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 (P_{AW}) 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 $Paco_2$ decreased from 44±15 to 29±12 mm Hg ($p<0.05$). During HFJV there was no change in Pao_2, although the Fio_2 decreased from 0.99±0.0 to 0.73±0.2 ($p<0.05$). There was no change in P_{AW}, 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 (P_{AW}) 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.[1–5] 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.[6–9] 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 P_{AW} when compared with CMV.[10–15] Its beneficial use in patients who have undergone the Fontan procedure has been documented.[16] Short-term use in patients after cardiac surgery has also been reported.[17–20] 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.

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Presented at the 64th Scientific Session of the American Heart Association, Anaheim, Calif., November 11, 1991.

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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 1).

TABLE 1. University of Michigan Criteria for Initiation of Extracorporeal Membrane Oxygenation

Pulmonary criteria	Cardiac criteria
Intrapulmonary shunt >30%	Cardiac index <2.0 l/min/m^2
Pao_2/Fio_2 <100	Hypotension
Persistent hypoventilation ($Paco_2$ >45)	Oliguria <0.5 ml/kg/hr
Pulmonary hypertension	Persistent acidosis
	Inability to wean from cardiopulmonary bypass

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. 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.

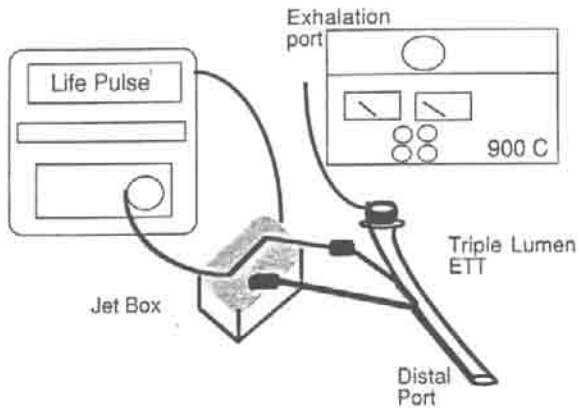

FIGURE 1. *Diagram illustrates the technique of high-frequency jet ventilation using the Bunnell Life Pulse ventilator in tandem with the Siemens Servo 900C ventilator. The triple-lumen Mallinckrodt endotracheal tube (ETT) is shown. Also demonstrated is the exhalation port on the Siemens ventilator where mean airway pressure is measured while on conventional mechanical ventilation.*

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 catheter measurement (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 $Paco_2$ decreasing from 44±15 to 29±12 mm Hg ($p<0.05$). The mean $Paco_2$ remained low during the course of HFJV (Figure 3). There was no significant change in mean 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

TABLE 2. Patients Placed on High-Frequency Jet Ventilation

Patient	Age (months)	Diagnosis	Surgery	Indication
1	0.2	D-TGA, VSD, CoA	Arterial switch	Pulmonary hypertension
2	0.4	TOF, AVSD	Shunt	Pulmonary hypertension
3	0.8	Cardiomyopathy	Transplantation	Pulmonary hypertension
4	3.2	TOF, absent pulm valve	Conduit repair	Pulmonary hypertension
5	4.0	Pulm vein stenosis	Pulmonary venorraphy	Pulmonary hypertension
6	22.0	Pulm atresia	Fontan	Pulmonary hypertension
7	9.9	Single ventricle	Damus-Kaye-Stansel	ARDS
8	39.0	D-TGA, AVSD	Fontan	ARDS
9	0.6	Tricuspid atresia	Shunt	Pneumonitis

ARDS, adult-type respiratory distress syndrome; AVSD, atrioventricular septal defect; CoA, coarctation of the aorta; D-TGA, D-transposition of the great arteries; pulm, pulmonary; VSD, ventricular septal defect; TOF, tetralogy of Fallot.

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 subsequent 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 reoperation (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, developed 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 pressures, positive end-expiratory pressures, and P_{AW}.[1-5] 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.[1,16] Death often ensues when respiratory failure is refractory to CMV.

ECMO has been used in patients with cardiorespiratory failure after surgery for congenital heart disease with variable success.[7-9] 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

	3 Hours before	1 Hour before	1 Hour after	6 Hours after	Final
n	9	9	8	8	8
pH	7.39±0.1	7.40±0.1	7.56±0.1*	7.56±0.1*	7.58±0.1*
P_{aCO_2}	43±15	44±15	29±12*	31±8*	27±9*
P_{aO_2}	70±42	55±23	64±25	76±64	69±28
HCO_3	26±7	27±8	26±8	27±5	25±5
F_{IO_2}	0.99±0.0	0.99±0.0	0.94±0.1	0.91±0.2	0.73±0.2*
PIP	34±8	35±7	33±7†	32±6†	28±7†
PEEP	4±3	4±3	4±3†	5±2†	6±2†
P_{AW}	11±2	13±3	13±3†	13±4†	11±3†
HR	161±24	159±17	166±24	158±26	150±36
MAP	52±11	65±20	64±20	57±7	66±22

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.

