

High-Frequency Jet Ventilation in Children With the Adult Respiratory Distress Syndrome Complicated by Pulmonary Barotrauma

David W. Smith, MChB, Lorry R. Frankel, MD, Melinda T. Derish, MD, Robert R. Moody, MD, Lehman E. Black III, MD, Bradley E. Chipps, MD, and Lawrence H. Mathers, MD

Summary. High-frequency jet ventilation (HFJV) was used in 29 children with severe ARDS complicated by pulmonary barotrauma (PBT). Treatment with HFJV was begun when PBT was progressing over a 24-h period while receiving conventional ventilation (CV). The mean (\pm SD) age was 0.95 ± 1.21 years (range, 0.03-4 years). The most common diagnosis was viral pneumonia ($n = 17$); other diagnoses included aspiration pneumonitis ($n = 4$), bacterial pneumonia ($n = 3$), multiple trauma ($n = 2$), and near-drowning ($n = 3$). The Bunnell Life-Pulse ventilator was used at a rate of 240/min or 300/min, with inspiratory time of 0.02 sec. Twenty children survived (69%). Survivors and nonsurvivors had equal disease severity prior to HFJV as assessed by ventilator settings, alveolar-to-arterial oxygen tension gradient, oxygenation index, and blood gas values. Survivors had spent significantly less time on conventional ventilation prior to HFJV than nonsurvivors, with a mean (\pm SD) of 3.7 ± 2.1 days vs 9.6 ± 4.5 days, respectively ($P < 0.05$). Survivors underwent an average of 4.4 ± 3.9 days of HFJV, which supported adequate gas exchange with lower airway pressures, and produced resolution or significant improvement in airleak on chest radiograph. In conclusion, we speculate that the application of HFJV early in the course of severe hypoxemic respiratory failure complicated by airleak, allows the reduction of airway pressures, thereby minimizing pulmonary barotrauma and allowing the lung to recover from the underlying insult. Further controlled evaluation of HFJV in this high risk group of patients is warranted. *Pediatr Pulmonol.* 1993; 15:279-286. © 1993 Wiley-Liss, Inc.

Key words: Disease severity; survivors vs. nonsurvivors; days on conventional vs. HFJV.

INTRODUCTION

The adult respiratory distress syndrome (ARDS) in children is frequently complicated by pulmonary barotrauma (PBT) with an incidence of approximately 50%.^{1,2} In adults the high peak airway pressures needed are most commonly implicated as causing PBT.³⁻⁷ Recent clinical and laboratory evidence indicates that limiting the peak transalveolar pressure gradient may minimize or prevent ventilator-associated lung injury.⁸ High frequency jet ventilation (HFJV) is a technique of ventilatory support which may provide adequate or improved gas exchange while requiring lower airway pressures than conventional ventilation (CV).⁹

A recently completed randomized controlled trial of HFJV in the management of pulmonary interstitial emphysema (PIE) in preterm neonates showed a significant improvement in PIE and a significantly lower mortality rate, for infants treated with HFJV compared to CV.¹⁰ While there have been no such controlled trials in children beyond the neonatal period, the use of high-frequency ventilation in a series of 10 children with severe ARDS has been reported by Wetzel and Gioia.¹¹

The purpose of this report is to describe our experience with HFJV in 29 children with severe ARDS complicated by PBT that was progressing while receiving CV.

MATERIALS AND METHODS

Patients

The study group consisted of 29 (mean \pm SD age, 0.95 ± 1.21 years; range, 0.03-4.0 years) children with a clinical diagnosis of ARDS (diffuse alveolar disease with hypoxemia). Treatment with HFJV was begun when ARDS was complicated by PBT that was progressing over a 24-hr period while receiving CV. Pulmonary

From the Departments of Pediatrics, Sutter Memorial Hospital, Sacramento, and Stanford University Medical Center, Stanford, California.

Received March 25, 1991; (revision) accepted for publication October 27, 1992.

Address correspondence and reprint requests to Dr. D.W. Smith, Pediatric Intensive Care Unit, Sutter Memorial Hospital, 52nd and F Streets, Sacramento, CA 95819.

barotrauma was diagnosed and followed by radiologists interpreting anteroposterior radiographs of the chest (CXR). Types of PBT included pulmonary interstitial emphysema, pneumothorax, pneumomediastinum, pneumoperitoneum, and bronchopleural fistula. Patients who developed PBT with thoracic trauma, following placement of a central venous catheter, or with PBT complicating asthma or bronchiolitis were excluded.

The study was conducted in the Pediatric Intensive Care Units of Sutter Memorial Hospital, Sacramento, California, and Stanford University Hospital, Stanford, California, from December 1987 to May 1992. All patients meeting the above study criteria were enrolled. Informed consent was obtained from the parent(s) prior to the approval of the high-frequency jet ventilator by the Food and Drug Administration of the United States in 1988.

Ventilator System

The patients were reintubated with an appropriately sized triple-lumen endotracheal tube (Mallinckrodt Inc., Argyle, NY) permitting CV, HFJV and distal tracheal pressure monitoring. Prior to beginning HFJV, diagnostic fiberoptic bronchoscopy was performed in 10 patients for bronchoalveolar lavage, and open lung biopsy was performed in 2 patients. HFJV was then begun utilizing the Bunnell Life Pulse HFJV device (Bunnell Inc., Salt Lake City, UT). This is a microprocessor controlled, time-cycled, pressure-limited ventilator.¹² An electronically controlled pinch valve regulates the inflow jet of gas from a pressure reservoir. The inflow jet gas passes through the "jet lumen" of the endotracheal tube, and exits into the airway 7 cm from the tip. Positive end-expiratory pressure, and intermittent "sigh" breaths were provided by a conventional ventilator (Sechrist Industries, Anaheim, CA) connected in parallel through the principal lumen of the endotracheal tube. A third lumen exiting at the tip of the endotracheal tube permits monitoring of distal tracheal pressure by the pressure transducer of the ventilator. The circuits of both the conventional ventilator and HFJV ventilator are humidified.

