CASE REPORT

Elective use of high frequency oscillatory ventilation with transcutaneous carbon dioxide monitoring during thoracoscopic diaphragmatic hernia repair

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ABSTRACT
Thoracoscopy, a minimally invasive technique, for congenital diaphragmatic hernia (CDH) repair has been shown to offer significant advantages versus open procedures. However, positive pressure ventilation during thoracoscopy can be challenging. Minimizing lung movement is important to improve surgical visualization, but one-lung ventilation can be difficult in neonates and infants. Ventilation-perfusion inequalities occur in the lateral decubitus position making it challenging to maintain oxygenation and control hypercarbia from carbon dioxide insufflation. High frequency oscillatory ventilation (HFOV) offers an alternative means of ventilation for such cases. It maintains a constant distending pressure for the alveoli and optimal lung volumes while limiting peak inflating pressures and thus lung over distention. This provides a means of ensuring adequate oxygenation and ventilation with minimal lung movement, allowing adequate intraoperative exposure. During HFOV, continuous monitoring of carbon dioxide (CO2) can be problematic as end-tidal technology is not feasible. As such, we used transcutaneous CO2 (PtcCO2) monitoring in our patient. We present the elective intraoperative use of HFOV with PtcCO2 monitoring in a 4-day-old infant for thoracoscopic repair of CDH. Previous reports regarding the intraoperative use of HFOV are reviewed and its application in this scenario is discussed. The utility of continuous PtcCO2 monitoring during such cases is presented.

Key words: High frequency oscillatory ventilation (HFOV); Thoracoscopy; Congenital diaphragmatic hernia; Oxygenation; Hypercarbia; Transcutaneous CO2 (PtcCO2) monitoring


INTRODUCTION
Congenital diaphragmatic hernia (CDH) has an incidence of approximately 1 in 2,000 live births. It results when a portion of the fetal diaphragm tissues fail to fuse, thereby allowing abdominal contents to ascend into the thoracic cavity and interfere with normal lung development. CDH most often manifests as severe respiratory distress in the neonate, a direct consequence of lung hypoplasia and inadequate pulmonary gas exchange. The initial management of neonatal respiratory failure associated with CDH is directed at ventilation and improving oxygenation.1,2 Currently, surgical repair is delayed until the patient’s physiologic functions have been optimized; the exact timing of the procedure being variable, based on individual patient’s presentation and the institutional expertise. Although traditional surgical management
HFOV and CDH repair

of CDH entails a laparotomy or thoracotomy, since 1995, both thoracoscopic and laparoscopic approaches to repair of CDH have been described. The benefits reported with thoracoscopic techniques include a quicker return to full enteral feeds, shorter duration of postoperative mechanical ventilation, decreased opioid requirements, shorter hospital stay and decreased overall hospital cost. Additionally, a reduced incidence of chest wall deformities has been reported following thoracoscopic versus open thoracotomy. Despite the immediate perioperative and long term benefits, the use of minimally invasive techniques such as thoracoscopy mandates specific changes in anesthetic management including the need for one-lung ventilation (OLV) and concerns regarding CO₂ absorption during insufflation. Although feasible in neonates and small infants, the conduct of OLV may be challenging and difficulties with oxygenation and ventilation are frequently encountered intraoperatively.

High-frequency oscillatory ventilation (HFOV) maintains mean airway pressure and optimal lung volumes while limiting peak inflating pressures and lung overdistention. Elective use has been suggested in the perioperative care of infants with CDH. Intraoperatively, the technique may be advantageous by limiting lung movement, allowing for thoracoscopic repair of CDH without the need for OLV, and maintaining oxygenation and ventilation. We present the elective intraoperative institution of HFOV in a 4 days old infant for thoracoscopic repair of CDH. Previous reports regarding the intraoperative use of HFOV are reviewed and its application in this scenario discussed.

