High-Frequency Jet Ventilation for Respiratory Failure After Congenital Heart Surgery

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Background. Extracorporeal membrane oxygenation (ECMO) is considered when respiratory failure (RF) persists despite increasing conventional mechanical ventilation (CMV). High-frequency jet ventilation (HFJV) can improve ventilation with comparable mean airway pressure (Paw) to that found on CMV. This study was undertaken to determine whether HFJV is an effective treatment and alternative to ECMO for RF after congenital heart surgery.

Methods and Results. HFJV was instituted in nine patients ranging in age from 6 days to 3.3 years with congenital heart disease meeting pulmonary criteria for ECMO. Indications for HFJV were pulmonary hypertension (six), adult-type respiratory distress syndrome (two), and pneumonitis (one). Seven patients (77%) were placed on HFJV within 24 hours of operation, and two patients required HFJV 2 weeks after operation. HFJV resulted in resolution of RF in eight of nine patients (89%). After 1 hour of HFJV, the arterial pH increased from 7.40±0.1 to 7.56±0.1 (p<0.05) and the PaCO₂ decreased from 44±15 to 29±12 mm Hg (p<0.05). During HFJV there was no change in PaO₂, although the FiO₂ decreased from 0.99±0.0 to 0.73±0.2 (p<0.05). There was no change in Paw, peak inspiratory pressures, positive end-expiratory pressures, heart rate, or mean arterial blood pressure during HFJV when compared with CMV. Mean duration of HFJV was 43 hours. Four patients were extubated and discharged from the hospital. Two patients were extubated but died from sepsis. Two patients had resolution of RF, but one died at reoperation and one from multisystem organ failure. The patient who failed HFJV therapy was placed on ECMO and died.

Conclusions. This study suggests that HFJV improves ventilation and is an alternative to ECMO in patients with RF after surgery for congenital heart disease. (Circulation 1992;86[suppl II]:II-127-II-132)

Key Words: ventilation, high-frequency jet, heart disease, congenital, hypertension, pulmonary, respiratory failure, oxygenation, children/infants

The majority of patients with normal lung compliance can be supported by conventional mechanical ventilation (CMV) after surgery for congenital heart disease. Respiratory failure after congenital heart surgery is a rare but potentially life-threatening occurrence. There are multiple causes of refractory respiratory failure in this population of patients, but the majority are related to pulmonary hypertensive crises and adult-type respiratory distress syndrome. CMV is the primary mode of support for patients with respiratory failure after surgery for congenital heart disease. However, high peak inspiratory pressures, positive end-expiratory pressures, and mean airway pressures (Paw) are often required to provide adequate oxygenation and ventilation in these patients. Although this may result in an improvement in oxygenation and ventilation, deleterious effects on cardiac function and barotrauma may result.1-3 When respiratory failure is refractory to CMV, mortality is high, and therapeutic options are limited. Currently, the only alternative therapy for refractory respiratory failure (RRF) is extracorporeal membrane oxygenation (ECMO). ECMO has been used to support patients with cardiopulmonary failure with variable success.4-9

Furthermore, institution of ECMO requires carotid artery ligation and systemic heparinization, both with potentially serious complications. High-frequency jet ventilation (HFJV) is a mode of ventilation that has the advantage of providing equivalent ventilation with similar or decreased Paw when compared with CMV.10-13 Its beneficial use in patients who have undergone the Fontan procedure has been documented.14 Short-term use in patients after cardiac surgery has also been reported.15-20 The purpose of this study was to prospectively determine whether HFJV is an effective treatment modality and an alternative to ECMO bypass for RRF after congenital heart surgery.

Methods

Patient Selection Criteria

HFJV was considered in all children who met institutional criteria for the initiation of ECMO after congenital heart surgery. The University of Michigan indications for the initiation of pediatric ECMO include both pulmonary and cardiac criteria (Table I).
Table 1. University of Michigan Criteria for Initiation of Extracorporeal Membrane Oxygenation

<table>
<thead>
<tr>
<th>Pulmonary criteria</th>
<th>Cardiac criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intrapulmonary shunt &gt;30%</td>
<td>Cardiac index &lt;2.0 l/min/m²</td>
</tr>
<tr>
<td>( \text{Pao}_2/\text{FiO}_2 ) &lt;100</td>
<td>Hypotension</td>
</tr>
<tr>
<td>Persistent hypoventilation ( \text{Paco}_2 &gt;45 )</td>
<td>Oliguria &lt;0.5 ml/kg/hr</td>
</tr>
<tr>
<td>Pulmonary hypertension</td>
<td>Persistent acidosis</td>
</tr>
<tr>
<td></td>
<td>Inability to wean from</td>
</tr>
<tr>
<td></td>
<td>cardiopulmonary bypass</td>
</tr>
</tbody>
</table>

Approval of the institutional review board and informed consent were obtained. All children were ventilated with CMV using the Siemens Servo 900C ventilator in either a volume-control or pressure-control mode. Continuous hemodynamic monitoring was performed using catheters placed intraoperatively. All patients were paralyzed, sedated using standard medications, and intubated with a Mallinckrodt triple-lumen endotracheal tube. High-frequency jet ventilation was then instituted using the Bunnell Life Pulse ventilator in tandem with the Siemens Servo 900C (Figure 1).

