High Frequency Oscillatory Ventilator (HFOV) Module
**HIGH FREQUENCY OSCILLATORY VENTILATION**

**INTRODUCTION**

Premature infants and those of low-birth-weight receiving positive pressure ventilation are vulnerable to Pulmonary Injury Sequence (PIS) of prematurity. PIS may begin when the infant, who lacks surfactant, initiates a tidal volume breath. In the immature lung, distal alveoli may prematurely collapse because of the lack of surfactant. The opening pressure required to expand these non-compliant areas is significant. Spontaneously breathing infants may not be able to generate the opening pressures required to inflate distal alveoli. Historically, when mechanical ventilation was initiated, tidal volumes of 10 – 15cc/kg of ideal body weight were used to ventilate the patient. These volumes are approximately 75 to 150% of the volumes that patients generate during spontaneous ventilation. While conventional ventilation usually provides adequate gas exchange, potentially irreversible lung damage may result. Damaging peak airway pressures, circulatory depression, and pulmonary air leaks are potential complications.

**DEVELOPMENT OF THE RESPIRATORY SYSTEM**

The basic respiratory system appears by about the fourth week of gestation. Most systems are developed by about 24-25 weeks of gestation. The pulmonary system however, continues to develop throughout gestation and the lung does not reach maturity until about 8 years of age.

Lung compliance (e.g. lung distensibility) is dependent on the production of surfactant, the product of Type II pneumocytes. Surfactant is synthesized and secreted by Type II alveolar pneumocytes contained within the alveolar walls. Surfactant is 90% phospholipids and 10% proteins. The phospholipids fraction is primarily lecithin. Other phospholipids, including sphingomyelin, make up a smaller portion of surfactant. Surfactant reduces surface tension at the air-liquid interface of the terminal airways and alveoli. This helps maintain alveolar stability and prevents atelectasis. At 18 weeks of gestational age, surfactant can be detected in the amniotic fluid. It is generally agreed that the lung is mature enough to support spontaneous ventilation at about 34-36 weeks of gestational age. Infants, who are born before 34 weeks of gestational age and require mechanical ventilation, are at risk for lung injury.

**PATHOPHYSIOLOGY OF LUNG INJURY**

In general, the majority of lung injuries can be placed into one of two categories. The two categories are **Diffuse Alveolar Disease (DAD)** or **Air Leak Syndrome (ALS)**. A term that seems to encompass both DAD and ALS is Pulmonary Injury Sequence.

Pulmonary Injury Sequence (PIS) of prematurity is a continuation of a disease that includes Respiratory Distress Syndrome (RDS), Air leak Syndrome (ALS), Pulmonary Interstitial Emphysema (PIE), and Bronchopulmonary Dysplasia (BPD). ALS/RDS can occur with conditions such as pneumonia, sepsis, meconium aspiration, aspiration of stomach contents, and inhalation injury due to toxic chemicals, oxygen toxicity and chest trauma.

Patients who develop ALS/RDS frequently develop respiratory failure. As ALS/RDS becomes more severe, the ability to oxygenate and ventilate decreases secondary to intrapulmonary shunting and ventilation-perfusion mismatch. In an attempt to improve ventilation and oxygenation, clinicians increase tidal volume, peep, and/or FiO₂. By increasing tidal volumes on lungs with significantly reduced compliance, the chances for volutrauma also increase. When FiO₂ is increased to what is considered toxic levels, (>50%), toxins such as free oxygen radicals are released further exacerbating the lung injury.
RDS is an acute inflammatory response in which the lung is not uniformly injured. The diffuse manner in which the lung is affected causes airway resistance and compliance changes. A product of airway resistance and compliance is a phenomenon known as a **time constant**. A time constant is the time required to make a step change in airway pressure equilibrated through the lungs. Lung regions that have either an increase in airway resistance or compliance will have a long time constant.

Conversely, regions with decreased airway resistance or compliance will have a short time constant. This is significant when mechanically ventilating a patient with lung disease. A patient with BPD will have time constants that are long (slow alveoli) because of increased resistance. In RDS, time constants are very short (fast alveoli) because of low compliance.

Bronchopulmonary Dysplasia (BPD) is a chronic lung disease (CLD) that develops in preterm and term neonates treated with oxygen and positive pressure ventilation. The frequency of BPD is dependent on the definition used and varies significantly between NICUs and geographic regions. BPD is generally defined as a patient with an oxygen requirement at 28 days of age to maintain a PaO₂ > 50 mm Hg and radiographic changes. The pathophysiology of BPD is multifactorial. The alveolar stage of lung development in the human is from about 36 week’s gestation to 18 months with most alveoli developing within 5 to 6 months of term birth. Mechanical ventilation and oxygen interfere with alveolar and vascular development in the preterm infant.

Pulmonary interstitial emphysema (PIE) is an iatrogenic pulmonary condition of the premature infant with immature lungs. PIE occurs almost exclusively with mechanical ventilation. The pressure used to keep the alveoli open may also rupture the alveoli duct. This usually occurs at the junction of the bronchiole and alveolar duct. Consequently, air escapes into the pulmonary interstitium, lymphatics and venous circulation.

The pathophysiology of PIE is fairly straightforward. Immature lungs are underdeveloped and lack an adequate amount of surfactant to keep the alveolar ducts and early alveoli open on inspiration and expiration. This results in a decrease in surface area to accommodate gas exchange and results in widespread atelectasis. This in turn leads to inadequate transfer of carbon dioxide and oxygen across the alveoli into the pulmonary vascular.

