High-frequency oscillatory ventilation in children: a 10-year experience

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KEYWORDS
High frequency oscillatory ventilation; Child; Acute respiratory failure; Bronchiolitis; Pneumonia; Acute respiratory distress syndrome

Abstract
Objectives: The aim of the study was to describe the experience with high-frequency oscillatory ventilation (HFOV) in a Portuguese Pediatric Critical Care Unit, and to evaluate whether HFOV allowed improvement in oxygenation and ventilation.
Methods: This was a retrospective observational cohort study of children ventilated by HFOV between January, 2002 and December, 2011. The following parameters were recorded: demographic and clinical data, and blood gases and ventilatory parameters during the first 48 hours of HFOV.
Results: 80 children were included, with a median age of 1.5 months (min: one week; max: 36 months). Pneumonia (n = 50; 62.5%) and bronchiolitis (n = 18; 22.5%) were the main diagnoses. Approximately 40% (n = 32) of the patients developed acute respiratory distress syndrome (ARDS). Conventional mechanical ventilation was used in 68 (85%) of patients prior to HFOV. All patients who started HFOV had hypoxemia, and 56 (70%) also presented persistent hypercapnia. Two hours after starting HFOV, a significant improvement in SatO2/FiO2 ratio (128 ± 0.63 vs 163 ± 0.72; p < 0.001) that was sustained up to 24 hours of HFOV and a decrease in FiO2 were observed. Since the beginning of HFOV, the mean PCO2 significantly decreased (87 ± 33 vs 66 ± 25; p < 0.001), and the pH significantly improved (7.21 ± 0.17 vs 7.32 ± 0.15; p < 0.001). Overall survival was 83.8%.
Conclusions: HFOV enabled an improvement in hypercapnia and oxygenation. It is a safe option for the treatment of ARDS and severe small airway diseases.

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Introduction

Acute respiratory failure is a frequent problem in children admitted to pediatric intensive care units (PICUs). It is well known that mechanical ventilation is associated with barotrauma, volutrauma, atelectrauma, and biotrauma.1-4 Avoiding ventilator-induced lung injury has become a major concern when considering which ventilatory strategy to apply to patients with lung diseases. High frequency oscillatory ventilation (HFOV) is a lung-protective ventilatory mode that ensures alveolar recruitment and an optimal lung volume.5,6 During HFOV, very small tidal volumes (1-2 mL/kg), high flow rates, and frequencies of 240-900 cycles per minute are used to open the lung, in order to avoid high peak airway pressures, alveolar overdistension, and repeated cycles of recruitment.5 HFOV has been most studied in the context of acute respiratory distress syndrome (ARDS), and several studies have demonstrated its safety as a lung volume recruitment strategy.7-9 However, there isn’t enough evidence to support the use of HFOV over conventional mechanical ventilation (CMV). To a lesser extent, HFOV has been applied in children with air leak or small airway disease, such as bronchiolitis.10-14

This study aimed to describe the authors’ experience using HFOV in pediatric patients, and to evaluate its effect on oxygenation, ventilation, and associated complications. This study was based on retrospective analysis of the patients treated at the PICU of Hospital Professor Doutor Fernando Fonseca in Amadora, Portugal.

Materials and methods

Design

This was an observational retrospective study from January, 2002 to December, 2011. The study was performed in an eleven-bed PICU of a Portuguese hospital with maximum capacity for six ventilated patients. The PICU is localized in the metropolitan area of Lisbon, which has 800,000 inhabitants, and admits approximately 500 children yearly. This study was approved by the institutional review board.

Patients and data collection

All patients that needed HFOV during the study period were considered eligible, except those who were ventilated on HFOV due to diaphragmatic hernia. 87 patients were initially eligible, but seven were excluded due to insufficient clinical data. Data was collected through patient chart review. The following data was recorded: demographic, diagnosis, maximal ventilatory settings during CMV, and hemodynamic status. Blood gases (pH and mean partial pressure of carbon dioxide (pCO2), fraction of inspired
oxygen (FiO₂), transcutaneous oxygen saturation (Sat. O₂), and ventilator settings of HFOV (mean continuous distending airway pressure [Paw], amplitude [delta-p] and frequency [Hz]) were recorded immediately before and at 2, 6, 12, 24 and 48 hours of HFOV.

