

# High-Frequency Jet Versus Conventional Ventilation in Infants Undergoing Blalock-Taussig Shunts

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Nine infants undergoing modified Blalock-Taussig shunts were randomized to both high-frequency jet ventilation (HFJV) and conventional ventilation (CV). Vital signs, blood gases, mean airway pressure, lung mechanics, functional residual capacity, and lung movement were compared on both modes of ventilation keeping peak inspiratory and expiratory pressures constant. The mean airway pressure was lower on HFJV than on CV (8.5 versus 10.9 cm H<sub>2</sub>O). Arterial partial pressure of oxygen was greater on HFJV than on CV (55 versus 46 mm Hg), arterial partial pressure of carbon dioxide was lower on HFJV than on CV (28 versus 37 mm Hg),

whereas compliance (0.54 versus 0.56 mL · cm H<sub>2</sub>O<sup>-1</sup> · kg<sup>-1</sup>) resistance (110 versus 95 cm H<sub>2</sub>O/L · s), and functional residual capacity (23 versus 22.5 mL/kg) remained the same. Lung movement and degree of retraction necessary for surgical exposure as evaluated by an independent observer was less with HFJV compared with CV. Compared with CV during the creation of Blalock-Taussig shunts, HFJV provides better gas exchange at lower mean airway pressure with similar lung function, lung volume, and hemodynamics.

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High frequency ventilation uses fast respiratory rates (150 to 600 breaths/min) and small tidal volumes (2 to 4 mL/kg) to achieve adequate ventilation and oxygenation. This mode of ventilation was first used intraoperatively to maintain gas exchange in a relatively motionless surgical field during airway operations [1]. Subsequently, this modality was found to achieve better carbon dioxide removal and equivalent oxygenation at lower mean airway pressures than conventional tidal ventilation [2, 3]. Effectiveness in treating neonatal lung disease and minimizing barotrauma has been demonstrated previously [4]. In addition to reducing barotrauma, lowering the mean airway pressure may improve cardiovascular dynamics, especially in patients with cardiac failure or little cardiovascular reserve [5, 6].

Cardiac operations in infants with congenital heart disease can be complicated by difficult exposure and a small surgical field, particularly when the lungs are exposed to high inflation pressures from conventional ventilation. The severe lung retraction required may cause ventilation and perfusion mismatch, atelectasis, and altered pulmonary function. The effect of lung manipulation on patient stability may be particularly apparent in

the thoracotomy position in which the nonretracted lung is compressed. We hypothesized that the intraoperative use of high-frequency jet ventilation (HFJV) during pediatric cardiac operations could maintain adequate gas exchange and lung function while reducing the need for lung manipulation and retraction as compared with conventional ventilation. The decreased lung movement may minimize lung manipulation and ease access to the surgical field.

## Material and Methods

### Patient Population

Nine term infants (mean study age, 5.4 ± 4 weeks; study weight, 3.3 ± 1.0 kg) were studied after obtaining informed parental consent. All infants had complex cyanotic congenital heart disease requiring the placement of a Blalock-Taussig shunt to provide pulmonary blood flow. All were free of primary pulmonary disease and intercurrent illness.

### Protocol

The study population was randomized and placed on either conventional or jet ventilation for the first set of measurements. All infants underwent a modified Blalock-Taussig shunt procedure using an artificial graft (WC Gore and Associates, Falkton, MI). The infants were anesthetized with fentanyl and low dose halothane and had standard monitoring with electrocardiogram, intraarterial blood pressure recording, end tidal CO<sub>2</sub> monitoring,

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transcutaneous oxyhemoglobin saturation (Nellcor, Inc, Hayward, CA), and arterial blood chemistries analyzed throughout the procedure.

