

Heliox Administration During High-Frequency Jet Ventilation Augments Carbon Dioxide Clearance

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We report the combined use of heliox and high-frequency jet ventilation to augment carbon dioxide clearance, with a focus on the important technical considerations. Our case is a 5-month old infant with acute respiratory failure associated with gas trapping, hypercarbia, respiratory acidosis, and air leak. Despite maximal conventional ventilation, bronchodilator therapy, corticosteroids, and sedation, the infant continued to demonstrate worsening gas exchange necessitating an escalation of support to high-frequency oscillatory ventilation. After the development of an air leak and continued difficulties with carbon dioxide clearance, the patient was transitioned to high-frequency jet ventilation. Persistent hypercarbia resulted in the addition of heliox to facilitate ventilation. Improvements in gas exchange occurred rapidly. The combination of heliox and high frequency jet ventilation resulted in improved carbon dioxide clearance, respiratory stabilization, and the ability to wean ventilator settings. Key words: heliox, high frequency ventilation, jet ventilation, carbon dioxide, pediatric mechanical ventilation. [Respir Care 2004;49(9):1038–1044. © 2004 Daedalus Enterprises]

Introduction

Acute lung injury can result in respiratory failure requiring endotracheal intubation and mechanical ventilation to maintain oxygenation and ventilation. If hypoxia and/or hypercarbia worsen, a substantial escalation of respiratory support may be required for adequate gas exchange. A subset of pediatric patients with acute respiratory failure require interventions beyond conventional mechanical ventilation to provide adequate gas exchange and minimize ventilator-induced lung injury. Therapies that have been investigated include high-frequency oscillatory ventilation (HFOV),^{1,2} high-frequency jet ventilation (HFJV),^{3–7} permissive hypercapnia,⁸ low-tidal-volume (low-V_T) ventilation,^{9,10} surfactant administration,^{11,12} in-

haled nitric oxide (INO) administration,^{13,14} and partial liquid ventilation.^{15–17} Although many of these therapies have shown great promise, none has been conclusively demonstrated to significantly improve mortality for pediatric patients with acute lung injury. Thus, there has been a growing trend toward the use of combination therapy.

Clinical data suggest that combination therapy may improve outcomes for pediatric patients with acute lung injury/acute respiratory distress syndrome. For example, the combination of HFOV and partial liquid ventilation has been demonstrated to improve alveolar recruitment and oxygenation.¹⁸ Several studies have described improved gas exchange when INO was combined with HFJV^{19,20} or HFOV.^{14,21,22}

Recently, helium-oxygen mixtures (heliox) have gained increased interest as a component of combination therapy for patients with acute lung injury. Heliox improves gas exchange in patients with asthma, bronchiolitis, postextubation stridor, croup, upper airway obstruction, and cystic fibrosis.^{23–37} Helium, having a density one-seventh that of air (Table 1), lowers airway resistance, results in a decreased work of breathing, improves gas flow, and improves gas exchange. This improvement in gas exchange is theorized to occur by favoring laminar gas flow over turbulent flow. Helium lowers the Reynolds number in those airways operating in a transitional zone of flow pat-

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Table 1. Density and Carbon Dioxide Diffusion Coefficient of 5 Gases

Gas	Density (g/L)	Carbon Dioxide Diffusion Coefficient (cm ² /s)
Nitrogen	1.251	0.165
Oxygen	1.429	0.139
Air	1.293	0.138
Helium	0.179	NA
Heliox*	0.43	0.56

NA = data not available
*heliox = mixture of 80% helium and 20% oxygen

terms and, thus, converts areas of turbulent flow into more efficient laminar flow with improved diffusion characteristics. Additionally, according to the Bernoulli equation, the lower density of helium improves gas flow within turbulent airways. Heliox gas mixtures also have a higher diffusion coefficient for carbon dioxide than is seen with oxygen-enriched air.^{25,34,38-40}

Heliox administration in combination with HFOV for acute lung injury has been demonstrated to improve gas exchange.^{40,41} However, the role of heliox in patients with acute lung injury remains uncertain. One combination of nonconventional strategies that has not been systematically studied for pediatric patients is heliox and HFJV. Thus, we present the case of an infant with acute respiratory distress syndrome and gas trapping associated with substantial hypercarbia and respiratory acidosis managed with a combination of heliox and HFJV.