Air leaks in the immature lung are unique when compared to that of the mature lung. In adults, the alveoli are relatively distensible and the surrounding airway, which is surrounded with cartilage and muscle, is relatively stiff. In infants with immature lungs, the opposite is true. With infants, the most common area for rupture is at the junction of the distal airway and the atelectatic alveoli. This is the region of greatest strain from airway overdistension. Air leaks are the most frequent life threatening complication for mechanically ventilated patients. ALS includes Pulmonary Interstitial Emphysema (PIE), pneumothorax, pneumopericardium, pneumomediastinum, and pneumoperitoneum.

Patients who have either Diffuse Alveolar Disease or Air Leak Syndrome present a unique set of challenges for mechanical ventilation. The challenge is to facilitate gas exchange without inflicting further damage to the lung. High Frequency Ventilation is one tool for meeting this challenge.

**HIGH FREQUENCY VENTILATION**

There are several variations of high frequency ventilation. They are generally classified as High Frequency Positive Pressure Ventilation, High Frequency Jet Ventilation, and High Frequency Oscillatory Ventilation. High Frequency Oscillatory Ventilation (HFOV) is the most common form of high frequency ventilation used today. HFOV is created when an oscillatory waveform is superimposed on a bias flow of gas at a respiratory rate greater than 60 breaths per minute. HFOV is unique for two reasons. First, the expiratory phase is active. The oscillating device that generates the high-pressure waveform is a reciprocating piston, which generates a negative expiratory pressure. This negative expiratory pressure promotes emptying of the lung. Second, the
delivered volume during HFOV is less than the anatomic dead space (1-2cc/kg ideal body weight). HFOV uses a very rapid respiratory rate; usually more than four times the normal rate, and small tidal volumes. Respiratory rates range from 3 to 15 Hertz. One hertz is 60 breaths per cycle. So if a patient is on a hertz of 10, they are receiving 600 breaths per minute.

With tidal volumes that are less than physiologic deadspace, how does gas exchange occur? With conventional ventilation, a bulk flow of gas enters the airway with each inspiration. Passive diffusion occurs and the exchange of CO₂ and O₂ occurs at the end of expiration. That said, how does gas exchange occur with HFOV? Here are four theories that are generally accepted.

1. **Convection Streaming**: During the inspiratory phase of high frequency ventilation, a pulse is created that moves central molecules further down the airway than those molecules that remain on the periphery of the airway.

2. **Pendeluft Effect**: The Pendeluft Effect is the mechanism in which over distended alveoli contribute to the inflation of the under inflated alveoli. This is important because of the variance of time constants seen in ARDS. The more compliant alveoli will empty into the less compliant alveoli during exhalation. During inspiration, less compliant alveoli empty into the more compliant alveoli. This theory is generally accepted to be as one of the most significant theories when defining gas distribution and the success of HFOV.

3. **Augmented Dispersion (Taylor Dispersion)**: Taylor dispersion is the theory of gas traveling in a tube. Gas that flows through a tube has a parabolic front (laminar flow). This occurs at the front of the column of gas or along the sides of the column. All the branching and complex structure of the lungs, which leads to turbulence or disruption in the laminar flow, causes the mixing of gases.

4. **Cardiogenic Mixing**: Cardiogenic mixing may augment gas exchange via an increase in turbulence in those parts of the lung contiguous to the heart. Lung units that border the heart are alternately compressed and then inflate as the heart beats. This leads to an increase in gas exchange.

The HFOV circuit is a simple concept in theory: gas flow is administered via a continuous positive airway pressure circuit. This flow is manufactured by gas coming in contact with a diaphragm that alternately pushes and pulls gas through the circuit. The initial high pressures (105 cm H₂O for 3100A and 130 cm H₂O for 3100B) of the amplitude pressure waves in the proximal airway are rapidly dampened by the conducting airway so the alveoli encounter a very low amplitude wave. This is called the **low pass filter effect**. Peak pressures slowly decrease from the proximal to the distal airway while the mean airway pressure remains constant. Although these ventilators are capable of generating oscillatory peak-to-peak pressures at the proximal endotracheal tube attachment point as high as 130 cm H₂O; no such pressures are developed in the trachea. This is because the respiratory system impedance (which the endotracheal tube is the dominant element) greatly diminishes these high frequency pressure waves and distorts their waveform into a nearly triangular pattern.

For instance, using 15 Hz and a compliance of 1ml/cm H₂O, the approximate losses are:

- 90% 2.5 mm ETT
- 80% 3.5 mm ETT
- 60% 4.5 mm ETT
- 47% 5.5 mm ETT
- 34% 6.5 mm ETT

With a larger endotracheal tube, the distal pressures are greater and the reduction in PaCO₂ is improved.
INDICATIONS FOR USE OF HIGH FREQUENCY OSCILLATORY VENTILATION

There are several indications for the use of High Frequency Oscillatory Ventilation. The two most common indications are Air Leak Syndrome and Acute Respiratory Distress Syndrome. Some general considerations for transitioning a patient from conventional ventilation to high frequency ventilation include a FiO₂ >60%, a peep >10 cm H₂O, an OI >16, and the inability to maintain a pH >7.25. There are specific disease processes that also merit consideration for initiating HFOV.

Patients with Diffuse Alveolar Disease (DAD) may benefit from management by HFOV. The strategy for managing these patients is to maintain a mean airway pressure high enough to recruit and distend collapsed alveoli. This recruitment and distention is intended to reverse the V/Q mismatch and decreases the need for toxic levels of oxygen. Patients with Diffuse Alveolar Disease have time constants in the lungs that vary from region to region. By maintaining a constant mean airway pressure, using small tidal volumes, and limiting pressure fluctuations, volutrauma and shearing injury is minimized.

Patients who have Air Leak Syndrome (ALS) may benefit from HFOV. Using a “low” lung volume strategy, adequate ventilation can be accomplished. By limiting tidal volumes to that above critical opening pressures, and by minimizing pressure fluctuations, the insult to the damaged region of the lung is decreased. Mean airway pressures should be kept as low as possible while maintaining adequate blood oxygen levels.