Before the initiation of the operation, the infants were intubated with an appropriately sized triple lumen endotracheal tube (Mallinckrodt Inc, Argyle, NY) permitting conventional ventilation, HFJV, and distal tracheal pressure monitoring. The infants placed on conventional ventilation first, had a peak inspiratory pressure (PIP) of approximately 20 to 30 cm of H<sub>2</sub>O and 4 to 5 cm H<sub>2</sub>O positive end expiratory pressure (PEEP). The PIP used was set to deliver the most optimum chest movement as determined by the anesthesiologist. The range in PIP in the ventilated subjects may have been a reflection of differences in patient compliance. The ventilator rate was set at 30 breaths/min and supplemental oxygen at 25% to 50% to maintain oxygen hemoglobin saturation greater than 75%. The volume ventilator used was Ohmeda 7810 (Madison, WI) adapted with a Bain circuit. The patients placed initially on HFJV, had settings of 420 breaths/min, inspiratory time of 0.2 seconds with the same inspired oxygen concentration, PIP, and PEEP as was used for the conventional ventilator. The conventional ventilator was used in tandem with the jet ventilator and was set to give 10 sigh breaths/min. The PIP of the conventional ventilator was set 4 or 5 cm less than that on the jet so as to not interrupt the jet ventilator. The ventilator used was the Bunnell Life Pulse HFJV Device, Bunnell Inc, Salt Lake City, UT.

After the induction of anesthesia, the inhalational anesthetics were turned off to prevent these gases from interfering with the pulmonary function tests. The infants were placed in a thoracotomy position, and adequate surgical exposure was obtained. After stabilization for 10 minutes, on either mode of ventilation, pulmonary mechanics, functional residual capacity (FRC), arterial blood gases, and vital signs were determined. The infants were then switched to the other mode of ventilation, stabilized for 10 minutes, and the studies were repeated. All measurements were made before the shunt was placed. Because of the noticeably improved surgical exposure while on jet ventilation, the operation was performed with the baby on jet ventilation. Photographs were obtained at end inspiration on conventional ventilation and jet ventilation.

#### *Pulmonary Mechanics Measurements*

Simultaneous signals of airflow and airway pressure were relayed to a software program for data analysis (Peds; MAS Inc, Hatfield, PA). Airflow was measured with a heated pneumotachometer (Fleisch model 00; Richmond, VA) and a differential pressure transducer (model MP45; Validyne Engineering Corp, Northridge, CA). This was attached to the endotracheal tube with a low volume adaptor (Vital Signs, Totowa, NJ). A tube from the sideport of this adaptor was attached to a differential pressure transducer (model P7D; Celesco Transducer Products, Inc, Canoga Park, CA) to measure airway pressure. The resistance and dead space of this assembly is 13.2 cm of H<sub>2</sub>O · L<sup>-1</sup> · sec<sup>-1</sup> and 1.7 mL, respectively. Sampling of

the pressure and pulse signals occurred during 60 seconds.

Signals for airway pressure, airflow, and volume were used to determine respiratory compliance (CL, mL · cm H<sub>2</sub>O<sup>-1</sup> · kg<sup>-1</sup>) and resistance (cm H<sub>2</sub>O · L<sup>-1</sup> · sec<sup>-1</sup>) by the previously described technique of least means square analysis [7].

#### *Lung Volume Measurement*

Functional residual capacity was measured with the closed circuit helium dilution technique described previously [8]. Briefly, at end exhalation, the patient was connected to a closed circuit containing a known volume and concentration of helium. The circuit was adapted to maintain ventilatory support during the measurement. The helium concentration then decayed for 90 seconds at a rate that was dependent on the infant's FRC as well as any leak around the endotracheal tube or face mask. The helium decay curve was then interpreted for the losses resulting from the leak, to arrive at a final helium concentration attributable only to the infant's FRC. A total of two to three measurements were obtained and the average of these values was considered to be the infant's FRC at that time. Measurements were excluded from analysis if there was excessive leak or if the helium decay was irregular.

#### *Data Analysis*

Differences in mechanics, FRC, and arterial blood chemistries under different ventilating conditions were evaluated with the paired Student's *t*-test (Stats Plus Human Systems Dynamics; Northridge, CA). Significance was defined at the *p* less than 0.05 level.