Ventilator Strategy

HFJV was provided at a rate of 240 or 300 breaths per minute, with an inspiratory time of 0.02 second. The inspiratory time was increased to 0.03 second if necessary, to allow the ventilator to reach the desired peak inspiratory pressure (PIP). Although recent reports^{10,13} have described the use of the Bunnell HFJV device at rates of 400–500 breaths/min in neonates, we used the device at a lower rate, and with the shortest possible inspiratory time, to provide the longest possible expiratory time. This strategy seemed reasonable because the longer respiratory system time constant in children beyond the newborn period makes gas-trapping during

HFJV more likely.⁸ In addition, our early experience with HFJV in older children suggested little if any improvement in ventilation at rates exceeding 300/min. Positive end-expiratory pressure (PEEP) was continued at the same level as that used on CV prior to HFJV. The initial PIP utilized was approximately 75% of the peak tracheal pressure measured during CV just prior to changing to HFJV. Peak inspiratory pressure and mean airway pressure (MAP) were subsequently adjusted to achieve adequate gas exchange, maintaining a P_{aO_2} of approximately 60 torr (Sa_{O_2} of 90%), and a P_{aCO_2} of 40–60 torr. Control of P_{aCO_2} was achieved by changes in pulmonary distending pressure (PIP-PEEP). Control of P_{aO_2} was achieved by changes in Fi_{O_2} and MAP. The ventilator strategy aimed to minimize airway pressures because of the severity and progression of PBT. The Fi_{O_2} was kept high (≥ 0.6) in the first 48 hr of HFJV, while PIP and PEEP were lowered in an attempt to improve PBT.

Atelectasis has been reported to occur if only HFJV is provided.¹³ Accordingly, a "sigh" rate of 6 breaths/min was used, with the PIP of the "sigh" breath approximately 5 cm H_2O below that of the PIP of the HFJV breaths, using an inspiratory time of 0.5 second, as recently described.¹³ Using this strategy, the HFJV breaths are superimposed on the conventional ventilator breath, and a "sigh" with higher PIP results.

Patient Monitoring

During CV, measurements of airway pressures were made at the endotracheal tube adapter at the airway opening, with data recorded from the ventilator monitor or a free-standing monitor of airway pressures. During HFJV, measurements of airway pressures were made in the trachea by the pressure monitor of the HFJV device, which has a digital display of PIP, PEEP, and MAP. We have tested the frequency response of this system using the method described by Jackson et al. Measured pressure was found to be within 2% of true pressure to a frequency of 20 Hz.¹⁴ This frequency response is adequate for the purposes of this study with ventilator rates of 4–5 Hz.

Arterial blood gas samples were obtained frequently after beginning HFJV, while initial adjustments in ventilator settings were made and after that at least every 4 hr until the patient stabilized. The alveolar-to-arterial oxygen tension gradient [$P_{(A-a)O_2}$] was calculated according to a standard formula with $P_{A_{O_2}} = P_{i_{O_2}} - P_{A_{CO_2}}/R$, where R is assumed to equal 0.8. The oxygenation index (OI) was calculated as $Fi_{O_2} \times MAP/P_{a_{O_2}}$. Continuous monitoring of oxyhemoglobin saturation was performed in all patients using pulse-oximetry. Continuous monitoring of transcutaneous CO_2 tension was performed in most patients.

A chest radiograph was obtained following reintubation prior to HFJV, again within 1 hr of beginning HFJV, and at least once daily while on HFJV. All patients were

monitored continuously for heart rate, and arterial and central venous pressures. Inotropic support with dopamine hydrochloride or dobutamine hydrochloride was used, if necessary, in order to maintain arterial pressure, urine output and skin perfusion. Patients were sedated and paralyzed while receiving HFJV. Flexible fiberoptic bronchoscopy was performed to assess the possibility of tracheal or airway injury following HFJV in 16 of the 20 survivors, and during the course of HFJV in 5 of the 9 nonsurvivors. Post-mortem examination of airways and lungs was performed in 5 nonsurvivors.

Data Analysis

Statistical methods used to evaluate the data included Student's *t* test, analysis of variance with repeated measures (ANOVA), and the Fisher exact test, as appropriate. Analysis prior to beginning HFJV was made using ANOVA with data from 24 and 2 hr prior to beginning HFJV. Analysis after beginning HFJV was made using ANOVA with data from 6, 12, 24, and 48 hr after beginning HFJV.

RESULTS

Of the 29 children who underwent HFJV, 21 were previously healthy and 8 had an underlying medical problem. Three children were born prematurely. Other underlying medical problems included previous repair of a tracheoesophageal fistula, repair of an atrioventricular canal defect, cystic fibrosis, chronic cholestasis, and α_1 -antitrypsin deficiency. The cause of acute respiratory failure was viral pneumonia (or suspected viral pneumonia) in 17 children. Other diagnoses included aspiration pneumonitis ($n = 4$), bacterial pneumonia ($n = 3$), multiple trauma ($n = 2$), and near-drowning ($n = 3$).

