clinical improvement which could have occurred on conventional ventilation. However, the degree of improvement in gas exchange within hours of transition to

Fig. 5 Mean values of mean airway pressure with 95% confidence intervals and linear regressions from prior to initiation (time 0) and throughout course of high-frequency percussive ventilation (HFPV) and high-frequency oscillatory ventilation (HFOV).

HFPV suggests that this was not a major confounder for this subset of patients.

Conclusions

HFPV is associated with rapid improvement in oxygenation and ventilation at acceptable airway pressures in patients with ARF of various etiologies. Introduction of HFPV into a PICU can be associated with wide variation in practice. In our institution, HFOV is initiated first in children with significant risk of mortality. There remains a paucity of evidence to support use of either mode. Prospective studies are needed to establish safety and efficacy of introducing new modes of ventilation as well as ventilator pathways and protocols that limit risk and maximize the potential benefits of HFPV and HFOV.

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