#### **Results**

The infants tolerated the cardiac surgical procedure, the pulmonary function tests, and the altering modes of mechanical ventilation. There was a short period (20 to 30 seconds) when a loss of airway pressure was observed when switching from conventional to HFJV until the ventilator achieved its maximal pressures. This was not associated with any change in the infant's vital signs.

Mean values for vital signs, arterial blood chemistries, mean airway pressure, respiratory mechanics, and FRC are summarized in Table 1. As shown, there was a significant difference between the two modes of ventilation for mean airway pressure, oxygenation, and CO<sub>2</sub> elimination. A still photograph is depicted during conventional ventilation and HFJV in Figure 1. There was a subjectively noticeable increase in lung excursion with tidal breaths at peak inspiration on conventional ventilation when compared with HFJV. Similar lung excursion between the two techniques is observed at FRC. Areas of atelectasis can be observed on the conventional ventilation at FRC.

#### **Comment**

High-frequency jet ventilation is a form of mechanical ventilatory support that uses respiratory frequencies

Table 1. Measurements Conventional Ventilation Versus High-Frequency Jet Ventilation<sup>a</sup>

Variable	CV	HFJV	p Value
Heart rate (beats/min)	159 ± 5	161 ± 5	NS
Blood pressure (mm Hg)			
Systolic	81 ± 5	80 ± 4	NS
Diastolic	43 ± 3	43 ± 3	NS
Mean airway pressure (cm H <sub>2</sub> O)	10.9 ± 1	8.5 ± 0.4	<0.01
Arterial pH	7.40 ± 0.03	7.46 ± 0.03	NS
pCO <sub>2</sub> (mm Hg)	37 ± 3	28 ± 3	<0.05
pO <sub>2</sub> (mm Hg)	46 ± 4	55 ± 6	<0.05
Respiratory			
Compliance (mL · cm H <sub>2</sub> O <sup>-1</sup> · kg <sup>-1</sup> )	0.54 ± 0.05	0.56 ± 0.05	NS
Resistance (cm H <sub>2</sub> O · L <sup>-1</sup> · s <sup>-1</sup> )	110 ± 12	95 ± 12	NS
Functional residual capacity (mL/kg)	23 ± 2	22.5 ± 3	NS

<sup>a</sup> Values are mean ± standard deviation.

CV = conventional ventilation; HFJV = high frequency jet ventilation; pCO<sub>2</sub> = partial pressure of carbon dioxide; pO<sub>2</sub> = partial pressure of oxygen.

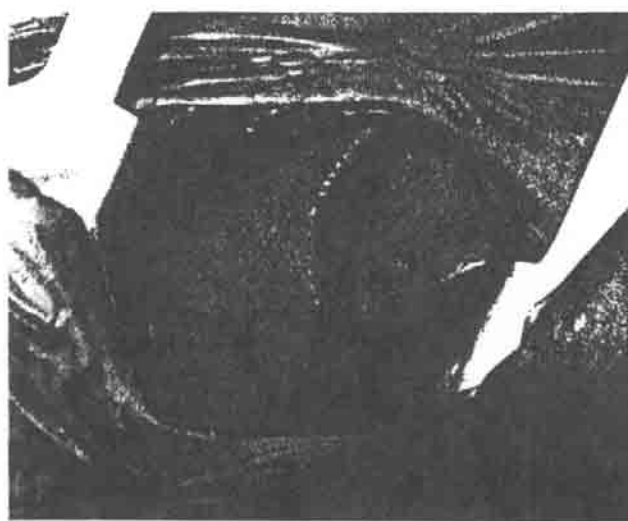
much greater than the normal respiratory rates. During HFJV, a pulse of gas is delivered by a jet cannula placed in the proximal airway. The accelerated gas velocities increase turbulence in the airways and improve gas mixing. Gas exchange occurs in part, by a process of augmented diffusion down the respiratory tree [9]. This process has been demonstrated to provide similar or better gas exchange with lower mean airway pressure in various models of lung disease [10, 11]. High-frequency jet ventilation has the potential advantage of ventilating with less tidal excursion than conventional ventilation at a similar FRC. This characteristic has facilitated the use of

HFJV during delicate airway operations and in adults during thoracic operations [12, 13]. Operating on patients in the thoracotomy position under general anesthesia causes significant changes in the distribution of ventilation and perfusion between the two lungs. Ventilation is greater in the nondependent upper lung and the perfusion is greater in the dependent lower lung causing a significant mismatch between the two. This pulmonary dysfunction may be exacerbated in the operative neonate whose lung is severely retracted. As a consequence of this respiratory embarrassment, the anesthesiologist may need to increase ventilatory support (ie, peak inflating pressures or end distending pressures) that can interfere with the surgical field. The surgeon then requires more lung retraction and manipulation and a vicious cycle begins.