Types of PBT prior to beginning HFJV included pulmonary interstitial emphysema ($n = 24$), pneumothorax ($n = 15$), pneumomediastinum ($n = 10$), pneumoperitoneum ($n = 6$), and pneumopericardium ($n = 1$).

Twenty of the 29 children survived (69%). The mean (\pm SD) age of the survivors was 0.9 ± 1.2 years (range, 0.03–4 years) and of the nonsurvivors was 1.0 ± 1.3 years (range, 0.1–3.7 years). The mode of death was cardiorespiratory failure in all cases. There was no significant difference between survivors and nonsurvivors in the incidence of underlying medical problems; 5 of 20 survivors were so compromised, compared to 3 of 9 nonsurvivors. Eight of the 9 nonsurvivors had viral pneumonia as the cause of acute respiratory failure. The remaining patient was multiply traumatized. Nine of the 20 survivors had viral pneumonia as the cause of acute respiratory failure. All patients with aspiration, near-drowning and bacterial pneumonia survived. Viral pneumonia was significantly more frequent as the cause of acute

TABLE 1—Ventilator Settings, Blood Gas, and Derived Values (Mean \pm SD) 2 hr Prior to Beginning HFJV

	Survivors ($n = 20$) ^a	Nonsurvivors ($n = 9$)
PIP (cm H ₂ O)	47.8 \pm 10.6	49.9 \pm 9.0
MAP (cm H ₂ O)	22.5 \pm 5.0	22.8 \pm 5.0
PEEP (cm H ₂ O)	9.0 \pm 2.3	9.7 \pm 4.4
FiO ₂	0.91 \pm 0.15	0.96 \pm 0.08
PaO ₂ (mm Hg)	80 \pm 37	79 \pm 78
PaCO ₂ (mm Hg)	45 \pm 12	46 \pm 13
P _{i(A-a)O₂} (mm Hg)	515 \pm 120	548 \pm 126
OI	31.1 \pm 16.3	41.6 \pm 18.1

PIP, peak inspiratory pressure; MAP, mean airway pressure; PEEP, positive end-expiratory pressure; PaO₂, PaCO₂, arterial blood gas tensions; OI, oxygenation index.

^aNo statistically significant differences.

respiratory failure in nonsurvivors compared to survivors ($P < 0.05$, Fisher exact test).

The mean (\pm SD) duration of CV prior to HFJV for survivors was significantly shorter at 3.7 ± 2.1 days (range, 1.5–7.5 days), compared to 9.6 ± 4.1 days (range, 5–18 days) for nonsurvivors ($P < 0.05$). The mean (\pm SD) duration of HFJV was 4.4 ± 3.9 days (range, 1.4–18.8 days) for survivors, and 7.3 ± 5.6 days (range, 2–16 days) for nonsurvivors ($P < 0.05$). Survivors required a mean (\pm SD) of 8.3 ± 6.7 days (range, 2.1–18 days) of conventional ventilator support after HFJV was discontinued. Supplemental oxygen was required at the time of discharge in 2 patients, for 40 and 95 days. Both infants had been born prematurely, and underwent a total of 23 and 41 days of mechanical ventilatory support, respectively.

There were no significant differences between survivors and nonsurvivors in any of the ventilator settings, blood gas values, or derived values, 2 hours prior to beginning HFJV (Table 1). Data from the ventilator course more than 2 hr prior to beginning HFJV were available for 23 of the 29 children, and are presented in Figures 1–3 (the remaining 6 children had been transported from other institutions and data from the ventilatory history could not be recovered). These figures present data from 72, 48, 24, and 2 hr before, and 6, 12, 24, 48, and 72 hr after, beginning HFJV.

Analysis of variance testing of data from 24 and 2 hr prior to HFJV did not reveal any significant differences between survivors and nonsurvivors (Figs. 1–3). However, statistically significant increases in PEEP, FiO₂, OI, and in P_{i(A-a)O₂} were observed over this same time interval when data from survivors and nonsurvivors were combined ($P < 0.001$ in each case).

The frequency of survival based on airway pressure data and on derived variables immediately prior to beginning HFJV is presented in Tables 2 and 3, respectively. There were no statistically significant differences in fre-

