High-frequency Oscillatory Ventilation
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THE improved viability of low- and very-low-birth-weight infants increases the need for providing safe and adequate anesthesia for those smaller and sicker infants. Premature infants have structurally and functionally immature lungs that predispose to hypoxia. As in critically ill neonates, low lung volumes and poor compliance increase intrapulmonary shunt and ventilation/perfusion mismatch. Those infants are very susceptible to oxygen toxicity and barotrauma. Therefore, anesthetic goals include minimizing the inspired oxygen concentration and the peak inspiratory pressures while maintaining adequate oxygenation and ventilation.1 High-frequency oscillatory ventilation (HFOV) is a widely used lung-protective strategy in neonatal and pediatric acute lung injury.2 The beneficial effects of HFOV on oxygenation and ventilation are well known, but only a few reports describe the use of this technique for intraoperative care.3 However, this mode of ventilation may be useful intraoperatively and should be familiar to anesthesiologists who take part in the treatment of those infants.

HFOV: Definition and Gas Exchange

High-frequency oscillatory ventilation utilizes oscillations generated by a piston pump or a diaphragm oscillator driven by a motor. It produces a sinusoidal or somewhat erratic pressure waveform that gives the expiratory phase its unique active characteristic. This component is created by the backward movement of the diaphragm or piston of the oscillator. A constant distending airway pressure is applied, over which small tidal volumes are superimposed at a high respiratory frequency.

Gas transport includes at least five different mechanisms as illustrated in figure 1: direct alveolar ventilation by bulk convection similar to conventional mechanical ventilation (CMV); mixing by high-frequency out-of-phase pendelluft, or gas exchange between adjacent alveolar units with different time constants; convective change due to asymmetrical velocity profiles; Taylor dispersion, the mixing that occurs along the front of a high-velocity flow profile; and molecular diffusion that occurs within the individual alveolar units.4,5

Oscillator variables adjusted by the operators are frequency, mean airway pressure (PMEAN), pressure amplitude or peak-to-peak pressure, fraction of inspired oxygen (FIO2), and, for some oscillators, percentage of inspiratory time.4

In most HFOV trials and clinical reports, rates of 10–15 Hz were used. This range of frequency covers the majority of clinical situations in neonates. Those rates are near the resonant frequency of the infant lung.6 Bohn has recommended a fixed frequency of 15 Hz.7 The frequency of the oscillation influences carbon dioxide removal in the direction opposite that which happens during CMV. A decrease in frequency from 15 Hz to 12 Hz is responsible for a decrease in arterial partial pressure of carbon dioxide (PACO2). Decreasing the frequency increases tidal volume. Below 12 Hz, a decrease in arterial partial pressure of oxygen (PAO2) is also observed.5

Mean airway pressure recruits alveoli and maintains alveolar volume. Therefore, the level of PMEAN is closely related to lung volume and oxygenation. Current recommendations include starting with a PMEAN of 2–4 cm H2O above the PACO2 on CMV, with stepwise adjustment of 2 cm H2O to allow a decrease in FIO2. After each PMEAN increment, a waiting period of a few minutes is allowed to obtain a new stable level of oxygenation. PMEAN is further increased up to the point that no improvement in oxygenation occurs, using oxygen saturation as a crude surrogate for lung recruitment. This high-lung-volume strategy ensures optimal lung volume recruitment and avoids hyperinflation with the aid of close monitoring of clinical and oxygenation parameters.2

There is a close relation between pressure amplitude and tidal volume. Tidal volume depends on the volume displaced by the piston or the diaphragm, the resistance of the airway, the compliance of the ventilator circuit, and the patient’s lung mechanics. Therefore, the effi-
ciency of oscillation is ensured by the visualization of chest vibrations. Changes in pressure amplitude are used to control ventilation and thus PaCO₂. Increasing pressure amplitude and, thus, tidal volume improves carbon dioxide elimination. To avoid hypocapnia, the level of peak-to-peak pressure may be adjusted clinically to the point that it just produces visible chest vibrations and to that which produces the desired PaCO₂ or transcutaneous carbon dioxide (TcCO₂) values.