Case Summary

A 5-month-old infant with a 2-day history of upper airway congestion and increased work of breathing was transferred to our pediatric intensive care unit from a referring hospital. The patient developed coarse grunting, minimal air movement, significant intercostal and subcostal retractions, and hypoxia. Minimally effective respiratory effort persisted despite bronchodilator therapy. Overall, systemic perfusion worsened, as manifested by mottled skin, delayed capillary refill, and decreased peripheral pulses. The infant was orotracheally intubated with resultant improved oxygenation. Initial ventilator (Servo 300, Siemens-Elema, Solna, Sweden) settings in the pressure control/pressure support mode were: peak inspiratory pressure (PIP) 28 cm H₂O, positive end-expiratory pressure (PEEP) 5 cm H₂O, pressure support 12 cm H₂O, inspiratory time 0.5 s, fraction of inspired oxygen (F_{IO₂}) 0.45, set respiratory rate 25 breaths/min, and mean airway pressure 7 cm H₂O. The initial post-intubation arterial blood gas

(ABG) analysis revealed: pH 7.13, P_{aCO₂} 84 mm Hg, P_{aO₂} 77 mm Hg, bicarbonate 27 mmol/L, base deficit -4 mEq/L, arterial oxygen saturation (S_{aO₂}) 90%. Culture of endotracheal tube secretions isolated *Haemophilus influenzae* (non-type B, β lactamase negative). In addition, an immunoassay was positive for respiratory syncytial virus.

The patient continued to have bilateral coarse inspiratory and expiratory rhonchi. Despite medical therapy with bronchodilators, corticosteroids, sedation, and neuromuscular blockade, the patient developed progressive hypercarbia and respiratory acidosis. Ventilator settings were increased in the pressure-control/pressure-support mode: PIP 30 cm H₂O, PEEP 9 cm H₂O, pressure support 10 cm H₂O, inspiratory time 0.45 s, and mean airway pressure 14 cm H₂O. ABG on these settings revealed: pH 7.08, P_{aCO₂} 80 mm Hg, P_{aO₂} 124 mm Hg, bicarbonate 23 mmol/L, base deficit -8 mEq/L, and S_{aO₂} 97%. Chest radiograph was notable for peribronchial thickening and multifocal subsegmental atelectasis.

Although a strategy of permissive hypercapnia may have been employed, the degree of acidosis (pH < 7.1) was of significant concern. Additionally, bicarbonate administration in this setting is controversial and, thus, was not utilized.⁴²⁻⁴⁴ At this time the patient was transitioned to HFOV (SensorMedics 3100A, Viasys Healthcare, Yorba Linda, California). Over the next 20 minutes HFOV parameters were increased to relatively high levels for a patient in this age group in response to the persistently elevated P_{aCO₂} levels: mean airway pressure 20 cm H₂O, F_{IO₂} 1.0, frequency 5 hertz, and amplitude 67. Subsequent ABG results were: pH 7.29, P_{aCO₂} 51 mm Hg, P_{aO₂} 444 mm Hg, bicarbonate 24 mmol/L, base deficit -3 mEq/L, and S_{aO₂} 99%. Chest radiograph on these settings demonstrated hyperinflation, with the development of pneumomediastinum and subcutaneous air on the right side of the neck and upper chest.

Although an acceptable management option could have been to modify the HFOV settings to minimize barotrauma while allowing some permissive hypercapnia, the patient care team opted for the conversion to HFJV (Life Pulse, Bunnell, Salt Lake City, Utah) to optimize carbon dioxide clearance at relatively lower airway pressures. Based on our experience and the medical literature,³ HFJV tends to be more effective at carbon dioxide clearance than does HFOV in infants. This overall decision was based on the clinical scenario of adequate oxygenation, poor ventilation, and the development of air leak.

Initial HFJV settings included: mean airway pressure 14.5 cm H₂O, rate 320 breaths/min, PIP 40 cm H₂O, F_{IO₂} 0.5, and inspiratory time 0.02 s. The displayed servo pressure was 5 psi. Based on a transcutaneous monitor (TCO₂M, model 860, Respirationics-Novametrix, Wallingford, Connecticut), carbon dioxide reading (P_{tCO₂}) in the 80s, the ventilator settings were increased to a mean airway pres-