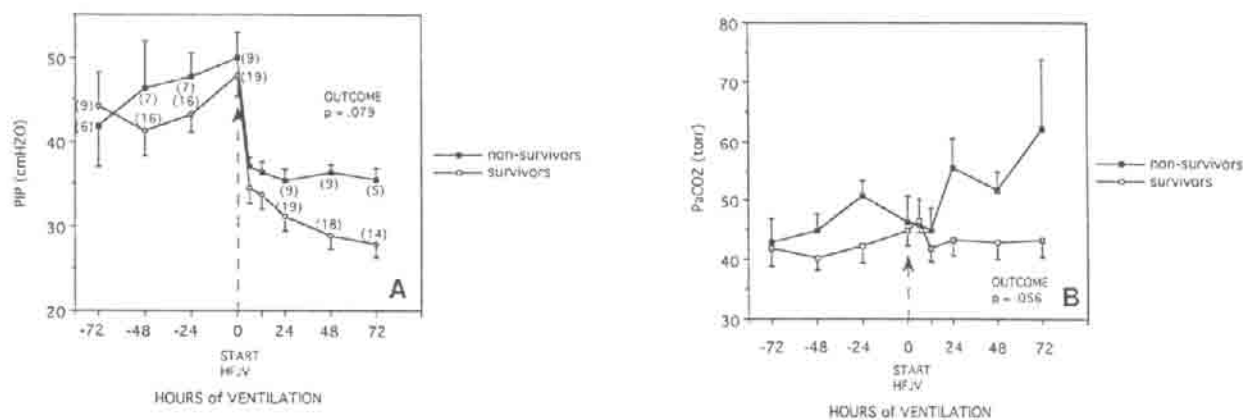


Fig. 1. Changes in PIP (A) and P_{aCO_2} (B) during 72 hr before and after beginning HFJV for survivors and nonsurvivors. Vertical bars indicate SEM. *P* values indicate comparison by ANOVA of difference between survivors and nonsurvivors between 6 and 48 hr after beginning HFJV. Parentheses in A show numbers of

frequency of survival among any of the groups identified in Tables 2 or 3.

Statistically significant differences between survivors and nonsurvivors were observed after beginning HFJV for MAP ($P = 0.003$), PEEP ($P = 0.01$), and OI ($P = 0.001$). For the group as a whole (survivors plus nonsurvivors), significant decreases in PIP ($P = 0.007$), MAP ($P = 0.005$), $P_{(A-a)O_2}$ ($P = 0.001$), and FiO_2 ($P = 0.001$) were observed.

After 48 hr of HFJV, levels of ventilator support could be identified which statistically differentiated children who ultimately survived from those who did not survive (Table 4).

After 48 hr of HFJV 17 of the 20 survivors had resolved or improved the airleak on the CXR, while only 3 of the 9 nonsurvivors demonstrated an improvement ($P < 0.05$). Five children developed new airleak during the first 72 hr of HFJV; 3 of the 9 nonsurvivors, and 2 of the 20 survivors. The difference in incidence was not statistically significant.

High-frequency jet ventilation was discontinued and CV was resumed when PIP was reduced to approximately 25 cm H₂O, and the chest radiograph demonstrated resolution or significant improvement in PBT. Two patients developed profuse airway secretions confirmed by fiberoptic bronchoscopy associated with an acute clinical deterioration. This occurred following substantial improvement in gas exchange and in the appearance of PBT on CXR. In both patients HFJV was discontinued with the rationale that profuse airway secretions could lead to airways obstruction and possibly worsening gas exchange given the short expiratory time used during HFJV. Both patients survived. No episodes of malfunction of the HFJV device or the humidification system occurred during the study. In two patients, a leak devel-

oped in the endotracheal tube at the point at which the jet lumen entered the main lumen. The endotracheal tube was replaced uneventfully in both cases.

There was no significant change in cardiovascular status following the change from CV to HFJV, despite a reduction in the mean (\pm SD) MAP from 22.6 ± 4.9 to 17.5 ± 5.0 cm H₂O. Values were averaged for a minimum of 2 hr and a maximum of 6 hr before HFJV, and for 6 hr after beginning HFJV. The mean (\pm SD) heart rate was 154 ± 19 beats/min before and 153 ± 19 beats/min after beginning HFJV. The mean (\pm SD) mean arterial pressure was 73 ± 10 mm Hg before and 73 ± 11 mm Hg after beginning HFJV. The mean (\pm SD) CVP was 6.5 ± 3.6 mm Hg before and 6.6 ± 3.5 mm Hg after beginning HFJV, in the 16 patients with central venous catheters in place prior to beginning HFJV. Sixteen children received inotropic support with dopamine hydrochloride prior to HFJV, with a mean (\pm SD) dose of 7.0 ± 3.1 μ g/kg/min. Seventeen children received inotropic support with dopamine hydrochloride once HFJV was begun, and the mean (\pm SD) dose was 6.5 ± 2.9 μ g/kg/min. Three children received inotropic support with dobutamine hydrochloride prior to, and after beginning, HFJV, with a mean (\pm SD) dose of 11.3 ± 1.2 μ g/kg/min and 9.3 ± 3.1 μ g/kg/min, respectively. There were no differences between survivors and nonsurvivors in average heart rate, mean arterial pressure or CVP, before or after beginning HFJV. There were no differences between survivors and nonsurvivors in the frequency of use of, or the mean dose of dopamine hydrochloride or dobutamine hydrochloride before or after beginning HFJV.

Flexible fiberoptic bronchoscopy was performed within 48 hr of completion of HFJV in 16 of the 20 survivors. There was no evidence for necrotizing tracheo-