CASE REPORT

Institutional Review Board approval and the need for parental consent for publication of single case reports are not required by Nationwide Children’s Hospital (Columbus, Ohio). A 4-day-old, 37-week gestational age, 2.84 kg infant was delivered at a referral hospital. Approximately one hour after birth, the infant appeared dusky with increased work of breathing. A chest radiograph revealed a bowel-filled left hemithorax, rightward mediastinal shift, with aeration seen only of the right lower lobe. The infant’s trachea was intubated and he was transported to our hospital. No other co-morbid conditions were noted. Echocardiography revealed a structurally normal heart with right ventricular pressures approximately half that of systemic pressures. Preoperatively, conventional positive pressure mechanical ventilation included synchronized intermittent mechanical ventilation (SIMV) mode with a peak inflating pressure of 21 cmH₂O, respiratory rate of 26 breaths per minute, positive end expiratory pressure of 5 cmH₂O, inspiratory time of 0.35 seconds, pressure support of 8 cmH₂O and an FiO₂ of 0.35. After evaluation and stabilization including repeat echocardiography to verify that pulmonary pressures remained lower than systemic pressures, the patient was scheduled for thoracoscopic repair of the CDH with planned intraoperative HFOV.

The patient was transported to the operating room and standard American Society of Anesthesiologists monitors were placed. An umbilical artery and vein catheter as well as a peripheral intravenous cannula were already in place. A transcutaneous CO₂ (TC-CO₂) monitor was applied (Sentec AG, Therwil, Switzerland). Anesthesia was induced and maintained with a combination of remifentanil (0.1-0.5 µg/kg/min), dexmedetomidine (0.8 µg/kg/hr) and midazolam (0.1 µg/kg/min). Neuromuscular blockade was provided by intermittent doses of rocuronium. To avoid interference with the surgical procedure from lung movement and facilitate CO₂ excretion, the patient was switched to HFOV in the operating room prior to the start of the surgical procedure (3102A HFOV, Sensormedics, San Diego, CA). A neonatal respiratory therapist was present during the case to maintain the HFOV and the transcutaneous CO₂ device. Initial HFOV settings included: mean airway pressure (MAP) 12 cmH₂O, amplitude (delta P) 20 cmH₂O, frequency 6 Hz, and FiO₂ of 0.4. There was no change in the patient’s hemodynamic status with the initiation of HFOV. The PtcCO₂ readings, arterial blood gas results, ventilator adjustments, and oxygen saturations are outlined in Table 1.

Following the initiation of HFOV, the TC-CO₂ was 60 mmHg and the PaCO₂ from the arterial blood gas was 42 mmHg (this was after the TC-CO₂ was in place for only 5 minutes). The amplitude was increased to 25 cmH₂O; however there was no change in the TC-CO₂, so the amplitude was further increased to 30 cmH₂O and the frequency was decreased to 5 Hz. This resulted in a TC-CO₂ value of 53 mmHg and a PaCO₂ of 41 mmHg. Throughout this time, the oxygen saturation was 100% with an FiO₂ of 0.4. The patient was placed in a right lateral decubitus position and the thoracoscopic procedure was started. Insufflation with CO₂ was initiated at a pressure of 2 mmHg. The oxygen saturation decreased from 99% to 92% and the MAP was increased from 12 to 14 mmHg which resulted in an increase of the oxygen saturation to 99-100 percent. When the CO₂ insufflation pressure was increased to 4 mmHg to facilitate reduction of the abdominal contents, the amplitude was increased from 30 to 35 mmHg. When the TC-CO₂ increased from 40-45 mmHg to 60-65 mmHg the amplitude was increased to 40 cmH₂O, resulting in a decrease in TC-CO₂ into the 50-55 mmHg range. A subsequent PaCO₂ was 44.6 mmHg, so the amplitude was increased to 45 cmH₂O. No further changes in ventilation were made. The
operative time was 2 hours and 14 minutes and the total time on HFOV was 2 hours and 36 minutes. There was adequate surgical visualization during thoracoscopy without interference from lung inflation or movement. The bowel contents were returned to the abdomen and the diaphragmatic defect closed primarily.