The initial HFJV settings consisted of a respiratory rate of 240–250 breaths per minute and an inspiratory time of 0.02 seconds. The peak inspiratory pressures and inspired oxygen concentration were set to similar values obtained while on CMV. The Servo 900C ventilator was adjusted to a respiratory rate of five per minute and a positive end-expiratory pressure similar to that on CMV.

Measurements

Peak inspiratory pressure and positive end-expiratory pressure were measured directly from the Siemens Servo 900C ventilator while on CMV and from the Bunnell Life Pulse ventilator while on HFJV. \( \text{P}_{aw} \) was measured at the exhalation port of the Siemens Servo 900C ventilator on CMV but measured at the distal tip of the Mallinckrodt endotracheal tube after initiation of HFJV (Figure 1). Arterial blood gas analysis was performed hourly in the immediate postoperative period until patients were stabilized, at which time analysis was performed every 4–6 hours. Heart rate and mean arterial blood pressure were measured from a pressure transducer connected to either a femoral or radial artery cannula.

Data Analysis

Statistical inference was made using multiple ANOVA. Comparisons were made between time periods 1 hour before HFJV and 1 hour, 6 hours, and final time period on HFJV.

Results

Study Patients

Using the pulmonary criteria outlined in Table 1, nine consecutive patients were placed on HFJV. The patients ranged in age from 6 days to 3.3 years (mean, 9±13 months). The study patient population is summarized in Table 2. Four of seven patients with cyanotic congenital heart disease underwent corrective surgery, and the other three patients had palliative operations performed. The two patients with acyanotic congenital heart disease had corrective surgery performed. All patients developed RRF and met institutional criteria for ECMO. Seven of the patients were placed on HFJV within 24 hours after operation, and two patients were placed on HFJV at 14 and 15 days after surgery. The indications for HFJV were pulmonary hypertension (six), adult-type respiratory distress syndrome (two), and pneumonitis (one). Pulmonary hypertension was diagnosed by Doppler echocardiography (three), pulmonary artery catheterization (two), and cardiac catheterization (one).

HFJV Data

The results are summarized in Table 3 as mean±1 SD at time periods before (3 hours and 1 hour) and after (1 hour, 6 hours, and final hour) institution of HFJV. These time periods were selected to be representative of the multiple measurements obtained during the course of assisted ventilation. The duration of HFJV ranged from 25 to 65 hours (mean, 43 hours). Comparisons were made between values on CMV 1 hour before HFJV and the time periods after institution of HFJV using multiple ANOVA and were reported as statistically significant with 95% confidence.

Respiratory alkalosis was achieved with the mean arterial pH significantly increasing from 7.40±0.1 on CMV 1 hour before HFJV compared with 7.56±0.1 1 hour after initiation of HFJV \( (p<0.05) \). Respiratory alkalosis continued during the course of HFJV (Figure 2). Alveolar ventilation improved significantly during the same time period, with the mean \( \text{Paco}_2 \) decreasing from 44±15 to 29±12 mm Hg \( (p<0.05) \). The mean \( \text{Pao}_2 \) remained low during the course of HFJV (Figure 3). There was no significant change in mean \( \text{Pao}_2 \) while on HFJV.

The mean concentration of inspired oxygen on CMV 1 hour before initiation of HFJV significantly decreased from 0.99±0.0 to 0.73±0.2 at the final measurement during HFJV \( (p<0.05) \). There was no significant decrease in the mean peak inspiratory pressure, positive

![Figure 1](image-url)
end-expiratory pressure, or $P_{aw}$ (Figure 4) during HFJV
when compared with CMV 1 hour before HFJV.

There was no significant change in mean heart rate or
mean arterial blood pressure during HFJV when
compared with CMV 1 hour before HFJV.