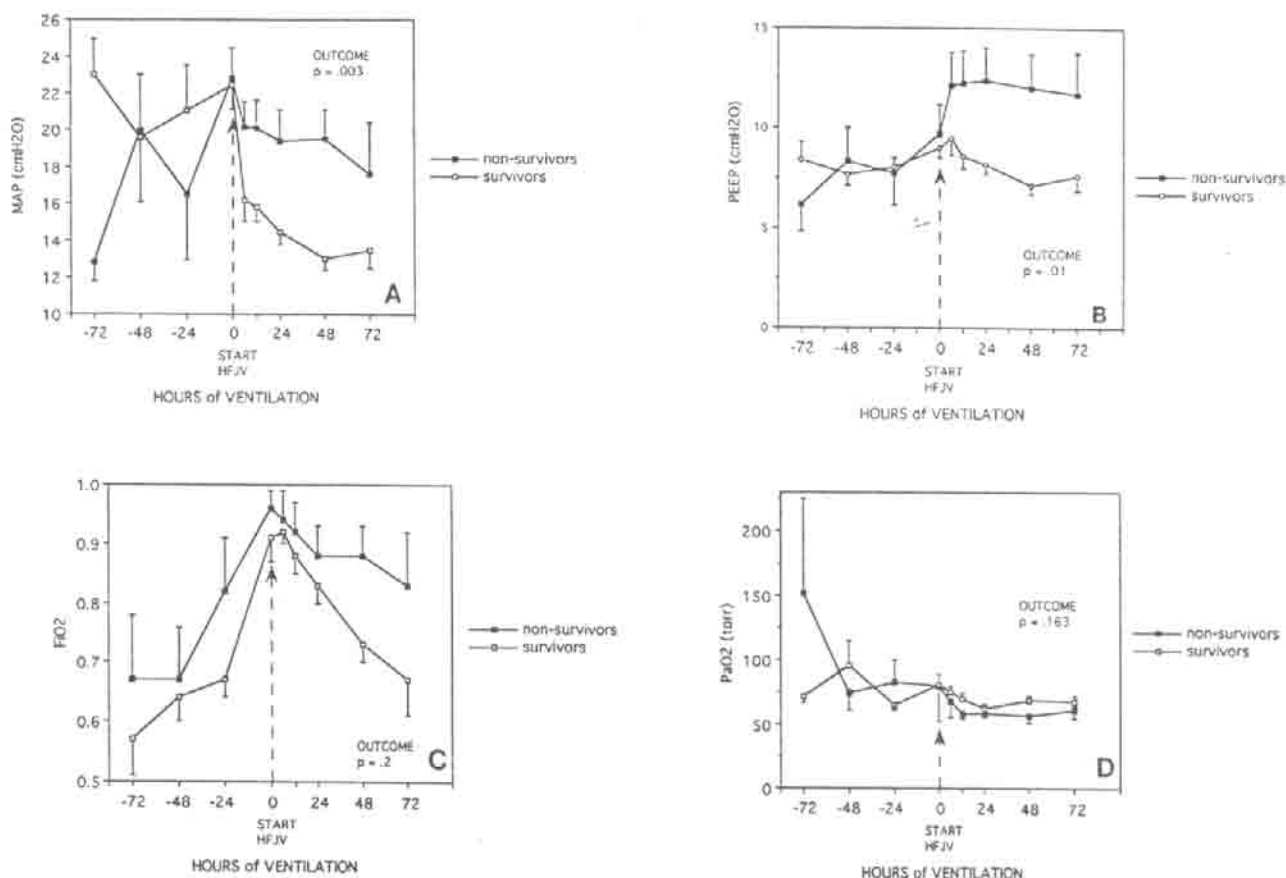


Fig. 2. Changes in MAP (A), PEEP (B), F_{iO_2} (C), and Pa_{O_2} (D) during 72 hr before and after beginning HFJV for survivors and nonsurvivors. Vertical bars indicate SEM. *P* values indicate comparison by ANOVA of difference between survivors and nonsurvivors between 6 and 48 hr after beginning HFJV. Time 0 refers to data on conventional ventilation immediately prior to

beginning HFJV. Number of subjects at each time point as in Figure 1. MAP, mean airway pressure; PEEP, positive end-expiratory pressure; F_{iO_2} , fractional concentration of inspired oxygen; Pa_{O_2} , partial pressure of arterial oxygen; HFJV, high-frequency jet ventilation.

bronchitis in any patient. Flexible fiberoptic bronchoscopy was performed during the course of HFJV in 5 of the 9 nonsurvivors, and no evidence of necrotizing tracheobronchitis was found.

Three of the nonsurvivors had developed diffuse microcystic changes on CXR prior to beginning HFJV. These 3 patients had spent an average of 13 days on CV prior to HFJV, with $F_{iO_2} \geq 0.6$, and $PIP \geq 50$ cm H₂O. An open lung biopsy in one of these three patients prior to beginning HFJV confirmed severe parenchymal injury with microcystic changes. Autopsies in all 3 cases revealed end-stage "honeycomb lung." It is unlikely that HFJV (or any other form of support) would have benefited patients with such advanced parenchymal injury.

Autopsies were performed in 5 of the 9 nonsurvivors. Severe parenchymal lung damage was confirmed in all patients, with the etiologic agent confirmed in two cases (adenovirus and parainfluenza virus). In one patient who underwent 11 days of HFJV, there was acute and chronic

injury to the mucosa of the airways, with prominent granulation tissue, denudation of mucosa and near occlusion of some peripheral airways. Surrounding a femoral venous catheter, a large thrombus of the inferior vena cava was identified and multiple thromboemboli (presumably catheter-related) were noted to have caused infarction of approximately 50% of the pulmonary parenchyma.