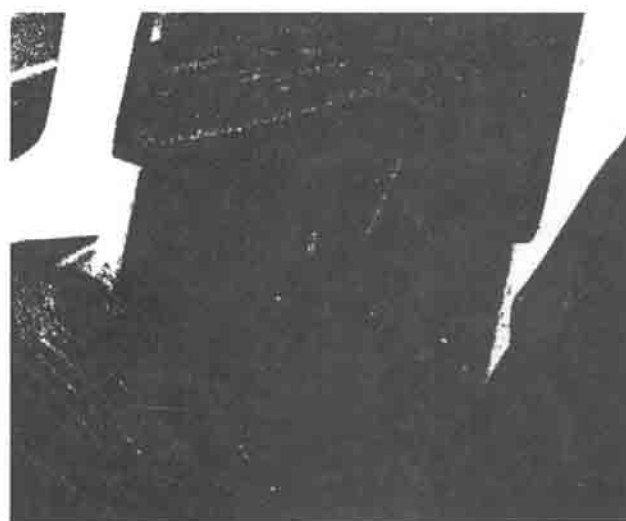
In the present study, Blalock-Taussig shunts were performed on 9 neonates supported with conventional ventilation and HFJV. The hemodynamics, pulmonary mechanics, and lung volume were similar with either mode of ventilation. However, these assessments were made at the beginning of the operation. It is quite possible that the similarities would not have continued throughout the course as the amount of lung retraction and manipulation was greater in the conventionally ventilated children.

Our study demonstrated significantly better oxygenation and CO<sub>2</sub> elimination on jet ventilation with a lower mean airway pressure. The advantages of a lower mean airway pressure include less barotrauma and less impact on venous return to the right heart. In situations of right ventricular dysfunction improved venous return may augment cardiac output. In addition, HFJV can serve as a treatment modality for patients with pulmonary hypertension who require hyperventilation to drop pulmonary vascular resistance, avoiding the consequences of positive pressure ventilation.

Respiratory failure after neonatal cardiac operations is



A



B

Fig 1. Photographs at end inspiration on conventional ventilation (A) and on jet ventilation (B).

common as demonstrated by abnormal lung mechanics [14]. The lung retraction used during cardiac procedures, particularly done in the thoracotomy position, may contribute to pulmonary dysfunction. Infants with normal pulmonary function preoperatively have been shown to have significant pulmonary compromise immediately after Blalock-Taussig shunts [15]. The etiology of this dysfunction may be the result of lung manipulation, perhaps explaining the significant differences in arterial oxygenation and CO<sub>2</sub> elimination seen in our two groups of ventilated patients. In this regard, areas of atelectasis were observed in our study population when the retraction was performed on conventional ventilation. This was not seen during HFJV possibly from the requirement for less manipulation. The fact that the atelectasis did not alter lung volume measurements may be explained by the areas of atelectasis being localized and not great enough to affect FRC. Obviously there is subjectivity when one evaluates degree of atelectasis and amount of retraction required to clear the surgical field. However, the same surgeon performed all the operations on both modes of ventilation lending some objectivity to the assessment of lung manipulation and retraction required.

The use of HFJV during infant cardiac operations provides adequate gas exchange with several important clinical advantages. There is an additional technical burden to bring another ventilator into an operating room, however, the requirements to do so are minimal and may be worth pursuing in certain patients. We speculate that the intraoperative use of the jet ventilator during an entire surgical case may diminish lung trauma and perhaps improve the postoperative pulmonary course.

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