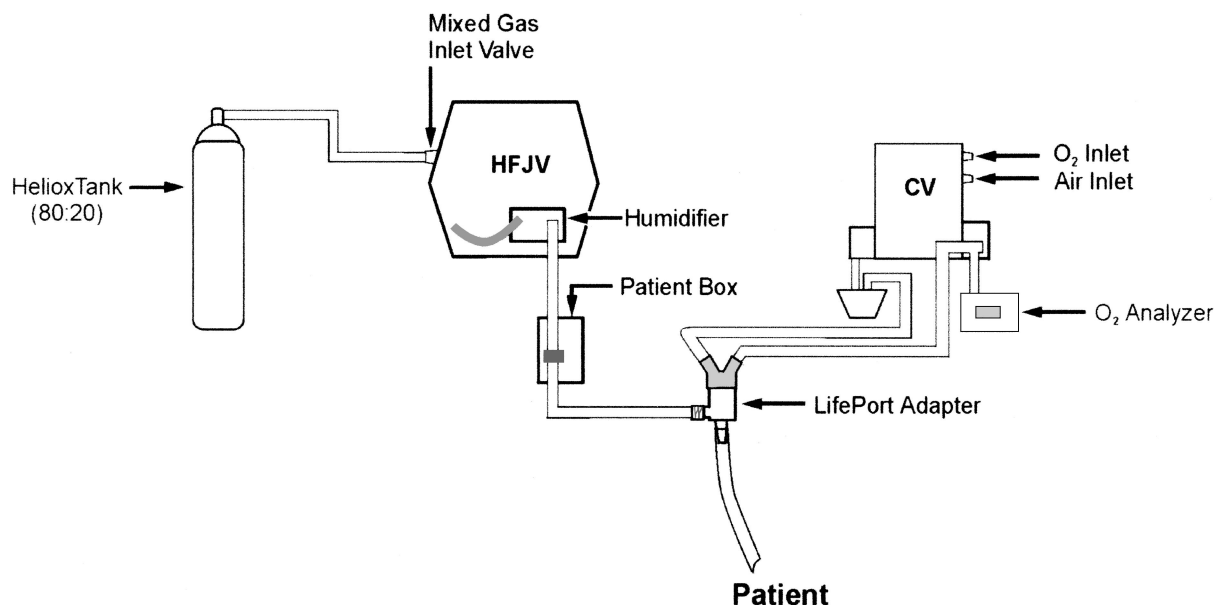


Fig. 1. Technical setup for adding heliox to high-frequency jet ventilation (HFJV). CV = conventional ventilator.

sure of 18 cm H₂O and a maximal PIP of 50 cm H₂O. P_{tcO_2} transiently decreased to 68 mm Hg on these settings with an ABG: pH 7.23, P_{aCO_2} 57 mm Hg, P_{aO_2} 112 mm Hg, bicarbonate 23 mmol/L, base deficit -5 mEq/L, and S_{aO_2} 98%. Although these maneuvers improved the respiratory acidosis, over the next 30 minutes, P_{tcO_2} again increased to 84 mm Hg.

Based on the theoretical benefits of improved carbon dioxide clearance, heliox was added to the HFJV therapy. A heliox tank (80% helium and 20% oxygen) was directly connected to the mixed gas input valve on the jet ventilator, thus providing a direct flow of helium into the airways from the LifePort adaptor at the end of the endotracheal tube (Fig. 1). The F_{IO_2} on the conventional ventilator was adjusted to the minimum amount required to maintain oxygen saturation $\geq 92\%$. The patient's response was rapid. Within 2 minutes, P_{tcO_2} decreased from 85 mm Hg to 38 mm Hg. Additionally, there was an instantaneous increase in the servo pressure from 5 psi to 7.3 psi. The ventilator settings were not altered during this time, so the changes in P_{tcO_2} and servo pressure directly correlated with the change in carrier gas from nitrogen to helium. An ABG analysis obtained 30 minutes after the addition of heliox was notable for a decrease in P_{aCO_2} to 34 mm Hg, and a rise in pH to 7.48.

The application of heliox as the driving gas for jet ventilation allowed us to aggressively wean the ventilator. Within 8 hours the ventilator settings decreased to: mean airway pressure 11.5 cm H₂O, frequency 320 breaths/min, PIP 35 cm H₂O, F_{IO_2} 0.6, and inspiratory time 0.02 s.

To verify that the improvement in carbon dioxide clearance was attributed to heliox, the patient was monitored

off heliox therapy the following day, during a routine change in the heliox tank. Prior to discontinuing heliox, the P_{tcO_2} was 48 mm Hg while the measured P_{aCO_2} was 39 mm Hg. The P_{tcO_2} increased to 72 mm Hg with the discontinuation of heliox. No other ventilator-setting changes were made during this time. With the reinitiation of heliox, P_{tcO_2} decreased to 62 mm Hg within 4 min and to 55 mm Hg within 10 min.

The patient remained on the combination therapy of HFJV and heliox for an additional 48 hours. At that time heliox was discontinued, and 12 hours later the patient was transitioned from HFJV to conventional ventilation. Extubation occurred on the fifth hospital day.