DISCUSSION

The use of high-frequency ventilation in the management of a series of 10 children with severe ARDS has been reported by Wetzel and Gioia.¹¹ Three of the 10 children survived, and displayed progressive improvement in oxygenation following the initiation of HFJV. The incidence and progression of airleak was not mentioned in this report. The incidence of PBT during mechanical ventilation in children has been reported by Pol-

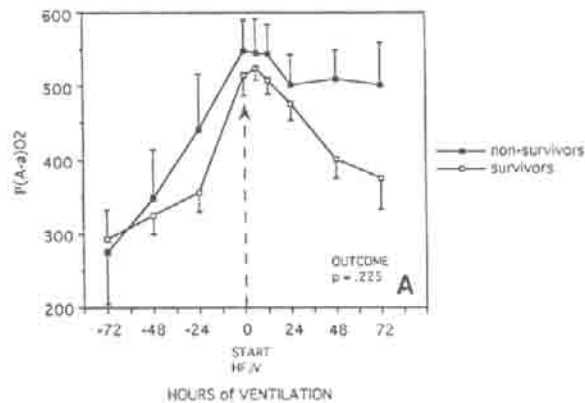
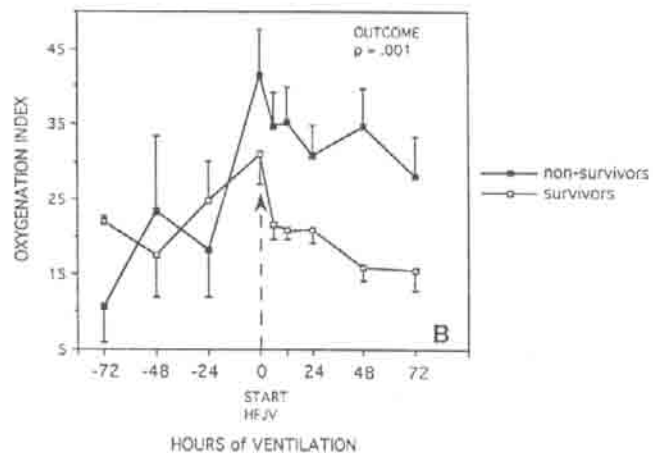


Fig. 3. Changes in $P_{(A-a)O_2}$ (A) and OI (B) during 72 hr before and after beginning HFJV for survivors and nonsurvivors. Vertical bars indicate SEM. *P* values indicate comparison by ANOVA of difference between survivors and nonsurvivors between 6 and 48 hr after beginning HFJV. Time 0 refers to data on conven-



tional ventilation immediately prior to beginning HFJV. Number of subjects at each time point as in Figure 1. $P_{(A-a)O_2}$, alveolar-to-arterial tension gradient for oxygen; OI, oxygenation index; HFJV, high-frequency jet ventilation.

TABLE 2—Survival by Airway Pressures (cm H₂O) Prior to Beginning HFJV, *n* = 28^a

	Total	Survivors	% Survival
PIP ≤40	3	3	100
PIP 40–45	6	4	67
PIP 45–50	9	5	56
PIP ≥50	10	7	70
MAP ≤20	11	8	73
MAP 20–25	7	5	71
MAP 25–30	9	5	56
MAP ≥30	1	1	100

^aData prior to HFJV missing for 1 survivor. HFJV, high-frequency jet ventilation; PIP, peak inspiratory pressure; MAP, mean airway pressure.

TABLE 3—Survival by Oxygenation Index and $P_{(A-a)O_2}$ Prior to HFJV, *n* = 28^a

	Total (<i>n</i>)	Survivors (<i>n</i>)	% Survival
OI ≤20	4	3	75
OI 20–30	10	9	90
OI 30–40	3	2	67
OI ≥40	11	5	45
$P_{(A-a)O_2}$ ≤400	4	3	75
$P_{(A-a)O_2}$ 400–500	3	2	67
$P_{(A-a)O_2}$ 500–600	14	11	79
$P_{(A-a)O_2}$ ≥600	7	3	43

^aData prior to HFJV missing for 1 survivor. HFJV, high-frequency jet ventilation; OI, oxygenation index; $P_{(A-a)O_2}$, alveolar-arterial oxygen tension gradient (mm Hg).

lack et al.¹⁵ In a group of 14 patients requiring high PEEP (greater than 15 cm H₂O), there was a 64% incidence of PBT, and 6 of these 9 patients died. Except for the young infants who had intraoperative pulmonary trauma (cardiovascular surgery), the only children who developed

TABLE 4—Survival by Airway Pressures (cm H₂O) and Oxygenation Index After 48 hr of HFJV (*n* = 29)

	Survivors (<i>n</i> = 20)	Nonsurvivors (<i>n</i> = 9)	% Survival
PIP ≥35	2*	5	29
MAP ≥17	1*	6	14
PEEP ≥10	1*	5	17
OI ≥25	2*	5	29

HFJV, high-frequency jet ventilation; PIP, peak inspiratory pressure; MAP, mean airway pressure; PEEP, positive end-expiratory pressure (values in cm H₂O); OI, oxygenation index. **P* ≤ 0.05 for incidence compared to nonsurvivors.

PBT had severe pulmonary disease. Pollack et al. did not describe PIE in their series. Although PIE is most frequently described as a complication of hyaline membrane disease in preterm infants, it has also been reported in adults with ARDS,^{16,17} but frequently is not diagnosed radiographically when present at autopsy.⁷ Woodring reported that 13 of 15 patients with severe ARDS developed PIE; only 3 of the 13 patients survived.¹⁶

It is important to recognize the radiographic finding of PIE because it indicates the dissection of gas along the peribronchiolar sheaths. The interstitial gas may compress the lung parenchyma and vasculature producing decreased ventilation and perfusion. This causes further impairment of already compromised pulmonary function. In addition, PIE may dissect to the mediastinum, producing PTX or PC, both potentially life threatening acute complications.^{1,15} Pulmonary interstitial emphysema is recognized as a complication of mechanical ventilatory support with associated high morbidity and mortality in neonates, and may well have similar implications for children beyond the neonatal period.