Maximal parameters during HFOV were considered as the highest ventilatory settings observed during six consecutive hours. Lung recruitment pressure was defined as the maximal mean airway pressure that allowed a stepwise decrease of FiO₂ until reaching 0.6.

ARDS was defined according to the American-European Consensus Conference on ARDS. Airway obstructive disease as bronchiolitis was defined as a respiratory disorder in children until two years of age with rhinitis, cough, tachypnea, wheezing, crackles, and use of accessory muscles, with or without fever and without consolidation on the X-ray. Pneumonia was defined as infiltrates on chest X-ray, in addition to one of the following: deterioration in pulmonary gas exchange, fever (temperature above 38 ºC), white blood cell count above 12.000/mm³, or a positive tracheal aspirate culture. Sepsis was defined according to the guidelines of the Surviving Sepsis Campaign. Multiple organ failure was considered when at least two of the following organ dysfunctions occurred: central nervous system, cardiovascular, hepatic, respiratory, gastrointestinal, renal, or hematologic.

High frequency oscillatory ventilation protocol

The ventilatory modes used in CMV (Servo®, Maquet Inc - Wayne, United States and Servo 300 Siemens Medical Systems - Solna, Sweden) were pressure control or pressure-regulated volume target. The authors opted to use CMV with non-aggressive settings (PIP < 30 cmH₂O, tidal volume < 8 mL/kg, respiratory rate [RR] < 50/min). When refractory hypoxemia, defined as Sat.O₂ below 90% with FiO₂ 1 or hypercapnia with severe acidosis (pH < 7.22 and pCO₂ > 80 mmHg) occurred, patients were switched to HFOV.

Sensor-Medics 3100A® (Sensor Medics Corporation - Yorba Linda, CA, USA) was used for HFOV. An “open lung strategy” was adopted. The initial settings were FiO₂ of 1.0, oscillation frequency of 10-12 Hz, a percentage inspiratory time of 33%, and bias flow of 20-30 L/ min. The Paw was set 5 cmH₂O above the mean airway pressure during CMV, and increments of 1 cmH₂O were used until an optimal lung volume was reached, avoiding over distension and atelectasis. The oxygenation target was an adequate SatO₂ (≥ 90%) with FiO₂ ≤ 0.6. The delta-p was initially set to achieve chest wall vibration to the level of thigh in infants, or to the umbilical level in newborns. The frequency and delta-p were adjusted to obtain an adequate pCO₂ and pH above 7.25. General supportive care included fluid restriction to 80% of daily needs, nutritional support, and antibiotics if needed. All patients were sedated with continuous infusion of an opioid (morphine), and a benzodiazepine (midazolam). Neuromuscular blockage agents were only used when there was a significant clinical deterioration related to spontaneous activity. Inotropic support, nitric oxide, and chest tube drainage were used if necessary. The weaning process from HFOV was started when FiO₂ was below 0.4. During this process, Paw was gradually decreased by 1-2 cmH₂O until a value below 14 cmH₂O was reached. After HFOV, patients started CMV (support mode), non-invasive ventilation, or nasal cannula oxygen.

Outcome measures

The primary outcome was to evaluate whether HFOV allowed improvement in oxygenation and ventilation. An improvement in oxygenation was considered if a decrease in FiO₂ allowed Sat.O₂ above 90%, and the ratio of Sat. O₂/FiO₂ increased along the study period. Evaluation of ventilation was performed through changes of pH and pCO₂ values obtained from capillary blood samples. HFOV success was defined as improvement in oxygenation and ventilation. HFOV failure was considered when death or intractable hypoxemia occurred.

The secondary outcomes were: a) to study complications related to HFOV and mortality rate. A new air leak, hypotension, hypoxemia or bradycardia during HFOV were considered as complications possibly related to HFOV; b) to compare clinical, blood gases, and therapeutic parameters in surviving and non-surviving patients; and c) to analyze predictive factors of mortality.

Statistical analysis

Quantitative variables were analyzed using measures of central location (mean and median) and dispersion (standard deviation). Qualitative or categorical variables were described as frequencies. To compare quantitative variables, Student’s t-test or Wilcoxon’s non-parametric test were used, depending on the distribution according to normality. Dichotomous variables were studied with the chi-squared test or Fisher’s exact tests. A multivariate analysis was performed using binary logistic regression through the Enter method. All tests were two-tailed, and a p-value < 0.05 was considered as significant. Statistical analyses were performed using the Statistical Package for Social Sciences (SPSS Inc. - Chicago, Illinois, USA) version 18.0 for Windows.