Discussion

Combination therapy of nonconventional ventilation strategies is being utilized to treat patients with acute lung injury at an increasing rate. Preliminary data are available for many of the possible combinations; however, no prior publication studying only the addition of heliox to HFJV in the pediatric population is available. Our case report illustrates the potential benefits of this combination.

It may be debated whether the transition to HFJV and heliox was necessary, as our patient could potentially have been managed with HFOV or HFJV alone. However, the purpose of this case report is to illustrate the successful use of the unique therapeutic combination of HFJV and heliox and not to discuss the potential advantages and disadvantages of the various ventilatory management strategies.

The rapid improvement following initiation of heliox in our patient strongly suggests a direct beneficial relation-

ship. We found the use of heliox instead of oxygen-enriched air in the setting of stable ventilator settings resulted in a rapid improvement in carbon dioxide clearance as noted by ABG and P_{tcO_2} levels. This beneficial effect of heliox was confirmed by the rebound hypercarbia noted during a brief trial without heliox.

Although the combination of heliox and HFJV has been previously described, our case significantly differs. A French study reported 10 adults on HFJV during laser treatment for tracheal granulomas that had significantly decreased P_{aCO_2} following heliox administration.⁴⁵ This study utilized a different brand of jet ventilator (Acutronic VS600S-LSA) and examined adults with discrete large-airway obstruction rather than pediatric patients with diffuse lung injury. The production of the Acutronic VS600S-LSA was discontinued in the 1980s and is currently not available for clinical use. Comparing the function of this ventilator when used on adult patients and our experience with a pediatric patient is difficult.

In an earlier pediatric case report, a 12-month-old patient with acute respiratory distress syndrome secondary to respiratory syncytial virus infection received both heliox (80:20) and INO at 40 parts per million while on HFJV.³⁹ It has been demonstrated that helium increases the diffusion velocity and delivery of INO to the alveolar level, with resultant improvements in vasodilation⁴⁶ as well as improved oxygenation and carbon dioxide clearance.⁴⁷ Given the improved effect of INO with heliox administration, it is not possible from that case report to separate the effects on gas exchange of INO from heliox. Our report is the first to demonstrate improved gas exchange on pediatric lung disease with the use of HFJV and heliox alone.

Technical Considerations

Heliox gas mixtures must be administered with vigilance and continuous monitoring. Chest radiographs and arterial blood gas monitoring provide indicators of effective lung volume and gas exchange. Continuous noninvasive monitoring is recommended in the form of pulse oximetry and transcutaneous monitoring. We also recommend the use of continuous in-line monitoring of F_{IO_2} as an additional measure to ensure adequate oxygen delivery to the patient. Any beneficial effect of heliox should become evident in a relatively short period of time. If heliox has been administered for more than approximately 30 min and the patient has not shown clinical improvement, then heliox therapy should be abandoned and alternative therapies considered.

Since HFJV requires the use of 2 ventilators (the Life Pulse and a standard conventional ventilator), there are 2 sources of gas entry into the ventilatory system. In theory, heliox could be administered via either ventilator or both. The conventional ventilator functions primarily to regulate

PEEP and provide background "sigh" breaths to promote alveolar recruitment. The majority of gas flow, as described below, is delivered by the jet ventilator. Although heliox can be administered via the conventional ventilator, the infrequent breaths administered and the potential risk of diluting the helium concentration from the gas delivered by the Life Pulse make this a less desirable option. As shown in Figure 1, we chose to connect the heliox tank directly to the jet ventilator at the mixed-gas input valve. A blender was not placed at this level of the system with our patient, thus preventing dilution of the inspired helium concentration. For patients who require supplemental oxygen, it would be necessary to add an oxygen blender at that location. Since oxygen blenders are calibrated for nitrogen-oxygen gas mixtures, they may not be accurate when used with heliox gas mixtures. Thus, for safety reasons, a continuous oxygen analyzer should always be placed in the ventilator circuit to measure the F_{IO_2} .

Studies involving the delivery of INO with HFJV have administered the gas at the level of the jet ventilator, and not through the conventional ventilator.^{19,20,48} Those investigators believe that significant differences in the delivered concentrations of INO may occur as a result of dilution from concurrent conventional ventilatory support.²⁰ For example, it has been demonstrated that the INO concentration measured at the end of the endotracheal tube differed from the delivered INO concentration at the jet ventilator by $\geq 10\%$.⁴⁸ One can infer from that study that at least 90% of the minute ventilation delivered to the patient is from the jet ventilator, with the conventional ventilator providing the remainder. Since the efficacy of heliox lies in the delivery of a lower density gas mixture, it is essential that there is minimal dilution of the helium concentration to maximize the beneficial clinical effect. Therefore, as the gas delivered from the jet ventilator constitutes the majority of gas flow delivered to the patient, it seems logical to administer heliox via the jet ventilator and not the conventional ventilator.