Despite initial enthusiasm that HFV would prevent or minimize PBT, evidence for its efficacy is limited. Sev-

eral case reports have described the successful use of HFJV in adults with tracheal or bronchopleural fistulae,¹⁸⁻²⁰ and in infants with PIE or BPF.^{13,21-24} A single case report describes the successful use of HFJV in the management of a large BPF in a 3-year-old child.²⁵ However, a randomized, controlled trial of HFJV in adults with ARDS failed to demonstrate a difference in the incidence of PBT (5%) between the HFJV and CV groups.²⁶ A recent randomized controlled trial compared high frequency oscillatory ventilation to CV in preterm neonates with respiratory failure.²⁷ The incidence of PBT was approximately 40% in both groups. However, a recently completed randomized, controlled trial of HFJV in the management of PIE in preterm neonates showed significantly more frequent improvement or resolution of PIE, and a significantly lower mortality rate, for infants treated with HFJV compared to CV.¹⁰

In this report, we present our experience with HFJV in children with severe ARDS complicated by PBT that was progressing while receiving CV. Analysis of ventilator and blood gas variables immediately prior to beginning HFJV failed to identify factors predictive of survival. However, the survivors had spent significantly less time on CV prior to beginning HFJV than the nonsurvivors. We speculate that the early application of HFJV provided adequate gas exchange at lower airway pressures, and avoided irreversible barotrauma to airways and lung parenchyma, thus allowing recovery from the underlying insult. We postulate that the rapid reduction in airway pressures decreased the severity of the airleak, and in particular the PIE, and produced an improvement of \dot{V}/\dot{Q} matching within the lung. It is unlikely that the underlying diseases changed significantly within the first 48 hr following the start of HFJV, producing the observed improvement in gas exchange, with a significant decrease in $P_{(A-a)O_2}$ for the group as a whole. The survivors in this study required a relatively short period of HFJV (mean 4.4 days) for airway pressures to be reduced and PBT to improve or resolve. Only 2 children survived who required HFJV for longer than 7 days because of persistent PBT and high airway pressures. High-frequency jet ventilation was well-tolerated from a hemodynamic standpoint. It is perhaps surprising that a reduction in PIP and MAP did not produce an improvement in cardiovascular function. However, cardiac output was not measured in any of the children, and could have changed during HFJV. There was no evidence for necrotizing tracheo-bronchitis in the short-term application of HFJV. A low incidence of chronic lung disease was observed in the survivors, when defined as a requirement for supplemental oxygen at the time of discharge. Two of the 20 (10%) of the survivors were so affected.

In this retrospective review, values for PIP, MAP, PEEP, and OI were observed which statistically differentiated survivors from non-survivors after a relatively short (48-hr) period of HFJV. Clearly, these factors need

to be evaluated in a prospective fashion, and may prove to be useful in predicting the likelihood of survival, and may assist in the use of advanced treatments such as extracorporeal membrane oxygenation and lung transplantation.

Recent reports have attempted to identify factors predicting death in children with ARDS and respiratory failure managed with conventional mechanical ventilation.^{28,29} The rate of survival in these series was 25 and 49% respectively, compared to a survival rate of 69% in this report. Interestingly, death was not accurately predicted for our series of patients when the criteria presented in these reports were applied. Seven of 12 (58%) of our children survived with $MAP \geq 23$ cm H₂O, and 15 of 23 (65%) survived with $P_{(A-a)O_2} \geq 470$ mm Hg, when they would have been predicted to have mortality rates of 90 and 81%, respectively.²⁸ Five of 10 (50%) of our children survived with $P_{(A-a)O_2} \geq 400$ mm Hg for ≥ 24 hr when predicted mortality was 100%.²⁹ In one of these reports the presence of pulmonary barotrauma during CV was not found to be predictive of death.²⁹ However, of a total of 30 children, 10/16 survivors (56%) and 12/14 (86%) of nonsurvivors had barotrauma. An increase in sample size to 75 patients would demonstrate statistical significance if the same rates of pulmonary barotrauma persisted.

More information is needed regarding the incidence and outcome of PBT in children requiring mechanical ventilation. It is possible that alternative strategies of conventional ventilation, aimed at reducing airway pressures, may be effective in reducing the incidence or severity of PBT, and improve outcome.⁸ Further investigation as to the role of HFJV in the management of this complication should involve patients with a predictably poor outcome. The role of HFJV should then be evaluated in a randomized, controlled fashion.³⁰ Patients should be selected for HFJV treatment as early as possible in the course of the disease, before lung damage is irreversible. Careful differentiation as to the etiology of ARDS is required. Adults with ARDS due to pulmonary aspiration have a higher survival rate than with ARDS due to other causes.³¹

When used as described in this report, HFJV is a safe, tolerated mode of ventilatory support. Based on this experience we support further evaluation of HFJV applied early in the management of PBT complicating ARDS in children.

ACKNOWLEDGMENTS

The authors wish to acknowledge the support of Drs. Aoki, Yeh, and Newman of Oakland Children's Hospital, and Dr. Hammer of Pacific Presbyterian Medical Center, for the referral of patients for this report. We also thank Ms. Carol Parise of the Sutter Institute for Medical Research for her assistance with statistical analysis.