Patients with Respiratory Syncytial Virus (RSV), Status Asthmaticus, or other disease with obstruction to flow are generally not placed on HFOV. These diseases require a long expiratory time and with respiratory rates as high as 15 Hz (900 breaths per minute), the expiratory time is inadequate and air trapping may result. However, patients who develop pneumonia secondary to RSV have been managed quite well on HFOV.

Patients born with Lung Hypoplasia Syndrome often benefit from the use of HFOV. Pulmonary Hypoplasia is a relatively common abnormality of lung development and is often associated with congenital diaphragmatic hernia (CDH). Patients benefit because with a single lung, the surface area of lung that participates in gas exchange is reduced by half if not more. The developed lung may be compressed by a mediastinal shift. This shift may cause a compression of the lung, reduce blood flow through the pulmonary veins, and may cause a decrease in venous return. By using MAPs that are fairly low and increasing the MAP in small increments, optimal lung volume can be achieved without extensive pressure increases thus preventing airleaks.

Hypoplastic lungs, which have a decrease in the vascular cross-section, develop persistent pulmonary hypertension (PPHN). There are multiple possible causes of PPHN but the management from a pulmonary point of view is basically the same. First, myocardial function must be optimized. Once that is done, the patient may be tried on Nitric Oxide prior to placing a patient on HFOV. If the patient does not respond to or has a minimal response to Nitric Oxide and conventional ventilation, the patient is placed on HFOV for the purpose of optimizing lung volume. It is a common practice to leave the patient on Nitric Oxide while on HFOV. Once optimal lung volume is achieved, the patient should be hyperventilated and hyperoxygenated to promote relaxation of the smooth muscle in the pulmonary vascular bed. Accomplishing this should decrease pulmonary vascular resistance.

3100A and 3100B HIGH FREQUENCY OSCILLATORY VENTILATION

The 3100B was developed to allow for HFOV on patients over 35 kg. Both the 3100A and B consists of 6 subsystems, external air/oxygen blender, and an external humidifier.
The 6 subsystems are:

1. Pneumatic Logic and Control
2. Patient circuit
   a. The circuit for the B is longer and more flexible
3. Oscillator Subsystem
4. Airway pressure monitor
5. Electronic control and alarms
6. Electrical supply

**COMPARISON OF THE 3100A AND 3100B**

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<th>3100A</th>
<th>3100B</th>
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<td>MAP</td>
<td>49 cmH₂O</td>
<td>59 cmH₂O</td>
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<tr>
<td>Bias Flow</td>
<td>40 LPM</td>
<td>60 LPM</td>
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<tr>
<td>Max Delta P</td>
<td>105 cmH₂O</td>
<td>130 cmH₂O</td>
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<tr>
<td>Safety Dump Press</td>
<td>50 cmH₂O</td>
<td>60 cmH₂O</td>
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<td>Safety Dump Alarm</td>
<td>No Delay</td>
<td>1.5 sec delay</td>
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<tr>
<td>Min Airway Pressure Limit</td>
<td>&gt;20% High Paw alarm set</td>
<td>5 cmH₂O</td>
</tr>
<tr>
<td>MAP Pressure Limit</td>
<td>Manual-approximately 10-45 cmH₂O</td>
<td>Automatic</td>
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<tr>
<td>Piston Centering</td>
<td>Manual</td>
<td>Automatic</td>
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<tr>
<td>Cooling Gas Flow</td>
<td>10 LPM</td>
<td>25 LPM</td>
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<tr>
<td>Circuit Length</td>
<td>31 inches</td>
<td>51 inches</td>
</tr>
<tr>
<td>Visual Max set</td>
<td>Red LED; non-latching</td>
<td>Red LED, latching</td>
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</tbody>
</table>
CONTROLS AND INDICATORS

This section will deal with the control knobs and indicators on both the 3100A and B. With a few exceptions, the functions of the control knobs are the same for both ventilators.

Bias Flow: controls and indicates the rate of continuous flow of humidified gas. This gas supplies fresh gas that aids in flushing the CO2. Bias flow is also a limiting factor for setting mean airway pressure. The maximum available flow is 40 LPM for the 3100 A and 60 LPM for the 3100 B.
Power/Delta P: determines the amount of power that is driving the oscillator piston back and forth. The knob scale is a 10-turn locking dial that is not calibrated in % power but is marked for purposes of establishing reference points. This knob has control of the displacement of the oscillator piston and the oscillatory pressure Delta P.

Mean Pressure Limit: controls the limit above which proximal mean airway pressure cannot be increased. The approximate range is 10 to 45cmH₂O and is set manually approximately 2cm H₂O above the mean. The 3100B mean pressure limit is internally set at 5cmH₂O above the mean airway pressure and requires no intervention by the clinician.

Mean Pressure Adjust: this adjusts the mean airway pressure by controlling the resistance of the Paw Control valve. When adjusted, the control fixes the mean pressure at the ETT/patient connection. Changes to Frequency, % I time, Power, Piston Centering, and adding water to the humidification chamber may affect the mean airway pressure.

When setting the power on the 3100A, the goal is to achieve chest wiggle from the clavicles to the umbilicus. With the 3100B, the goal is to achieve chest wiggle from the clavicles to mid-thigh.
Amplitude: pressure gradient between peak inspiratory and peak expiratory pressures within the oscillatory circuit. Note: The gradient in the airways is significantly less than the pressure gradient in the circuit. For patients on the 3100B, the amplitude should be set 20 above the PaCO₂.

% Inspiratory Time: determines the amount of time the piston is in the inspiratory position. When the clinician changes the % Inspiratory Time, it changes the starting position of the piston to begin inspiration. A % Inspiratory Time of 33% gives an I:E ratio of 1:2. A % Inspiratory Time of 50% gives an I:E ration of 1:1. Since this control affects the shape of the waveform, changing % Inspiratory Time will affect the Mean Airway Pressure and the Delta P.