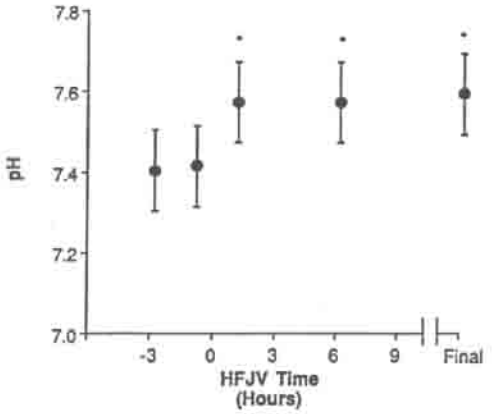

FIGURE 2. *Graph illustrates mean arterial pH±1 SD 3 hours and 1 hour before high-frequency jet ventilation (HFJV) and 1 hour and 6 hours after initiation of HFJV. Also shown is the final mean value measured during HFJV before conversion back to conventional mechanical ventilation.* *$p<0.05$ *1 hour before HFJV vs. 1 hour, 6 hours, and final measurement during HFJV.*

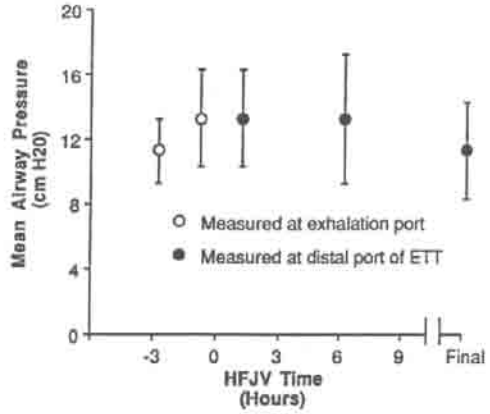

FIGURE 4. *Graph illustrates mean airway pressure measured at the exhalation port of the Siemens ventilator during conventional mechanical ventilation (open circles) and at the distal tip of the Mallinckrodt endotracheal tube (ETT) during high-frequency jet ventilation (HFJV) (closed circles). Data shown are the mean±1 SD 3 hours and 1 hour before HFJV and 1 hour and 6 hours after initiation of HFJV. Also shown is the final mean value measured during HFJV before conversion back to conventional mechanical ventilation.*

for patients with congenital heart disease, the overall survival was 43%.[9] 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.[10] 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.[11–13] 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.[10–12] In addition, improved cardiopulmonary interactions may occur.[16] However, its use in patients with congenital heart disease is limited, and

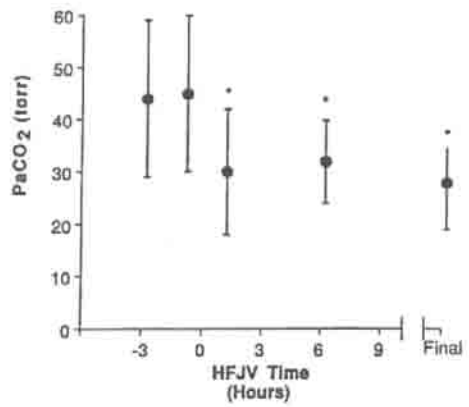

FIGURE 3. *Graph illustrates mean partial pressure of carbon dioxide in arterial blood ±1 SD 3 hours and 1 hour before high-frequency jet ventilation (HFJV) and 1 hour and 6 hours after initiation of HFJV. Also shown is the final mean value measured during HFJV before conversion back to conventional mechanical ventilation.* *$p<0.05$ *1 hour before HFJV vs. 1 hour, 6 hours, and final measurement during HFJV.*

there are currently no data concerning long-term use of HFJV in this patient population.[17–19]

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 $Paco_2$ decreased from a mean of 44–29 mm Hg during this time period. In addition, the $Paco_2$ 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 $Paco_2$. 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

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

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; MSOF, multisystem organ failure; pulm, pulmonary; resp, respiratory; TOF, tetralogy of Fallot; VSD, ventricular septal defect.

lation is increased by increasing ventilatory support. When CMV is unsuccessful in improving alveolar ventilation, HFJV is then used. HFJV was successful in improving alveolar ventilation when airway pressures were matched to those on CMV. No attempt to decrease airway pressures is begun until respiratory failure resolves as evident by excessive hyperventilation (pH >7.55 and $Paco_2$ <20). As lung compliance improves, HFJV is weaned by decreasing airway pressures, and conversion to CMV is accomplished.

Oxygenation improved significantly in our patients during the course of HFJV and allowed a significant decrease in the mean concentration of inspired oxygen from 0.99 before HFJV to 0.73 at the end of HFJV. There was no significant change in the mean Pao_2 in our population, as would be expected due to the combination of residual cyanotic and acyanotic lesions present.

It should be noted that although there was no significant decrease in the mean P_{AW} during HFJV, the method of obtaining this parameter differs for the two modes of ventilation. The P_{AW} is measured at the exhalation port of the Siemens Servo 900C, whereas it is measured at the distal end of the Mallinckrodt endotracheal tube while on HFJV (Figure 1). Preliminary data from an ongoing study at our institution reveal that the P_{AW} is approximately 15% less when measured at the exhalation port rather than at the distal end of the endotracheal tube. Although not documented in our patients, this may translate into improved ventilation at a decreased P_{AW}.

Hemodynamically, there was no change in the mean heart rate or mean arterial blood pressure. This could be expected because of the improvement in ventilation without elevation of airway pressures. Unfortunately, objective measures of cardiac output were not performed.

The only complication to occur during HFJV was development of a pneumothorax in one patient after 9 hours of HFJV. This was successfully treated with placement of a chest tube. This is in contrast to the many reported complications that occur in patients placed on ECMO after surgery for congenital heart disease.[9] Although necrotizing tracheitis has been reported during HFJV,[13,21] this was not seen in our patients at autopsy.

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[9]: 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

The authors are indebted to Huhta Rosen, RRT, Kenneth Bandy, RRT, and the pediatric cardiothoracic intensive care nurses.

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