The inspiratory:expiratory time ratio is generally fixed to 1:1. However, some oscillators allow manipulation of this ratio in the range of 1:2 to 1:1. It is thought that reducing this ratio reduces gas trapping. However, gas trapping does not seem to be a significant problem during HFOV. Moreover, it seems that an inspiratory:expiratory ratio of 1 is associated with minimal difference between mean alveolar pressure and mean airway opening pressure.⁸

HFOV and Pulmonary Function

HFOV is an efficient mode of ventilation for infants with a variety of lung conditions. HFOV maintains lung volumes above functional residual capacity, avoiding high peak inspiratory pressure. Pulmonary compliance is higher in HFOV than in CMV when using a similar P̄MEAN in saline-lavaged rabbits over a 4-h period.⁹ However, if P̄MEAN settings exceed optimal values, lung overdistension can occur, with potentially serious adverse effects, such as pneumothorax or circulatory impairment.⁴

When compared with CMV, HFOV reduces the conversion of surfactant into small aggregate forms, at least in an experimental model of acute lung injury.¹⁰ This beneficial effect of HFOV stabilizes alveoli and thus expands the lungs to a greater extent than CMV does.

HFOV may reduce ventilator-induced lung injury by reducing the risk of gross air leak and volume overdistension of terminal airways. Meta-analyses of elective HFOV with high-volume strategy in preterm infants with respiratory distress syndrome have shown benefits in terms of decreased incidence of chronic lung disease, supplemental oxygen at discharge, and mortality, without an increase in the rate of intraventricular hemorrhage.¹¹

HFOV and Hemodynamics

Systemic Circulation

The effects of HFOV on cardiac output, organ blood flow, and central venous pressure are the same when compared with CMV. The interaction between HFOV and cardiovascular function is largely determined by the level of P̄MEAN and respiratory compliance but is independent of frequency rates. If a high P̄MEAN is used, lung distension might occur, leading to impaired venous return, cardiac function, and reduced cerebral perfusion.¹²,¹³ If
PMEN is carefully reduced when arterial oxygenation improves, HFOV can be achieved without depressing cardiovascular dynamics more than CMV. Moreover, severe paroxysmal sinus bradycardia has been reported and was related to overdistension of alveoli as compliance was improving.

Cerebral Circulation

The effects of PMEN on cerebral circulation are not significantly different in HFOV and CMV, but the possibility for lung overdistension may contribute to the development of ischemic–hemorrhagic injury in the brain of a premature neonate. Therefore, careful clinical management is necessary to reduce the risks of unnecessarily high levels of PMEN. In addition, HFOV is effective in eliminating carbon dioxide, and avoiding hypocapnia is essential to prevent neonatal brain damage.

HFOV in the Neonatal Intensive Care Unit

The first successful use of HFOV was reported by Marchak et al. in 1981 in eight neonates with neonatal respiratory distress syndrome. Since that time, many clinical trials have been performed and extensively reviewed in the Cochrane database. These clinical trials varied widely in design, neonatal care, and ventilation strategies, explaining conflicting results.

Positive trials are characterized by a recruitment strategy in the HFOV group; the use of slow rates, large tidal volume, and low positive end-expiratory pressure in the CMV group; or both. Negative trials are characterized by the absence of recruitment strategy in the HFOV group, a delayed randomization using HFOV as a rescue mode of therapy, or both. Two recently published multicenter trials of early HFOV intervention showed no differences in adverse outcome, particularly in intraventricular hemorrhage and periventricular leukomalacia. The U.S. HFOV trial enrolling 500 infants weighing less than 1,200 g showed improved pulmonary outcome in the HFOV group with the use of a high-volume strategy and vigorous control of carbon dioxide levels, avoiding hypercapnia.

Clinical experience with HFOV for the treatment of acute hypoxic respiratory failure in term and near-term infants now extends over 20 yr. HFOV is used in pulmonary interstitial emphysema, persistent pulmonary hypertension, meconium aspiration syndrome, congenital

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**Table 1. Intraoperative Use of High-frequency Oscillatory Ventilation (HFOV)**