Frequency: sets the oscillator frequency in Hertz. One Hertz is 60 cycles and is measured in cycles per minute. An example of this is a hertz of 5 is 300 cycles per minute. Both A and B have a range of 3 to 15 Hertz.
**Mean Airway Pressure**: displays the Paw on a digital meter in cmH2O

**Set Max Paw**: this determines the level at which the Max Paw Exceeded Warning Alarm is activated. The 3100B does not have a manual alarm to set; it is internal and is preset at 5 cmH2O above the set Paw.

**Set Min Paw**: this determines the level at which the Min Paw Exceeded Warning Alarm is activated.

**Alarm silence**: silences alarms for 45 seconds

**Reset**: this momentary push button resets all Safety Alarms and the Power Failure alarm. Certain conditions must first be corrected before the reset and restart of the oscillator will occur.

**Start/Stop**: this changes the oscillator between enable and disable.
**Paw>50 cmH2O**: this indicates that the preset Safety alarm has been activated. On the 3100B, this alarm is set at 60 cmH2O. When this alarm is activated, both the 3100A and 3100B will automatically shut down. When this occurs, bias flow continues, the dump valve opens and holds the airway pressure near the current atmospheric pressure. The only way to reset this alarm is to correct the problem and push the reset button.

**Paw<20% of “Set Max Paw”**: This alarm is activated when the Paw level is equal to 20% of the thumbwheel setting. When this alarm is activated, both the 3100A and 3100B will automatically shut down the oscillator. When this occurs, bias flow continues, the dump valve opens, and atmospheric pressure is held. The 3100B alarm is internally set to alarm at 5 cmH2O above the Set Max Paw. Additionally, there is no delay in the dump valve opening with the 3100A. With the 3100B, there is a 1.5 second delay. After the 1.5 second delay, the 3100B will reset itself whereas the 3100A does not.
**Piston Centering Control**: Determines the center position of the oscillator piston.