Following the surgical procedure, the patient was returned to conventional mechanical ventilation (same settings as preoperatively). The infant was transported to the Neonatal Intensive Care Unit (NICU). The patient’s trachea was successfully extubated to nasal CPAP on postoperative day five. Despite initial difficulties taking oral feeds, he was discharged home on postoperative day 17 on room air and full oral feeds. No perioperative complications were noted.

**DISCUSSION**

The evolution of thoracoscopic intervention for neonates and infants undergoing repair for complex procedures such as congenital diaphragmatic hernia (CDH) and tracheoesophageal fistula/esophageal atresia represents a milestone in pediatric surgery. In 1995, van der Zee et al reported the first laparoscopic repair for CDH in a 6-month-old while Becmeur et al reported the first thoracoscopic repair of CDH in a 9-month-old in 2001.4,5 Since these first reports, increased surgical experience and technique, advances in surgical instrumentation as well as improved anesthetic care and monitoring has allowed for minimally invasive surgical intervention in younger and smaller patients so that these procedures are now feasible in neonates. In a retrospective review of 649 minimally invasive surgical cases in patients ≤ 5 kilograms, Ponsky and Rothenberg reported a low conversion rate to open procedures of 1.2% for the 43 different procedures performed, a complication rate of 3%, and no surgery-related deaths with an average operative time of less than 2 hours.16 These findings underscore the notion that the minimally invasive approach is a viable alternative for infants and neonates who require operative interventions.

Various factors may make ventilator support challenging during thoracoscopic procedures. As noted previously, although minimizing lung movement is mandatory to improve surgical visualization, even in experienced hands, the techniques of one-lung ventilation may be difficult. Additionally, maintaining oxygenation and ventilation during these procedures may be further complicated by increased ventilation-perfusion inequalities in the lateral decubitus position, hypercarbia from the insufflation of CO\textsubscript{2}, and the inhibitory effect of volatile anesthetic agents on hypoxic-pulmonary vasoconstriction. The potential for intraoperative ventilatory problems are demonstrated by a retrospective review of 49 neonates undergoing either laparoscopy or thoracoscopy.17 Oxygen saturation decreased, especially with thoracic insufflation or high-pressure pneumoperitoneum. Although easily corrected by volume expansion, systolic blood pressure decreased in 20% of the patients. Ten anesthetic incidents occurred, three of which required temporary or definitive interruption of insufflation due to an oxygen saturation of less than 70%. Risk factors for an incident included low preoperative temperature, high end-tidal CO\textsubscript{2} readings, and a surgical time more than 100 minutes. The end-tidal CO\textsubscript{2} increased in 88% of the cases and in 56% of the cases, it was not possible to return the end-tidal CO\textsubscript{2} value to baseline despite hyperventilation. The end-tidal CO\textsubscript{2} returned to baseline only with cessation of insufflation. In this study, mean insufflation pressure was 6.7 mm Hg (range: 3-13 mmHg). In a retrospective study of 40 pediatric patients who underwent thoracoscopy and compared to 20 patients who underwent laparoscopy, McHoney et al reported a significantly greater increase in end-tidal CO\textsubscript{2} during thoracoscopy versus laparoscopy despite lower insufflation pressures.18 With conventional mechanical ventilation, end-tidal CO\textsubscript{2} values were higher during single-lung ventilation when compared

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**Table 1: Intraoperative arterial CO\textsubscript{2}, transcutaneous CO\textsubscript{2}, HFOV settings and adjustments.**

<table>
<thead>
<tr>
<th>Time</th>
<th>1115</th>
<th>1130</th>
<th>1150*</th>
<th>1155**</th>
<th>1217</th>
<th>1255</th>
<th>1337</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaCO\textsubscript{2}</td>
<td>42</td>
<td>41</td>
<td>37</td>
<td>45</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PtcCO\textsubscript{2}</td>
<td>60</td>
<td>53</td>
<td>61</td>
<td>47</td>
<td>51</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>SpO\textsubscript{2}</td>
<td>100</td>
<td>100</td>
<td>92</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