The outcome of patients placed on HFJV is
summarized in Table 4. There was rapid improvement
in ventilation with resolution of RRF after initiation of
HFJV in eight of nine patients (89%). RRF was
considered resolved in patients with pulmonary
hypertensive crises when hyperventilation and oxygenation
was achieved with significant reduction in pulmonary artery
pressure with subsequent weaning to potentially
extubatable ventilatory settings. For patients with adult-type
respiratory distress syndrome and pneumonitis, resolution
of RRF was considered present when normal
oxygenation and ventilation was achieved and subse-
quent reduction of respiratory support to potentially
extubatable ventilatory settings. Four patients were
extubated and discharged from the hospital. Two
patients were extubated but died late from sepsis 13 and
83 days after institution of HFJV. Two patients had
resolution of RRF but died. One died at reopera-
tion (fenestration of Fontan baffle) and the other had a
tracheostomy placed for tracheomalacia and chronic
lung disease and died 8 months later from multisystem
organ failure. The patient who did not respond to HFJV
after 90 hours was placed on ECMO for 9 days, devel-
oped an intracerebral hemorrhage, and died. There did
not appear to be a learning curve associated with the
use of HFJV because there was no improvement in
patient outcome with increasing experience with HFJV.

**Discussion**

CMV is the primary mode of support for respiratory
failure after surgery for congenital heart disease. CMV
improves ventilation, but deleterious effects on cardiac
function may result from high peak inspiratory pres-
ures, positive end-expiratory pressures, and $P_{aw}$. The
increased airway pressures exert a negative effect
on cardiac function that may be magnified in patients
who already have decreased function early after major
cardiac surgery. In addition, complex cardiopulmonary
interactions can occur in patients with congenital heart
disease. Death often ensues when respiratory failure is
refractory to CMV.

ECMO has been used in patients with cardiorespira-
tory failure after surgery for congenital heart disease
with variable success. In a recent retrospective
review of the international registry data on the use of ECMO

**Table 3. Arterial Blood Gas Analysis, Ventilator Settings, and Hemodynamic Assessment During High-Frequency Jet Ventilation**

<table>
<thead>
<tr>
<th></th>
<th>3 Hours before</th>
<th>1 Hour before</th>
<th>1 Hour after</th>
<th>6 Hours after</th>
<th>Final</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi$</td>
<td>9</td>
<td>9</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>pH</td>
<td>7.39±0.1</td>
<td>7.40±0.1</td>
<td>7.56±0.1*</td>
<td>7.56±0.1*</td>
<td>7.58±0.1*</td>
</tr>
<tr>
<td>$Paco_2$</td>
<td>43±15</td>
<td>44±15</td>
<td>29±12*</td>
<td>31±8*</td>
<td>27±9*</td>
</tr>
<tr>
<td>$PaO_2$</td>
<td>70±42</td>
<td>55±23</td>
<td>64±25</td>
<td>76±64</td>
<td>69±28</td>
</tr>
<tr>
<td>$HCO_3$</td>
<td>26±7</td>
<td>27±8</td>
<td>26±8</td>
<td>27±5</td>
<td>25±5</td>
</tr>
<tr>
<td>$FeO_2$</td>
<td>0.99±0.0</td>
<td>0.99±0.0</td>
<td>0.94±0.1</td>
<td>0.91±0.2</td>
<td>0.73±0.2*</td>
</tr>
<tr>
<td>PIP</td>
<td>34±8</td>
<td>35±7</td>
<td>33±7</td>
<td>32±6†</td>
<td>28±7†</td>
</tr>
<tr>
<td>PEEP</td>
<td>4±3</td>
<td>4±3</td>
<td>4±3†</td>
<td>5±2†</td>
<td>6±2†</td>
</tr>
<tr>
<td>$P_{aw}$</td>
<td>11±2</td>
<td>13±3</td>
<td>13±3</td>
<td>13±4†</td>
<td>11±3†</td>
</tr>
<tr>
<td>HR</td>
<td>161±24</td>
<td>159±17</td>
<td>166±24</td>
<td>158±26</td>
<td>150±36</td>
</tr>
<tr>
<td>MAP</td>
<td>52±11</td>
<td>65±20</td>
<td>64±20</td>
<td>57±7</td>
<td>66±22</td>
</tr>
</tbody>
</table>

Final, final measurement on high-frequency jet ventilation; HR, heart rate; MAP, mean arterial
blood pressure; $P_{aw}$, mean airway pressure; PEEP, positive end-expiratory pressure; PIP, peak inspiratory
pressure.

*$p<0.05$. †Measured at distal tip of Mallinckrodt endotracheal tube. Values are mean±SD.
for patients with congenital heart disease, the overall survival was 43\%. There was a variable response to ECMO based on the specific lesion, and mortality ranged from 39\% to 82\%. Complications occurred in 81\% of patients, and the frequency significantly correlated with outcome.

HFJV is defined as mechanical ventilation at rates greater than 150 breaths per minute. It provides effective ventilation using small tidal volumes (4–6 ml), which supports gas exchange at low airway pressures and has been used successfully in neonatal trials for respiratory distress syndrome and barotrauma. HFJV is a mode of ventilation that offers the potential benefits of providing improved ventilation at lower peak inspiratory pressures and similar or lower \( P_{AW} \) when compared with CMV. In addition, improved cardiopulmonary interactions may occur. However, its use in patients with congenital heart disease is limited, and there are currently no data concerning long-term use of HFJV in this patient population.