**Power Switch**: Turns power on to the 3100A and B system.
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<th>Possible Causes</th>
<th>Possible Remedies</th>
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<tr>
<td>Displayed Paw &gt; 50cmH₂O</td>
<td>1. Patient at high Paw and spontaneously breathing</td>
<td>1. Bias flow rate possibly insufficient, re-adjust Paw using higher flow</td>
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<tr>
<td>Alarm</td>
<td></td>
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<td></td>
<td>2. Obstruction in exp limb</td>
<td>2. Replace patient circuit</td>
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<tr>
<td></td>
<td>3. Obstruction in pressure sense line</td>
<td>3. Replace patient circuit</td>
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<tr>
<td></td>
<td>4. Interference from radio transmitter</td>
<td>4. Remove source of interference</td>
</tr>
<tr>
<td>Displayed Paw &lt; Set Min thumbwheel alarm</td>
<td>1. Patient spontaneously breathing</td>
<td>1. Bias Flow rate possibly insufficient, re-adjust Paw using higher flow</td>
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<tr>
<td></td>
<td>2. Improper setting of thumbwheel switch</td>
<td>2. Change setting</td>
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<tr>
<td></td>
<td>3. Improper setting of Paw adjust or flow meter</td>
<td>3. Change setting</td>
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<tr>
<td></td>
<td>4. Patient circuit temp drop</td>
<td>4. Check and correct circuit temperature</td>
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<tr>
<td></td>
<td>5. Improper setting of Paw limit</td>
<td>4. Change setting</td>
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<tr>
<td></td>
<td>6. Leak in patient circuit</td>
<td>6. Eliminate leak or replace circuit</td>
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<td></td>
<td>7. Cap diaphragm leak</td>
<td>7. Replace cap diaphragm</td>
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<tr>
<td></td>
<td>8. Interference from a radio transmitter</td>
<td>8. Remove source of interference</td>
</tr>
<tr>
<td>Displayed Paw &gt; Set Max Paw thumbwheel alarm</td>
<td>1. Patient spontaneously breathing</td>
<td>1. Bias Flow rate possibly insufficient, re-adjust Paw using higher flow</td>
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<tr>
<td></td>
<td>2. Improper setting of thumbwheel switch</td>
<td>2. Change setting</td>
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<td></td>
<td>3. Obstruction of exp limit</td>
<td>3. Replace the patient circuit</td>
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<tr>
<td></td>
<td>4. Obstruction of pressure sense line</td>
<td>4. Replace the Patient circuit</td>
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<td>5. Patient circuit temperature</td>
<td>5. Check and correct circuit rise temperature</td>
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<td></td>
<td>6. Interference from a radio transmitter</td>
<td>6. Remove the source transmitter of interference</td>
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<tr>
<td>Conditions</td>
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<td>Possible Remedies</td>
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<tr>
<td>Displayed Paw &lt; 20cmH\textsubscript{2}O Set Max Thumbwheel Alarm</td>
<td>1. Improper setting of thumbwheel switch</td>
<td>1. Change setting</td>
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<tr>
<td></td>
<td>2. Improper setting of Paw adjust or flow meter</td>
<td>2. Change Setting</td>
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<td></td>
<td>3. Improper setting of Paw limit</td>
<td>3. Change Setting</td>
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<td></td>
<td>4. Leak in humidifier or patient circuit, including patient disconnect</td>
<td>4. Eliminate leak or replace circuit</td>
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<tr>
<td></td>
<td>5. Cap diaphragm leak</td>
<td>5. Replace cap diaphragm</td>
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<tr>
<td></td>
<td>6. Interference from a radio transmitter</td>
<td>6. Remove source of interference</td>
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<tr>
<td></td>
<td>7. Open water trap stopcock</td>
<td>7. Close water trap stopcock</td>
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<tr>
<td>Oscillator stopped with no other alarm occurring</td>
<td>1. Power setting too low and ΔP is less than 6 cm H\textsubscript{2}O</td>
<td>1. Bias Flow rate possibly insufficient, re-adjust Paw using higher flow</td>
</tr>
<tr>
<td></td>
<td>2. Oscillator piston not centered</td>
<td>2. Change setting</td>
</tr>
<tr>
<td></td>
<td>3. Oscillator failure</td>
<td>3. Remove from service</td>
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<tr>
<td>Source Gas Low Alarm</td>
<td>1. Input pressure less than 30 psi, either from blender or cooling gas</td>
<td>1. Check input gas line</td>
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<tr>
<td></td>
<td>2. Input filter needs replacement</td>
<td>2. Replace filters</td>
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<td></td>
<td>3. Flow restriction in gas supply lines</td>
<td>3. Replace the patient circuit</td>
</tr>
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<td></td>
<td>4. Internal leak</td>
<td>4. Call Sensormedics</td>
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<tr>
<td>Battery Low Alarm</td>
<td>1. Battery voltage less than optimal</td>
<td>1. Replace battery</td>
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<tr>
<td></td>
<td>2. Battery disconnected</td>
<td>2. Properly reconnect battery</td>
</tr>
<tr>
<td>Oscillator Overheated Alarm</td>
<td>1. No cooling gas flow</td>
<td>1. Assure cooling gas supply is attached</td>
</tr>
<tr>
<td></td>
<td>2. Oscillator overheated due to poor cooling gas flow</td>
<td>2. Check cooling gas flow for blocked filter element or restricted supply hose replace if necessary</td>
</tr>
<tr>
<td></td>
<td>3. Oscillator overheated to mis-centered at very high ΔP setting</td>
<td>3. Readjust centering while monitoring Paw</td>
</tr>
<tr>
<td></td>
<td>4. Oscillator overheated due to mechanical failure of oscillator subsystem</td>
<td>4. Call Sensormedics</td>
</tr>
<tr>
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<td>----------------------------</td>
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<tr>
<td>Reset/ Power Failure</td>
<td>1. AC power removed from system or main power interruption</td>
<td>1. Check line cord</td>
</tr>
<tr>
<td></td>
<td>2. Internal power failure</td>
<td>2. To start oscillator after correcting problem, apply power to system, press and hold &quot;Reset&quot; to establish Paw, and then press Stop/ Start switch</td>
</tr>
<tr>
<td>Failure to meet Patient</td>
<td>1. Leak in patient circuit or humidifier connections</td>
<td>1. Eliminate leak or replace patient circuit</td>
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<tr>
<td>Circuit Calibration</td>
<td>2. Improper flow meter setting</td>
<td>2. Set flow meter to 20 lpm sighting on center of ball</td>
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<td>3. Open water trap stopcock</td>
<td>3. Close water trap stopcock</td>
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<td></td>
<td>4. Internal Leak or maladjustment</td>
<td>4. Call Sensormedics</td>
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<tr>
<td>Failure of ventilator</td>
<td>1. Incorrect Patient Circuit calibration</td>
<td>1. Perform Patient Circuit calibration</td>
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<tr>
<td>Performance Check -</td>
<td>2. Center of flow meter ball not used to make 20 lpm adjustment</td>
<td>2. Adjust flow to center of ball</td>
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<tr>
<td>Paw out of range (low)</td>
<td>3. Incorrect altitude range being used</td>
<td>3. Use appropriate altitude range for your facility</td>
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<td>4. Oscillator not centered properly</td>
<td>4. Center piston using centering control</td>
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<td>5. Internal failure</td>
<td>5. Call Sensormedics</td>
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<tr>
<td>Failure of ventilator</td>
<td>1. Incorrect Patient Circuit calibration</td>
<td>1. Perform Patient Circuit calibration</td>
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<tr>
<td>Performance Check -</td>
<td>2. Center of flow meter ball not used to make 20 lpm adjustment</td>
<td>2. Adjust flow to center of ball</td>
</tr>
<tr>
<td>Paw out of range (high)</td>
<td>3. Incorrect altitude range being used</td>
<td>3. Use appropriate altitude range for your facility</td>
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<tr>
<td></td>
<td>4. Oscillator not centered properly</td>
<td>4. Center piston properly using centering control</td>
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<td></td>
<td>5. Paw set with Paw limit and not Paw adjust</td>
<td>5. Correct settings</td>
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<tr>
<td></td>
<td>6. Internal failure</td>
<td>6. Call Sensormedics</td>
</tr>
<tr>
<td>Failure of Ventilator</td>
<td>1. Bias flow tubing from humidifier to circuit has been cut to less than 30 &quot;,</td>
<td>1. Use bias flow tubing supplied with circuit and do not shorten</td>
</tr>
<tr>
<td>Performance Check -</td>
<td>or tubing not supplied with patient circuit being used</td>
<td></td>
</tr>
<tr>
<td>ΔP out of range (low)</td>
<td>2. Oscillator not centered properly</td>
<td>2. Center piston properly using centering control</td>
</tr>
<tr>
<td></td>
<td>3. Power not set at 6</td>
<td>3. Set power to 6</td>
</tr>
<tr>
<td></td>
<td>4. Compression characteristics of humidifier allowing ΔP to drop</td>
<td>4. Bypass humidifier for performance check, then reattach</td>
</tr>
<tr>
<td></td>
<td>5. Internal failure</td>
<td>5. Call Sensormedics</td>
</tr>
</tbody>
</table>
## TROUBLE SHOOTING THE 3100A AND 3100B cont.