**HFOV Settings:**

| Frequency | 6 (Hz) | 5    | 5     | 5      | 5    | 5    | 5    |
| Amplitude | 20 (cmH\textsubscript{2}O) | 30   | 30    | 30     | 30   | 30   |
| MAP       | 12 (cmH\textsubscript{2}O) | 12   | 14    | 14     | 14   |

**Alterations to HFOV settings**

- Increased amplitude to 25, then 30
- Increased MAP to 14
- Increased amplitude to 40
- Increased amplitude to 45
- No change

PaCO\textsubscript{2} = arterial CO\textsubscript{2}; PtcCO\textsubscript{2} = transcutaneous CO\textsubscript{2}; SpO\textsubscript{2} = oxygen saturation by pulse oximetry; HFOV = high frequency oscillatory ventilation; MAP = mean airway pressure. *Surgery start time 1147. *Insufflation to 0.5 mmHg. **Insufflation to 2 mmHg.
with two-lung ventilation (P = 0.02). The maximum change in the end-tidal CO₂ was greater in the younger and smaller patients. The concerns regarding CO₂ insufflation in neonates may involve more than ventilator issues. In animal studies, the effects of hypercarbia and CO₂ insufflation on the cardiovascular system (mean arterial pressure and cardiac output) have been shown to be more pronounced in neonatal versus adolescent animals.¹⁹ With the use of HFOV in our patient, we were able to rapidly control TC-CO₂, PaCO₂, and oxygen saturation with minor adjustments in the HFOV settings. Control of PaCO₂ may be particularly relevant in neonates with CDH given its effects on pulmonary artery pressure in patients at risk for pulmonary hypertension. No clinically significant changes in our patient’s hemodynamic status were noted. Given the limited lung movement produced by HFOV, adequate surgical visualization was obtained with an insufflation pressure of 4 mmHg.

Concurrent with advances in minimally invasive surgical techniques has been the improvement of anesthetic care and monitoring for thoracoscopic procedures. The collaborative practice between the surgeon, anesthesiologist, neonatologist, and respiratory therapist allows the use of low pressure (4-6 mmHg) CO₂ insufflation into the operative hemithorax and the necessary adjustments in airway and ventilator management including directed hyperventilation at low tidal volumes using HFOV. HFOV provides a means of ensuring adequate oxygenation and ventilation while minimizing lung movement and interference with surgical visualization.

HFOV was introduced into ICU care as a means of providing ventilation and oxygenation in the treatment of respiratory failure while potentially limiting the risk of barotrauma and volutrauma in patients with acute lung injury. The potential risks are limited by avoiding high peak inflating pressures and tidal volumes. High frequency ventilator techniques rely on respiratory rates greater than 120 breaths per minute (2 Hz) with tidal volumes that are generally less than dead space. Gas exchange is theorized to occur via the process of convection rather than the process of bulk flow as with conventional mechanical ventilation.²⁰ HFOV uses a piston-driven, diaphragm oscillator that provides a constant mean (distending) airway pressure. Superimposed around the MAP are the oscillations provided by the inward and outward movement of the diaphragm. The movement of the diaphragm results in active inspiration and expiration. Active exhalation may decrease gas trapping from impaired exhalation and prevent inadvertent PEEP.²¹ Tracheal injuries which have been reported with jet ventilatory techniques have not been reported with HFOV.²² Lung volumes are maintained above functional residual capacity thereby providing a constant distending pressure for alveoli while avoiding high peak inflating pressures. Unlike conventional mechanical ventilation, HFOV is unique in that oxygenation and ventilation are separated with the independent adjustments of MAP and FiO₂ for oxygenation and amplitude (delta P), Hz and inspiratory time for ventilation. In general, when caring for patients with acute lung injury, the MAP is set at 2.4 cmH₂O above the MAP on conventional ventilation and adjusted up as needed to allow for a decrease of the FiO₂ to the desired level. In the ICU setting, the efficacy of the MAP and its effect on alveolar recruitment is assessed by a chest radiograph showing lung expansion of 8-9 ribs. Ventilation is controlled primarily by adjusting the amplitude (delta P) using the power setting on the ventilator. The power knob is adjusted to control the amplitude which is changed in increments of 2.4 cmH₂O to provide for adequate chest movement and CO₂ removal. Given the low tidal volumes, end tidal CO₂ cannot be used for monitoring during HFOV. Our experience as noted in this case and previous reports has suggested the utility of TC-CO₂ monitoring with the need for limited arterial blood gas monitoring once a correlation is established.²³ Additionally, as the anesthesia machine is not used, the administration of volatile anesthesia is not feasible thereby mandating the use of total intravenous anesthesia (TIVA). In our patient, TIVA included a combination of remifentanil, dexmedetomidine and midazolam.