In an effort to improve the outcome of patients with cardiopulmonary failure while avoiding the potential complications of ECMO, we used HFJV prospectively in nine consecutive patients after surgery for congenital heart disease. The predominant indication for HFJV was pulmonary hypertension (67\%), followed by adult-type respiratory distress syndrome (22\%) and pneumonitis (11\%). Eight of the nine patients responded favorably to HFJV with improved ventilation. The single patient who did not respond to HFJV was placed on ECMO and died after 9 days secondary to an intracerebral hemorrhage.

Respiratory alkalosis resulted from the improved ventilation in response to HFJV that was maintained during the course of HFJV. The \( \text{Paco}_2 \) decreased from a mean of 44–29 mm Hg during this time period. In addition, the \( \text{Paco}_2 \) remained low during the course of HFJV even as the peak inspiratory pressure and \( P_{AW} \) were decreased. This improvement in ventilation was accomplished at peak inspiratory pressures, positive end-expiratory pressures, and \( P_{AW} \) similar to that on CMV.

It should be noted that these patients were managed under our respiratory failure protocol. This is different from our management strategy in patients with normal lung compliance and cardiac dysfunction. In patients with normal lung compliance and cardiac dysfunction, the airway pressures are transmitted directly to the cardiovascular system. The goal for these patients is to minimize the airway pressures in order to minimize their impact on the cardiovascular system while maintaining normal \( \text{Paco}_2 \). These patients typically have unimpaired alveolar ventilation. Patients with abnormal lung compliance and impaired alveolar ventilation with minimal cardiac dysfunction represent a different pathophysiological problem, and a different management strategy is used. In these patients, alveolar venti-
**Table 4. Outcome of Patients Placed on High-Frequency Jet Ventilation**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Diagnosis</th>
<th>Resp failure</th>
<th>HFJV time (hours)</th>
<th>Extubation</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>D-TGA, VSD, CoA</td>
<td>Resolved</td>
<td>51</td>
<td>Yes</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>2</td>
<td>TOF (conduit)</td>
<td>Resolved</td>
<td>25</td>
<td>Yes</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>3</td>
<td>Tricuspid atresia</td>
<td>Resolved</td>
<td>38</td>
<td>Yes</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>4</td>
<td>Pulm vein stenosis</td>
<td>Resolved</td>
<td>45</td>
<td>Yes</td>
<td>Discharged from hospital</td>
</tr>
<tr>
<td>5</td>
<td>D-TGA, AVSD</td>
<td>Resolved</td>
<td>66</td>
<td>Yes</td>
<td>Died late from sepsis</td>
</tr>
<tr>
<td>6</td>
<td>Cardiomyopathy</td>
<td>Resolved</td>
<td>27</td>
<td>Yes</td>
<td>Died late from sepsis</td>
</tr>
<tr>
<td>7</td>
<td>TOF (shunt)</td>
<td>Resolved</td>
<td>48</td>
<td>No</td>
<td>Died late from MOF</td>
</tr>
<tr>
<td>8</td>
<td>Pulm atresia</td>
<td>Resolved</td>
<td>45</td>
<td>No</td>
<td>Died at reoperation</td>
</tr>
<tr>
<td>9</td>
<td>Single ventricle</td>
<td>Persisted</td>
<td></td>
<td>No</td>
<td>Died on ECMO</td>
</tr>
</tbody>
</table>

ARDS, adult-type respiratory distress syndrome; AVSD, atrioventricular septal defect; CoA, coarctation of the aorta; D-TGA, D-transposition of the great arteries; ECMO, extracorporeal membrane oxygenation bypass; HFJV, high-frequency jet ventilation; MOF, multisystem organ failure; pulm, pulmonary; resp, respiratory; TOF, tetralogy of Fallot; VSD, ventricular septal defect.

The major limitation of this study is the lack of concurrent controls. Comparison with patients placed on ECMO is reasonable because both met similar criteria. Criteria for the initiation of ECMO are institution specific and predict a 90% mortality.6 The recent review of the ECMO registry data reported a 57% mortality while on ECMO for patients with congenital heart disease.7 Our institutional experience is similar. We report resolution of RRF in 89% of patients with the use of HFJV. Although our experience is limited, it appears that HFJV is an effective alternative treatment to ECMO in patients with RRF after surgery for congenital heart disease.

**Conclusions**

HFJV is useful in patients after surgery for congenital heart disease who develop respiratory failure refractory to CMV. We recommend that HFJV be considered as an alternative treatment modality to ECMO for patients with RRF after congenital heart surgery who meet the pulmonary criteria for the initiation of ECMO. In addition, further studies should be undertaken to evaluate the effectiveness of HFJV for other forms of respiratory failure.

**Acknowledgments**

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**References**


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