### Unexplained Operation

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Possible Causes</th>
<th>Possible Remedies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Failure of Ventilator</td>
<td>1. Oscillator not centered</td>
<td>1. Center piston</td>
</tr>
<tr>
<td>Performance check - $\Delta P$</td>
<td>2. Oscillator not warmed up</td>
<td>2. Allow Oscillator to warm for 5 minutes</td>
</tr>
<tr>
<td>out of range (High)</td>
<td>3. Incorrect altitude range being used</td>
<td>3. Use appropriate altitude range for your facility</td>
</tr>
<tr>
<td></td>
<td>4. Internal failure</td>
<td>4. Call Sensormedics</td>
</tr>
<tr>
<td>Oscillator shuts down and Dump valve opens during Operation</td>
<td>1. Set Max Thumbwheel set to high. Paw &gt; 20% set max</td>
<td>1. Reset the thumbwheel to lower setting closer to target Paw</td>
</tr>
<tr>
<td></td>
<td>2. Drastic change in Paw over-aggressive control change using the Paw adjust</td>
<td>2. Re-establish Paw and make any small adjustments to Paw using flow meter adjust</td>
</tr>
<tr>
<td></td>
<td>3. ETT has become disconnected</td>
<td>3. Reconnect ETT</td>
</tr>
<tr>
<td></td>
<td>4. Radio frequency interference</td>
<td>4. Locate and distance offending devise</td>
</tr>
<tr>
<td>Oscillator will not restart After temporary Disconnect (such as for routine suctioning)</td>
<td>1. Set max thumbwheel control set too high</td>
<td>1. Reset thumbwheel to lower setting closer to target Paw</td>
</tr>
<tr>
<td></td>
<td>2. To restart oscillator, Paw must first be &gt;20% of set max, but in order to achieve Paw &gt;20% of set oscillator must be on</td>
<td>2. Reduce Max thumbwheel setting temporary until oscillator starts. If it still will not start, reduce power and increase Paw to target level using flow meter and Paw control valve- then increase power while keeping Paw on target by adjusting flow meter or Paw control valve down</td>
</tr>
<tr>
<td>Paw unstable- jumps by 2-3 cm H$_2$O</td>
<td>1. Water collecting at Paw adjust valve</td>
<td>1. Adjust circuit height for better draining</td>
</tr>
<tr>
<td></td>
<td>2. Patient spontaneously breathing</td>
<td>2. Bias flow rate possibly insufficient, re-adjust Paw using higher flow</td>
</tr>
<tr>
<td></td>
<td>3. Worn or defective cap diaphragm</td>
<td>3. Replace cap diaphragms</td>
</tr>
<tr>
<td></td>
<td>4. Internal failure</td>
<td>4. Call Sensormedics</td>
</tr>
</tbody>
</table>
ASSEMBLING THE PATIENT CIRCUIT

Connect the patient circuit body to the bellows/water trap assembly.

Snap the three identical cap/diaphragm assemblies on to the three valve bodies located on the patient circuit body.
Note: Be sure to check the diaphragm assemblies to ensure there are no leaks.

2. Attach the assembled patient circuit to the face of the oscillator compartment using the four T-handle quarter turn fasteners.
Attach the three color-coded tubes to their corresponding valve caps, following the color-coding scheme: **Color of Line Attaches To**
1. Green Paw Control Valve
2. Blue Paw Limit Valve
3. Red Dump Valve
4. Clear Paw Sensing Port

**Note:** The differing lengths and color coding of the tubes and the physical arrangement of the valves within the Patient circuit minimizes the possibility of cross connection. The colored lines are **not** disposable.
Insert the humidifier temperature probe in the tapered-opening near the patient “Y”.

PATIENT CIRCUIT CALIBRATION PROCEDURE

On the side of both the 3100A and 3100B ventilator, is Patient Circuit Calibration Procedure that is to be performed before a patient is placed on the 3100A or 3100B High Frequency Ventilator. This check is to be done off patient.
VENTILATOR PERFORMANCE CHECKS

On the top of both the 3100A and 3100B ventilator, is a Ventilator Performance Check that is to be performed before a patient is placed on the 3100A or 3100B High Frequency Ventilator. This check is to be done off patient.
START-UP PROCEDURES

A “Quick-Checklist” label for pre-patient hook-up verification is attached to the ventilator. An example for both the 3100A and 3100B is below.
TASKS AND CONSIDERATIONS FOR INITIATING HFOV

When a patient is being considered for HFOV, there are several tasks and considerations to be kept in mind when initiating HFOV.

**Labs:** An ABG should be drawn prior to and approximately 30 minutes after initiating HFOV. A blood gas should be drawn within 1 hour of all changes and when clinically indicated.

**Radiology:** A chest x-ray should be taken prior to initiation if possible. A follow-up chest x-ray should be taken 1 hour after initiation of HFOV. The clinician should look for a more expanded chest, usually to 9 ribs. Ideally, a cxr should be obtained after changes to the mean airway pressure. Routine cxr’s are recommended every 6 hours for the first 24 hours and then every day. Changes in chest radiographs may not be appreciated for at least 4-6 hours to allow a patient time to fully recruit collapsed alveoli.
**Sedation:** Patients should be sedated to the point of being comfortable and not fighting the ventilator. Paralytic agents are not necessarily indicated unless previously in use. If a paralytic was in use prior to initiating HFOV, it should be discontinued, as tolerated by the patient.