Various anecdotal experiences have been reported regarding the efficacy of HFOV during open thoracotomy and thoracoscopic procedures (table 2).²⁴⁻²⁸ Tobias and Burd reported anecdotal experience with the use of HFOV in various clinical scenarios in neonates.²⁴ In infants with CDH, the use of HFOV has become more prevalent as the selected mode of ventilation during surgical repair. In 2000, Bouchut et al. reported the use of HFOV in 22 neonates for open CDH repair.²⁵ No significant differences were noted for any of the studied respiratory parameters (pH, PaO₂, PaCO₂) recorded at preoperative, perioperative, and postoperative times. The authors noted that the surgeons were satisfied with the more stable operative field with less pulmonary expansion and limited diaphragmatic movements. Currently a European multi-center randomized control trial (VICI-trial) is underway to determine if there is a difference in the incidence of bronchopulmonary dysplasia and/or mortality between neonates treated with HFOV and those treated with conventional mechanical ventilation (CMV) prior to, during and after the open CDH repair.²⁶
intervention. Liem et al. reported the use of HFOV during the thoracoscopic repair of CDH in 3.5 kg patient who was unable to tolerate CMV.27 Chest movement and lung vibration at low amplitude did not interfere with surgical visualization and normal vital signs and SpO2 values were maintained during the operation. More recently, Mortellaro et al retrospectively reviewed their experience with HFOV in 17 neonates during thoracoscopic procedures.28 In their cohort of 12 infants with esophageal atresia and 5 with CDH, HFOV provided good intraoperative exposure while allowing effective oxygenation and elimination of CO2 with minimal ventilator adjustments.28

Although its use has decreased in the care of critically ill neonates, other authors have reported the intraoperative application of high-frequency jet ventilation (HFJV) for thoracic surgery procedures in neonates and infants.29,30 To determine the pulmonary response to HFJV ventilation in infants during cardiac surgery, Greenspan et al. evaluated lung function in 9 infants supported with either conventional mechanical ventilation or HFJV during open thoracotomy for placement of a Blalock-Taussig shunt.29 There was no difference in hemodynamic parameters, pulmonary mechanics, functional residual capacity, or PaO2 between the two modes of ventilation. Arterial PaCO2 and mean airway pressure were lower on HFJV when compared with conventional ventilation. As assessed by the surgical team, there was a subjective decreased need for lung manipulation and improved ease of access to the surgical field with HFJV.

We report the successful repair of a neonate with CDH with HFOV guided by TC-CO2 monitoring. Coordinated efforts by Pediatric Surgery, Neonatology, Respiratory Therapy and Anesthesiology allowed the smooth introduction of this ventilatory modality into the operating room without issue. One limitation of this form of ventilation is that routine capnography is not possible. Included in the anesthetic care and monitoring of the patient was the use of TC-CO2 to guide ventilatory management, which to date has not been reported in previous publications in neonatal patients undergoing thoracoscopic intervention. The potential application of TC-CO2 monitoring during HFOV in the ICU setting has been previously reported.23 The TC device estimates PaCO2 by measuring CO2 levels in skin capillaries that have been arterialized by the application of heat. This method is independent of pulmonary status as well as the mode of ventilation but may be altered by the adequacy of skin perfusion. When first initiated in our patient, the gradient between the TC-CO2 monitor and the PaCO2 was 18 mmHg; however, the blood gas value was obtained less than 5 minutes after the initiation of TC-