Results

Demographics

Eighty patients were included in the study. The median age was 1.5 months (1 week-36 months), and 41 (51.3%) were male. Most children (n = 38; 47.5%) were ventilated between January and March. The median PICU hospitalization was 15 days (4-105 days). Pneumonia was the most frequent diagnosis, present in 50 (62.5%) children. Other diagnoses were bronchiolitis in 18 (22.5%), and sepsis in 10 (12.5%) patients. Approximately 40% of the patients (n = 32) developed ARDS before the institution of HFOV. Table 1 shows patient’s demographic characteristics, underlying diseases, and diagnoses.
Table 1  Patient demographics, underlying diseases, and ARDS.

<table>
<thead>
<tr>
<th>Variable</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg), mean±SD</td>
<td>4.1±2.1</td>
</tr>
<tr>
<td>Past medical history</td>
<td></td>
</tr>
<tr>
<td>Prematurity, n (%)</td>
<td>25 (31.3)</td>
</tr>
<tr>
<td>Cardiac disease, n (%)</td>
<td>7 (8.8)</td>
</tr>
<tr>
<td>Cardiac insufficiency, n (%)</td>
<td>2 (2.5)</td>
</tr>
<tr>
<td>ARDS, n (%)</td>
<td>32 (40)</td>
</tr>
<tr>
<td>Multiorgan failure, n (%)</td>
<td>15 (18.8)</td>
</tr>
</tbody>
</table>

ARDS, acquired immunodeficiency syndrome; ARDS, acute respiratory distress syndrome; SD, standard deviation.

Ventilatory characteristics

CMV was performed in 68 (85%) of patients prior to HFOV, and non-invasive ventilation was the first option in 33 (44%) patients. The median time on CMV before HFOV was 12 hours (1-360 h). Maximum parameters during CMV were (mean±SD): PEEP 6±1 cmH₂O, PIP 26±6 cmH₂O, RR 52±8 cpm, and FiO₂ 0.70±0.25.

Immediately before starting HFOV, the median Sat. O₂/FiO₂ ratio was 156 (43-376) and the median value of PCO₂ was 82.3 torr (31-200). Before HFOV, four patients presented a clinical deterioration due to pulmonary air leak (pneumothorax, n = 3; pulmonary interstitial emphysema, n = 1). HFOV was initiated based on hypercapnia in 56 (70%), hypoxemia with hypercapnia in 13 (16.3%), and hypoxemia without hypercapnia in 11 (13.8%) patients. HFOV was performed for a median time of 103 hours (12-576 h). The median of the highest parameters used during HFOV were: FiO₂ 0.8 (0.3-1), Paw 19 cmH₂O (14-44 cmH₂O), and delta-p 50 (30-93). The median frequency used was 10Hz (5-12 Hz). A median Paw of 19.5 cmH₂O (15-44 cmH₂O) was used to perform lung recruitment. All patients were sedated with morphine and midazolam. Inotropic support was needed in 52 (65%) patients before starting HFOV. Dopamine was used alone in 29 (36%) patients, and two or more inotropics were needed in 18 (22.5%) cases. 22 (27.5%) patients were curarized for a median time of 60 hours (24-960 h). Nitric oxide was administered to 14 (17.5%) children.

Primary outcome

With HFOV, immediate and significant increase was achieved in the Sat. O₂/FiO₂ ratio (128±0.63 vs. 163±0.72; p < 0.001) that was sustained until 24 hours of HFOV. A FiO₂ of approximately 0.6 was reached after 6 hours of HFOV. Immediately after starting HFOV, mean PCO₂ significantly decreased (87±33 vs. 66±25; p < 0.001) and remained within target ranges during the entire study period. Also, pH significantly improved at the beginning of HFOV (7.21±0.17 vs. 7.32±0.15; p < 0.001), and remained within normal values during the 48 hours of the study. Figure 1 shows blood gases, FiO₂, and Sat.O₂/FiO₂ ratios during the study period.