<table>
<thead>
<tr>
<th>Procedure</th>
<th>Reference</th>
<th>PMEN Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thoracic Procedures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Congenital diaphragmatic hernia</td>
<td>23-24</td>
<td>Increase PMEN after viscera re-integration in the abdomen.</td>
</tr>
<tr>
<td>Congenital cystic adenomatoid malformation</td>
<td>25-29</td>
<td>Avoid lung hyperinflation by cautious and incremental changes in PMEN.</td>
</tr>
<tr>
<td>Esophageal atresia</td>
<td>31</td>
<td>Increase PMEN before lateral decubitus to ensure an optimizing recruitment.</td>
</tr>
<tr>
<td>Patent ductus arteriosus</td>
<td>3, 31</td>
<td>Beware of reducing PMEN at the end of the procedure to reduce the risk of lung overdistension.</td>
</tr>
<tr>
<td>Abdominal Procedures</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Abdominal wall defect</td>
<td>3, 31</td>
<td>Increase PMEN after viscera reintegration in the abdomen to counteract intra-abdominal pressure to ensure carbon dioxide elimination.</td>
</tr>
<tr>
<td>Enterocolitis</td>
<td>3, 31</td>
<td>Use HFOV if ventilation/perfusion altered by sepsis.</td>
</tr>
</tbody>
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PMEN = mean airway pressure
diaphragmatic hernia, and many cases in which CMV has failed to improve oxygenation and ventilation.4,22

HFOV in the Operating Room

Mechanical ventilation of preterm newborn infants and critically ill neonates induces major challenges in the operating room. When caring for these patients, clinicians can choose between different strategies to produce efficient ventilation despite the limitations of technology. An old and traditional approach is to ventilate manually with a bag. A recent approach is to fit the ventilator settings to a clinical assessment during volume-controlled or pressure-controlled ventilation to achieve adequate oxygenation and carbon dioxide elimination. In patients with altered respiratory compliance as seen in congenital diaphragmatic hernia and abdominal wall defects, standard anesthesia ventilators or intensive care unit ventilators are not very convenient to provide adequate gas exchange and oxygenation without high FiO2 and high peak inflating pressures. Reducing the factors responsible for the development of lung injury or retrolental fibroplasia may be beneficial for children in growth. In this way, anesthesiologists are involved in minimizing the risks related to prematurity.1

Continuity in perioperative ventilatory management of these infants is another potential advantage of this technique.22,23 HFOV is instituted before surgery, applied

### Table 2. Guidelines for Adjusting Ventilatory Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Initial Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Frequency</td>
<td>10 to 15 Hz</td>
</tr>
<tr>
<td>2. I/E ratio</td>
<td>If not fixed 1/2 to 1/1</td>
</tr>
<tr>
<td>3. Gas bias flow</td>
<td>If not fixed 15 to 20 l/min (beware of flow influence on Pmean)</td>
</tr>
<tr>
<td>4. Pmean</td>
<td>Starting with a Pmean of 2-4 cm H2O above the Pmean on CMV (adjustment by stepwise of 1-2 cm H2O). Adjusted to SaO2</td>
</tr>
<tr>
<td>5. Amplitude pressure</td>
<td>Adjusted to the point that chest vibrations can be seen and to TcCO2 or PaCO2 (adjustment by stepwise of 2-4 cm H2O)</td>
</tr>
<tr>
<td>6. FiO2</td>
<td>Adjusted to SaO2</td>
</tr>
</tbody>
</table>

CMV = conventional mechanical ventilation; I/E = inspiratory/expiratory ratio; Pmean = mean airway pressure; PaCO2 = arterial partial pressure of carbon dioxide; PaO2 = arterial partial pressure of oxygen; SaO2 = arterial oxygen saturation; TcCO2 = transcutaneous carbon dioxide.

### Table 3. Management of Common Nontechnical Problem with High-frequency Oscillatory Ventilation

<table>
<thead>
<tr>
<th>Problems</th>
<th>Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hypoxia</td>
<td>Increase Pmean by stepwise of 2 cm H2O adjusted to SaO2 and hemodynamic tolerance.</td>
</tr>
<tr>
<td>Hypercapnia or no chest vibration</td>
<td>Increase amplitude pressure so that chest vibration can be seen and to obtain adequate TcCO2 or PaCO2. If not sufficient, reduce frequency.</td>
</tr>
<tr>
<td>Hypocapnia</td>
<td>Decrease amplitude pressure to obtain adequate TcCO2 or PaCO2.</td>
</tr>
<tr>
<td>Hypotension</td>
<td>If not related to hypovolemia and/or anesthetics, reduce Pmean.</td>
</tr>
</tbody>
</table>

Pmean = mean airway pressure; PaCO2 = arterial partial pressure of carbon dioxide; SaO2 = arterial oxygen saturation; TcCO2 = transcutaneous carbon dioxide.
intraoperatively, and continued during postoperative management. Surgeons may appreciate a relatively stable operative field, which may facilitate repair.22

In addition, HFOV has been used for thoracic and abdominal procedures in term and preterm infants (table 1).