**3100B HIGH FREQUENCY OSCILLATORY VENTILATION PATIENT SET UP**

1. Perform circuit calibration. **Note:** Remember that this is done off the patient
2. Perform Ventilator performance check. **Note:** Remember that this is done off the patient
3. **Patient set up:**
   A. Adjust “Bias Flow” to 30 lpm initially
   B. Set the MAP adjust knob to achieve the desired MAP, usually 5cmH2O above the mean on conventional ventilation, per physician orders 1. Set MAP alarm “limit” to +5cmH2O above MAP
   C. Set the Frequency to physician’s orders, usually 3-6 Hz
   D. Set Inspiratory time to 33%
   E. Set the Power to achieve amplitude 20 above the PaCO2. Depending on the size of the patient, power is set in a range of 4-9.
   F. Adjust the “Set Min” alarm to 3cmH2O below the MAP and readjust as needed
   1. Depress and hold the Restart Button until the MAP increases to >5cmH20. Press the “Start/Stop” to start the piston. **Note:** Prior to connecting the ventilator, suction the patient well. Place the patient on the oscillator. Set the MAP to 40 cmH2O for 40 seconds, and then start the ventilator. Immediately assess the “Chest Wiggle” and adjust the power setting to achieve optimal wiggle. “Chest Wiggle” for patients on the 3100B is a visual vibration between the clavicles and upper thigh. The power required to achieve optimal chest wiggle is the baseline measurement.
   G. Start with a FiO2 of 100% and wean as tolerated
   H. Adjust the MAP according to the O2 saturation
   I. Obtain an ABG approximately 30 minutes after initiating HFOV.
      1. To improve ventilation, increase the ΔP in increments of 5cmH20. If the ΔP is 3 times greater than the Paw, decrease frequency by 1 Hz to decrease CO2 and allow for the decrease in ΔP.
      2. To improve oxygenation, optimal lung volume must be maintained. Optimal lung volume is reached once you see stable O2sats. Once the desired saturation is obtained, decrease FiO2 until it is <50%.
   J. Approximately 1-2 hours after initiating HFOV, obtain a CXR. The diaphragm should be approximately at the 9th rib on the right side.

**3100A HIGH FREQUENCY OSCILLATORY VENTILATION PATIENT SETUP**

1. As with all patients, perform circuit calibration. **Note:** Remember that this is done off the patient
2. Patient set up:
   A. Adjust “Bias Flow” to 20 lpm initially
B. Set the MAP adjust knob to achieve the desired MAP per physician orders
   1. High Volume Strategy: RDS, PPHN
      a. MAP usually 2-3cmH2O above MAP on conventional ventilation
      b. Start with an FiO2 of 100%. Once optimal lung volume has been achieved, start weaning the FiO2
   2. Low Volume Strategy: Pulmonary Interstitial Emphysema
      a. MAP usually set at or below MAP used on conventional ventilation
      b. Gradually decrease the MAP by 1cmH2O Every 15 minutes as tolerated, accepting pH > 7.25 and PaCO2 < 65 torr
         Note: Diaphragmatic Hernia and MAS do not fall into either category and must be managed accordingly
C. Set the power to obtain an amplitude equal to the PIP on conventional ventilation per physicians to:
   1. Make adjustments until good chest wiggle and optimal PaCO2 is achieved
D. Set the frequency for infants per physician orders to:
   1. weighing < 750 grams 15Hz
   2. weighing > 750 grams 10 Hz
E. Inspiratory time should always be set at 33% to avoid air trapping unless otherwise ordered by a PICU attending or fellow.

MANAGEMENT OF HIGH FREQUENCY OSCILLATORY VENTILATOR

A. Respiratory Care Practitioner Responsibilities
1. Check orders
   a. Orders should be rewritten, by the ICU Fellow or Attending, every 24 hours
   b. Make sure that the settings are appropriate for the patient
2. Perform patient assessment per CMCD Patient Assessment Guidelines
3. Chest X-ray
   a. Verify chest expansion by counting the number of ribs. At CMCD, chest expansion is considered adequate if the diaphragm is at the level of the 9th rib.
   1. Chest expansion is one of the clinical indicators for adequate Paw.
   a. Assess the position of the ETT. It should be comfortably above the carina.
4. Equipment
   a. Thoroughly inspect ventilator circuit
   b. Verify that all wheels are locked and secured
   c. Verify that circuit is stable and secure
   d. Verify that there is adequate water in the humidifier and that humidification is adequate. 1. Note that if the water level is low in the humidification chamber, this will affect the Mean Airway Pressure
   e. Calibrate and insure proper operation of the O2 analyzer
   f. Verify that there is a back up oscillator. If not, notify the Team Leader for that unit immediately.
5. Ventilator Checks are done every hour
   a. Assess patient circuit for proper gas exhaust.
   b. Verify water level in the humidification chamber.
c. Drain the water from the bellows and the 60cc syringe
   1. Do not empty the syringe completely. Leave approximately 1/4” of water in the syringe to seal and prevent a leak.
d. Perform a patient assessment in compliance with CMCD Guidelines
e. Assess for adequate chest wiggle.
   1. Patients on the 3100A: clavicle to umbilicus
   2. Patients on the 3100B: clavicle to mid-thigh
f. Check recent lab results
6  Lab and Chest X-ray frequency
   a. Arterial blood gases
      1. 30 to 60 minutes following initiation of HFOV
      2. Q2H for the first 8 hours following initiation
      3. Q4H per physician order for the duration of time on HFOV
      4. 1 hour after changes made to HFOV settings
   b. Chest X-ray
      1. 30 minutes to 1 hour following initiation of HFOV
      2. Q12H for the following 24 hours
      3. Qam for duration of time on HFOV
      4. When clinically indicated
      5. Following changes in MAP
7.  Invasive and Non-Invasive monitoring
   a. Placement of any invasive monitoring device; Art line, CVP, or Swann Ganz Catheter should be done prior to initiation of HFOV
   a. Continuous Cardiac Monitoring and Pulse oximetry
8.  Blood pressure and urine output should be assessed with each ventilator check to assure that both are adequate and that no acute change has occurred
9.  Head ultrasounds
   a. Should be done on patients with a open fontanel prior to initiation of HFOV.
   b. Follow up ultrasounds should be done when clinically indicated.