According to the protocol design, during the first two hours of HFOV an increment of Paw (17.8±3.5 vs. 18.0±3.4; p = 0.03) was observed to reach lung recruitment. After this time, significant oscillations in Paw were not registered. Significant variations of delta-p and frequency during the study were not observed. Table 2 shows ventilator settings and hemodynamic parameters during the 48 hours.

Mean arterial pressure did not show significant oscillations during the 48 hours studied. After 12-hours of HFOV, a significant decrease was observed in heart rate (149±21 vs. 141±23; p < 0.001). At 24 and 48-hours the heart rate was significantly lower (Table 2).

37 (46.3%) patients were successfully weaned from HFOV: 25 to non-invasive ventilation, and 12 directly to supplementary oxygen through face masks or nasal cannula.

Secondary outcome

During HFOV, seven patients presented with a new air leak related to central line insertion (two patients), to high-pressure hand-mask ventilation (two patients), and to fatal ARDS (three patients). HFOV did not cause worsening of pneumothorax in those patients with a diagnosis of air leak prior to HFOV. Endotracheal tube suction was associated with transitory hypoxemia and/or bradycardia in 16 (20%) patients. During the course of HFOV, reintubation was needed in eight (10%) patients due to endotracheal tube obstruction or accidental extubation. Most patients (n = 51; 63.8%) did not present complications during HFOV.

Overall survival was 83.8% (67 patients). Five patients died from multi-organ failure, four from cardiac failure (hypoplastic left heart syndrome), and four from both septic shock and refractory respiratory failure. Children who died had a median age of 4 months (min = 1; max = 36 months), and were significantly older than those who survived, who presented a median age of 1 month (min = 9 days; max = 35 months) (p = 0.015). A relevant past medical history was more prevalent in the group of non-survivors (77% vs. 36%; p = 0.006). Also, in this group, mechanical ventilation before HFOV was performed for a significantly longer period when compared to survivors (72±106 vs. 24±39; p = 0.01). Differences in ventilator settings during HFOV between both groups are shown in Table 3. Non-survivors presented a lower Sat.O₂/FiO₂ ratio (133±60 vs. 104±78; p = 0.006) since the beginning of HFOV when compared to survivors. This difference was observed during the 48 hours of the study period. Values of pH and PCO₂ were similar between both groups up to 24 hours of HFOV. After that time, a significant improvement was observed only in the group of survivors.
During HFOV, lower frequencies and higher Paw and delta-p were used in the group of patients who died (p < 0.05) (Table 3). In the univariate analysis, predictive factors of mortality were: pH and PCO₂ at 2 hours, pH at 24-hours, and Sat.O₂/FiO₂ ratios at 2 hours, 6 hours, 12 hours, 24 hours, and 48 hours. In the multivariate analysis, these were not independent factors.

**Table 2**  Mean ventilator settings, gas exchange, blood pressure, and heart rate of the study population at multiple time intervals during HFOV.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>At beginning HFOV Mean±SD</th>
<th>2 hours Mean±SD</th>
<th>6 hours Mean±SD</th>
<th>12 hours Mean±SD</th>
<th>24 hours Mean±SD</th>
<th>48 hours Mean±SD</th>
<th>p-value</th>
</tr>
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<tbody>
<tr>
<td><strong>Ventilator settings</strong></td>
<td></td>
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<tr>
<td>Paw (cmH₂O)</td>
<td>17.8±3.5</td>
<td>18.0±3.4</td>
<td>18.1±3.1</td>
<td>18.1±3.1</td>
<td>17.8±4.3</td>
<td>17.6±4.5</td>
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<tr>
<td>delta-p</td>
<td>45±12</td>
<td>45±12</td>
<td>45±12</td>
<td>46±13</td>
<td>44±15</td>
<td>45±17</td>
<td>ns</td>
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<tr>
<td>Frequency (Hz)</td>
<td>10±1</td>
<td>10±1</td>
<td>10±1</td>
<td>10±1</td>
<td>10±1</td>
<td>10±1</td>
<td></td>
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<tr>
<td><strong>Hemodynamic data</strong></td>
<td></td>
<td></td>
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<tr>
<td>Mean arterial pressure</td>
<td>48±11</td>
<td>48±10</td>
<td>50±12</td>
<td>48±13</td>
<td>49±9</td>
<td>51±11</td>
<td>b</td>
</tr>
<tr>
<td>Heart rate (cpm)</td>
<td>145±23</td>
<td>145±22</td>
<td>149±21</td>
<td>141±23</td>
<td>136±18</td>
<td>129±17</td>
<td>c</td>
</tr>
</tbody>
</table>

delta-p, amplitude; ns, non-significant; HFOV, high-frequency oscillatory ventilation; paw, airway pressure; SD, standard deviation.