The concept of maximizing the delivery of helium is further exemplified by studies involving heliox in comparison to oxygen-enriched air to nebulize bronchodilators. One group of investigators initially found no benefit with heliox versus oxygen to nebulize albuterol in patients with status asthmaticus.⁴⁹ After changing the delivery system to prevent the entrainment of room air, thus maintaining the lower density of the heliox gas mixture, this same group demonstrated that the use of heliox to nebulize albuterol resulted in a significant improvement in spirometric measurements.⁵⁰

The mechanism of action by which heliox improved gas exchange for our patient remains unclear. Perhaps the rate of carbon dioxide clearance was increased because of helium's higher diffusion coefficient for carbon dioxide, thus allowing for improved gas exchange at the alveolar level.

Alternatively, the decrease in gas density with heliox may have increased laminar flow, thus improving gas flow properties and carbon dioxide clearance. Most likely, an increase in delivered V_T and minute ventilation resulted from the addition of heliox. For the same pressure pulsation from the jet ventilator (ie, PIP and inspiratory time), it can be theorized that a larger V_T would be delivered by a lower-density gas. This proposed increase in V_T is supported by the instantaneous increase in the servo pressure that was seen. Similarly, an increase in delivered V_T has also been suggested as the mechanism for improved gas exchange when delivering heliox with HFOV.⁴¹ This theory has been confirmed in a recent laboratory study.⁵¹ With V_T maintained constant, no improvement in gas exchange was detected when combining heliox with HFOV.

Cost Considerations

The clinician should consider cost when deciding whether to utilize heliox as an adjuvant therapy. In our institution, a tank of 80:20 heliox costs approximately \$50. Although the number of tanks required varies with ventilator settings, our infant required 5 tanks of heliox per 24 hours. Thus, the estimated daily cost of heliox (\$250 per day) is very reasonable, as compared to a day of mechanical ventilation. If the administration of heliox can be demonstrated to decrease duration of ventilation, then heliox would be a cost saving therapy. In addition to economics, a shorter duration of ventilation would equate with less morbidity and improved patient/family satisfaction. Future randomized controlled studies are required to determine the effect of heliox on duration of ventilation.

Patient Selection

The Life Pulse high-frequency jet ventilator has limited efficacy for adult and older pediatric patients. However, HFJV can be a beneficial ventilatory strategy for neonates, infants, and some small children with severe lung injury and/or right ventricular failure. The gas delivery characteristics of HFJV allow for more optimal cardiorespiratory interactions. For example, HFJV provides improved gas exchange at lower ventilator pressures as compared to HFOV.³ In postoperative pediatric cardiothoracic patients, HFJV has been demonstrated to improve cardiac function after the Fontan procedure⁵² and to improve gas exchange at lower mean airway pressures (compared to conventional ventilation) in patients after Blalock-Taussig shunt.⁵³ HFJV is also beneficial for patients with air leak syndrome.⁵⁴ The addition of heliox to HFJV in these patient populations may be reasonable if carbon dioxide clearance is inadequate, especially if the clinician is approaching the upper limits of HFJV technology. If the improved ventilation seen with HFJV and heliox is secondary to im-

proved V_T delivery, then, theoretically, the administration of heliox could expand the application of HFJV to larger pediatric patients.

In general, heliox therapy provides the greatest benefit when high airway resistance is a principal component of the clinical picture (ie, bronchiolitis,²⁸ status asthmaticus,^{23,32,34} upper airway obstruction,^{29,37,55} and croup^{56,57}). Heliox seems most effective during conditions involving density-dependent increases in airway resistance, especially when utilized early in an acute disease process. More data are needed to know if these same patterns apply to the administration of heliox with HFJV.

It is important to note that no adverse effects of heliox have been reported. If the clinician opts to provide heliox in conjunction with HFJV and the patient does not improve within 30 min, then heliox therapy should be abandoned and alternative therapies considered.

Conclusions

Various ventilator strategies, modes, and adjunct therapies must be further investigated to determine combinations that might significantly impact the morbidity and mortality associated with respiratory failure in infants and children. The higher carbon dioxide diffusion coefficient and improved flow properties of heliox make it an interesting adjunct respiratory treatment. The combined therapies of heliox and HFJV for pediatric respiratory failure have not been previously reported. Our case report applies these 2 treatment modalities in combination with a significant synergistic, beneficial effect.

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