Miguet et al.22 and then Bouchut et al.23 reported their experience with HFOV during repair of congenital diaphragmatic hernias. No differences in ventilatory settings, blood gas values, or oxygenation index values before, during, and immediately after surgery were recorded. The authors suggest that no aggressive ventilatory management (high inspiratory peak pressure or Fio2) was required during surgical repair, when there was deterioration in respiratory mechanics. The technique may have a protective ventilatory strategy; however, studies were not designed to compare the effectiveness of HFOV with that of CMV. This same team reported the elective perioperative use of HFVO in congenital cystic adenomatoid malformation management.24 HFOV was initiated immediately after birth and was continued during surgical repair and into the postoperative period. Other surgical teams have reported the same successful application of HFOV in congenital cystic adenomatoid malformation.24–27 HFOV has also been used in the thoracic procedures of term infants.26,29 It achieves a more stable operative field, with fewer pulmonary expansions and diaphragmatic movements. HFOV was also used during closure of abdominal wall defects.3,30 Reintegration of viscera into the abdomen may increase intraabdominal pressure, reduce lung volume, and impair diaphragmatic movement. HFOV provides effective ventilation and oxygenation in infants with increased intraabdominal pressure.31

Tobias and Burd3 reported the intraoperative use of HFOV in three neonates during surgical ligation of a patent ductus arteriosus, closure of a gastrochisis, and an exploratory laparotomy for necrotizing enterocolitis. This report emphasized the main applications of HFOV during surgery: anesthetic care for neonates already receiving HFOV, minimizing lung movement and interference with the surgical field, and application when altered respiratory compliance led to ineffective intraoperative oxygenation/ventilation.

In a retrospective study, Miguet et al.30 described 57 newborn infants ventilated by HFOV during surgical procedures that included repair of esophageal atresia, pulmonary malformation, patent ductus arteriosus, congenital diaphragmatic hernia, and abdominal wall defect. The authors reported the same advantages as those emphasized by Tobias and Burd. Despite successful reports with this mode of ventilation during intraoperative use of HFOV, some limitations must be pointed out.

Routine capnography is not possible during this form of ventilation. Berkenbosch and Tobias32 recommend the use of TCO2 monitoring. However, TCO2 may be limited by the lack of reliability when skin perfusion is reduced. Chest vibrations should be closely clinically monitored and have been shown to be a reliable indicator to adapt the pressure amplitude to achieve acceptable Paco2 during surgery.25 Because hypocapnia and hypercapnia are deleterious, clinical assessment of ventilation and TCO2 or blood gas monitoring should be used when caring for small neonates.

The use of inhalational anesthetic agents is not ordinarily used with HFOV because this technique does not use the anesthesia machine ventilator. Therefore, total intravenous anesthesia agents that supply analgesia, amnesia, hypnosis, and neuromuscular blockade are recommended.

The use of HFOV is not possible during transport between the neonatal intensive care unit and the operating room, and manual bag-valve ventilation is often required during this period. Surgical procedure on-site in the neonatal intensive care unit is often proposed particularly in neonates whose cardiopulmonary status is unstable.

In our experience, the main limitation of HFOV during surgery is related to anesthesiologists who are unfamiliar with this mode of ventilation.

The characteristics of commercially available oscillators differ markedly between each other.33 Ventilatory setting guidelines differ with each HFOV device. Nevertheless, common recommendations may be proposed for the use of HFOV during neonatal surgery (tables 2 and 3).

Perspectives

The global clinical impression is that the use of HFOV during neonatal surgery improves surgical comfort and respiratory status compared with conventional ventilation. As neonatal care improves, anesthesiologists will be faced with an increasing number of high-risk neonates and therefore must be familiar with this mode of ventilation. The history of HFOV clinical trials shows the difficulty in evaluating this technique despite a large population.34 Notwithstanding the absence of randomized controlled trials, HFOV seems to be a useful adjunct for providing preoperative respiratory support. Nevertheless, studies are necessary to better determine which infants may benefit most from HFOV during surgery.

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