*A significant increase was observed during the first 2 hours of the study (p = 0.03). During the remainder of the study, there were no significant variations.

*Mean arterial pressure was stable during the entire study.

*Heart rate significantly decreased from the 12th hour of the study (p < 0.05 for 24-hour and 48-hour comparisons).
ventilation and oxygenation. These effects were registered after 2 hours of HFOV. Similar results with HFOV have also been reported in pediatric and adult populations.Published studies refer to the adult population; their extrapolation to pediatric patients is not always feasible. In this study, only three cases of air leak occurred during HFOV. However, a direct relationship between air leaks and HFOV could not be established. All three patients had severe ARDS, which could also be responsible for the air leak. In the study by Ben Jaballah N et al., HFOV did not cause any new air leak syndrome; Arnold JH et al. found that HFOV was not associated with a higher number of air leaks when compared to CMV. In PICU, only one prospective study comparing HFOV and CMV was performed, and a statistically significant difference in mortality with HFOV could not be proved.

In this study, maximum parameters in CMV were not aggressive, since HFOV was used as an early intervention strategy in the course of disease and when lung recruitment was needed. The optimal timing to initiate HFOV is not yet defined, and different approaches can be found in literature. In this study’s population, patients with bronchiolitis were mainly infants aged less than 3 months with minimal physiological time constant, so an approach of high volume and low respiratory rate was not used. HFOV proved to be very efficient in patients with diffuse alveolar disease or with increased airway resistance and hyperinflation. Slee-Wijffels et al. reported a single-center experience, which included 17 patients with small airway disease who were successfully ventilated on HFOV. In this study, maximum parameters in CMV were not aggressive, since HFOV was used as an early intervention strategy in the course of disease and when lung recruitment was needed. The optimal timing to initiate HFOV is not yet defined, and different approaches can be found in literature. In this study’s population, patients with bronchiolitis were mainly infants aged less than 3 months with minimal physiological time constant, so an approach of high volume and low respiratory rate was not used. HFOV proved to be very efficient in patients with diffuse alveolar disease or with increased airway resistance and hyperinflation. Slee-Wijffels et al. reported a single-center experience, which included 17 patients with small airway disease who were successfully ventilated on HFOV.

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in the present study, they did not observe hemodynamic instability in their patients, and after transition to HFOV changes in vasoactive or inotropic support were not performed.\textsuperscript{22} In the present study, the overall survival rate was 83.8\%, higher than others reported in the literature (between 45\% and 75\%).\textsuperscript{21,24} This difference could be due to the variety of underlying diseases that led to HFOV, and also probably due to the early institution of this ventilatory strategy. Persistent hypoxemia at 48 hours of HFOV was associated with a poor prognosis. There were no other independent mortality factors.

The retrospective design and data collection were the major limitations of the present study. Patients were not randomly selected, and data were collected relying on nurses and medical records. Blood gases were mainly obtained from capillaries, thus oxygen partial pressure could not be calculated. A recently validated ratio in the pediatric population (Sat.O₂/FIO₂) was used to study improvements in oxygenation.\textsuperscript{14} This index is important for monitoring oxygenation in situations where PaO₂ is not obtained.

### Conclusion

HFOV is an efficient ventilation strategy in a variety of clinical settings, and it is associated with a rapid improvement in oxygenation and ventilation. Lung injury associated with alveolar disease or with increased airway resistance was safely treated with HFOV. Minimal complications and high survival rates contributed to the successful use of HFOV. It can be concluded that an approach using HFOV instead of aggressive CMV appears to be safe.

An adequate HFOV protocol remains important in order to avoid complications. Future randomized controlled trials comparing conventional ventilation and HFOV will be crucial to delineate the role of HFOV as an early strategy in lung recruitment.

### Conflicts of interest

The authors have no conflicts of interest to declare.

### References