REFERENCES

- Pollack MM, Fields AI, Holbrook PR. Cardiopulmonary parameters during high PEEP in children. *Crit Care Med.* 1980; 8:372-377.
- Lyrene RK, Truog WE. Adult respiratory distress syndrome in a pediatric intensive care unit: Predisposing conditions, clinical course, and outcome. *Pediatrics* 1981; 67:790-795.
- Lenaghan R, Silva YJ, Walt AJ. Hemodynamic alterations associated with expansion rupture of the lung. *Arch Surg.* 1969; 99:339-343.
- Barash PG, Kosarussavadi B. Acute respiratory failure in the surgical patient. *Conn Med.* 1977; 41:73-76.
- Ovenfors C, Hedgcock MW. Intensive care unit radiology problems of interpretation. *Radiol Clin North Am.* 1978; 3:407-439.
- Kumar A, Pontoppidan H, Falke KJ, Wilson RS, Laver MB. Pulmonary barotrauma during mechanical ventilation. *Crit Care Med.* 1973; 1:181-186.
- Rohlfing BM, Webb WR, Schlobohm RM. Ventilator-related extra-alveolar air in adults. *Radiology* 1976; 121:25-31.
- Marini JJ, Kelsen SG. Re-targeting ventilatory objectives in adult respiratory distress syndrome. *Am Rev Respir Dis.* 1992; 146:2-3.
- Froese AB, Bryan AC. High frequency ventilation. *Am Rev Respir Dis.* 1987; 135:1363-1374.
- Keszler M, Donn SM, Bucciarelli RL, Alverson D, Hart M, Lunyong V, Modanlou HD, Noguchi A, Pearlman SA, Puri A, Smith DW, Stavis R, Watkins MN, Harris TR. Multi-center controlled trial comparing high-frequency jet ventilation and conventional ventilation in newborn infants with pulmonary interstitial emphysema. *J Pediatr.* 1991; 119:85-93.
- Wetzel RC, Gioia FR. High frequency ventilation. *Pediatr Clin North Am.* 1987; 34:15-38.
- Bunnell JB. High-frequency ventilation of infants. In *Current Perinatology*, Vol II. New York: Springer-Verlag, 1990: 172-200.
- Spitzer AR, Butler S, Fox WW. Ventilatory response to combined high frequency ventilation and conventional mechanical ventilation for the rescue treatment of severe neonatal lung disease. *Pediatr Pulmonol.* 1989; 7:244-250.
- Jackson AC, Vinegar A. A technique for measuring frequency response of pressure, volume, and flow transducers. *J Appl Physiol.* 1979; 47:462-467.
- Pollack MM, Fields AI, Holbrook PR. Pneumothorax and pneumomediastinum during pediatric mechanical ventilation. *Crit Care Med.* 1979; 7:536-539.
- Woodring JH. Pulmonary interstitial emphysema in the adult respiratory distress syndrome. *Crit Care Med.* 1985; 13:786-791.
- Johnson TH, Altman AR. Pulmonary interstitial gas: First sign of barotrauma due to PEEP therapy. *Crit Care Med.* 1979; 7:532-535.
- Carlson GC, Ray C, Klain M, McCormack PM. High frequency positive-pressure ventilation in management of a patient with bronchopleural fistula. *Anesthesiology* 1980; 52:160-162.
- Derderian SS, Rajagopal KR, Abbrecht PH, Bennett LL, Doblar DD, Hunt KK. High frequency positive pressure jet ventilation in bilateral bronchopleural fistulae. *Crit Care Med.* 1983; 10:119-121.
- Turnbull AD, Carlson G, Howland WS, Beattie EJ. High-frequency jet ventilation in major airway or pulmonary disruption. *Ann Thorac Surg.* 1981; 32:468-474.
- Frantz ID, III, Werthammer J, Stark AR. High-frequency ventilation in premature infants with lung disease: Adequate gas exchange at low tracheal pressure. *Pediatrics* 1983; 71:483-488.
- Pokora T, Bing D, Mammel M, Boros S. Neonatal high-frequency jet ventilation. *Pediatrics* 1983; 72:27-32.
- Boynton BR, Mannino FL, Davis RF, Kopotic RJ, Friederichsen G. Combined high-frequency oscillatory ventilation and intermittent mandatory ventilation in critically ill neonates. *J Pediatr.* 1984; 105:297-302.
- Gaylord MS, Quissell BJ, Lair ME. High-frequency ventilation in the treatment of infants weighing less than 1500 grams with pulmonary interstitial emphysema: A pilot study. *Pediatrics* 1987; 79:915-921.
- Meeuwis H, Vaes L, Klain M. Long-term high frequency jet ventilation in a 3-year-old child. *Crit Care Med.* 1983; 11:309-310.
- Carlson GC, Howland WS, Ray C, Miodownik S, Griffin JP, Groeger JS. High-frequency jet ventilation: A prospective randomized evaluation. *Chest* 1983; 84:551-559.
- HIFI Study Group. High-frequency oscillatory ventilation compared with conventional mechanical ventilation in the treatment of respiratory failure in pre-term infants. *N Engl J Med.* 1989; 320:88-93.
- Timmons OD, Dean JM, Vernon DD. Mortality rates and prognostic variables in children with adult respiratory distress syndrome. *J Pediatr.* 1991; 119:896-899.
- Tamburro RF, Bugnitz MC, Stidham GL. Alveolar-arterial oxygen gradient as a predictor of outcome in patients with non-neonatal pediatric respiratory failure. *J Pediatr.* 1991; 119:935-938.
- Matthay MA. New modes of mechanical ventilation for ARDS: How should they be evaluated? *Chest* 1989; 95:1175-1177.
- Hudson LD. Survival data in patients with acute and chronic lung disease requiring mechanical ventilation. *Am Rev Respir Dis.* 1989; 140:S19.