### Table 2: Reports of intraoperative use of HFOV.

<table>
<thead>
<tr>
<th>Authors and Reference</th>
<th>Demographic data</th>
<th>HFOV or HFJV. Elective use, intraoperative placement or already in place</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tobias and Burd24</td>
<td>Retrospective case series of 3 patients. 1. 14 day old, 27 weeks GA, 900 gram infant for PDA ligation. 2. 1 day old, 37 week GA, 3600 gram infant for closure of gastrochisis and bladder extrophy. 3. 30 day old, 30 week GA, 1500 gram infant for exploratory laparotomy for NEC.</td>
<td>HFOV for all 3 patients. Elective placement prior to the procedure, one patient already on HFOV, and intraoperative use secondary to increased CO2, PIP and decreased SpO2 despite manual ventilation and surfactant administration</td>
<td>HFOV facilitated surgical visualization and effectively controlled oxygenation and ventilation in all 3 patients. Two of the patients were transitioned back to conventional mechanical ventilation while one infant expired 12 hours following the surgical procedure secondary to acidosis and hypo-perfusion.</td>
</tr>
<tr>
<td>Bouchut J et al.25</td>
<td>Retrospective review of 22 newborn infants with a mean GA of 38.3 weeks and birth weight of 3120 grams for CDH repair.</td>
<td>HFOV already in place preoperatively.</td>
<td>HFOV continued intraoperatively through the postoperative period until weaning of ventilation. Adequate surgical visualization with limited lung movement and control of intraoperative oxygenation and ventilation.</td>
</tr>
<tr>
<td>Liem NT et al.27</td>
<td>Single patient case report. 5 day old, 350 gram term infant for thoracoscopic CDH repair</td>
<td>HFOV already in place.</td>
<td>Intra-operative course uneventful with no clinically significant change in vital signs. HFOV use for 48 hours postoperatively followed by conventional ventilator for 44 hours. Tracheal extubation on POD 5.</td>
</tr>
<tr>
<td>Mortellaro VE et al.28</td>
<td>Retrospective room of 17 neonates with a median age of 4 days and weight of 2900 grams. Thoracoscopic repair of EA in 12 d CDH in 5.</td>
<td>HFOV elective use in all patients. Six patients on conventional mechanical ventilation in 6 and spontaneous ventilation in 11.</td>
<td>No intra-operative complications. Good intraoperative exposure with adequate oxygenation and elimination of CO2.</td>
</tr>
</tbody>
</table>

HFOV = High frequency oscillatory ventilation; HFJV = High frequency jet ventilation; GA = Gestational age; PDA = Patent ductus arteriosus; PIP = Peak inspiratory pressure; POD = Postoperative day; NEC = Necrotizing enterocolitis; CDH= Congenital diaphragmatic hernia; EA = Esophageal atresia.
CO₂ monitoring. At the conclusion of the procedure, the gradient had decreased to 1 mmHg. In the future we would consider placing the TC-CO₂ monitor earlier in the care of the patient prior to the initiation of HFOV to allow adequate time for calibration.

In summary, thoracoscopic repair of neonatal conditions such as CDH continues to evolve with increased surgical experience complemented with improvements in technique, instrumentation, anesthetic care, and monitoring. Reported advantages of thoracoscopic versus open thoracic repair include superior surgical visualization, decreased postoperative pain, decreased hospital stay, and a shorter time to oral feeds. Furthermore, the use of high frequency techniques avoids the need for OLV and is effective in reversing the hypercarbia which frequently accompanies thoracoscopic procedures in neonates and infants. The intraoperative application of HFOV allows for adequate oxygenation and ventilation while maintaining good intraoperative exposure. We propose that TC-CO₂ monitoring can be used as a non-invasive measurement of PaCO₂ serving as a continuous, non-invasive guide to ventilation during HFOV and facilitating a proactive ventilatory strategy.

REFERENCES