B. High Frequency Oscillatory Ventilation Management Guidelines

1  Ventilation Management
   a. Decreasing CO2 is accomplished primarily by adjusting the Delta P. Monitor adjustments in Delta P by watching chest wiggle.
   b. If maximum Delta P is unable to improve ventilation, decreasing the frequency (Hertz) will increase the displacement of the piston increasing tidal volumes.
      a. If these two adjustments are not successful, consider increasing the bias flow. This may lead to an increase in the CO2 washout.
      
      Note: Ensure that there is an adequate airleak around the ETT. If the cuff is inflated, deflate the cuff until an airleak can be heard. In extreme cases, the patient may need to be reintubated with a smaller tube to facilitate an adequate airleak. With patients on the 3100B, deflate the cuff on the ETT until MAP decreases by 5 cmH2O. At this point, increase the MAP back to ordered parameter.

      a. If elevated PaCO2 persists, an adjustment to % Inspiratory Time may be indicated. An increase of approximately 10% may be obtained by increasing the I Time % to 50%.
Note that this is not a common practice at CMCD and must be done only with a physician order and observed by either the PICU Fellow or Attending.

2 Oxygenation Management

a. Oxygenation is a primary function of Peak Airway Pressure (Paw). Paw is usually set 10 to 30% higher than that of conventional ventilation.

b. Proper inflation or Paw is reflected by a chest x-ray that reveals expansion to 9 ribs above the diaphragm.

c. The clinician should be aware of the disease process that is being managed. Higher Paw should be used when the patient has **Diffuse Alveolar Disease (DAD)**. The theory is that higher Paw’s will recruit and distend collapsed alveoli. Patients who have **Air Leak Injury (ALI)** should be maintained on a minimal Paw and oxygenation managed with increasing FiO2. Higher Paw may cause additional injury or exacerbation of the injury to the lung.

c. Increasing the FiO2 is another way of improving oxygenation. Once the desired improvement in oxygenation is achieved, the clinician should wean the FiO2 to a level of 50% or less as the patient tolerates. Once a level of <50% is achieved, weaning the Paw may be appropriate.

C High Frequency Treatment Strategies

**Clinical Indicators Therapeutic Intervention Rationale**

**FiO2 above 60%**

**High PaCO2 with:**

- PaO2 = OK Increase Delta P Achieve optimal PaO2
- PaO2 = low Increase Paw, Delta P, FiO2 Improves O2 delivery
- PaO2 = high Increase Delta P, Decrease FiO2 to
  - Decrease FiO2 Decrease FiO2 to minimize O2 exposure

**Normal PaCO2 with:**

- PaO2 = OK No action No action
- PaO2 = low Increase Paw, FiO2 Improves O2 delivery
- PaO2 = high Decrease FiO2 Decrease FiO2 to
  - Decrease FiO2 to minimize O2 exposure

**Low PaCO2 with:**

- PaO2 = OK Decrease Delta P Achieve optimal PaO2
- PaO2 = low Increase Paw/FiO2
  - decrease Delta P Improve O2 delivery
- PaO2 = high Decrease FiO2, Delta P Decrease FiO2 to
  - Decrease FiO2 to minimize O2 exposure

**FiO2 below 60%**

**High PaO2 with:**

- PaO2 = OK Increase Delta P Achieve optimal PaCO2
- PaO2 = low Increase FiO2
Delta P Improve PaO₂
PaO₂ = high Increase Delta P
decrease Paw Decrease Paw to decrease PaO₂

Normal PaO₂ with:
PaO₂ = OK No Action No Action
PaO₂ = low Increase FiO₂ Improves PaO₂
PaO₂ = high Decrease Paw, FiO₂ Reduces PaO₂

Low PaCO₂ with:
PaO₂ = okay Decrease Delta P Achieve optimal PaCO₂
PaO₂ = low Increase FiO₂, decrease
Delta P Improves PaO₂
PaO₂ = high Decrease Paw, Delta P Achieve optimal PaO₂ and PaO₂

D. Suctioning: Indications and Proper Technique

1. Indications
   a. Acute increase in Delta P
   b. Decreased chest wiggle and increased Delta P
   c. Sudden or acute drop in SpO₂

2. Proper Technique
   a. Patients on HFOV should be suctioned only as needed.
      It is strongly recommended that a closed suction system be used when suctioning a patient on HFOV.
      Patients may de-recruit and collapse alveoli if disconnected from HFOV.
   b. Suction Technique
      1. Pre oxygenate with 100% FiO₂
      2. Manually ventilate patient with 100% oxygen with ambu bag
      1. Pass the catheter quickly and return patient to ambu bag.
      2. Repeat suctioning if needed.
      3. When finished suctioning, perform a Sustained Maximal Inflation
   c. Sustained Maximal Inflation
      1. For patients on the 3100A, connect patient to ventilator and increase MAP 2 cmH₂O above set ventilator MAP
         a. Restart ventilator
         b. Once O₂ saturations return to normal levels, decrease MAP to previous settings.
      2. With the 3100B, connect patient to ventilator and increase MAP to 40 for 40 seconds.
         a. Restart ventilator
         b. Decrease MAP to previous settings as tolerated

E. Sedation and Paralysis
At CMCD, patients are routinely sedated when being ventilated on HFOV. The decision to medically paralyze a patient is physician driven. Each attending has their preference.

1. Indications for sedation may include the following:
   a. tachycardia
   b. hypertension
c. increased Delta P
a. pressure limiting ventilator
b. spontaneous breathing
c. increased agitation

2. Indications for paralyzing may include the following:
   a. inability to adequately ventilate or oxygenate
   b. pressure limiting ventilator
   c. patient safety

F. Positioning
Studies in adults have shown that positioning patients, who have ARDS, prone is an effective way of increasing Functional Residual Capacity (FRC) thus improving oxygenation. Currently, a multi-center study is under way to determine if the pediatric population will benefit from being placed prone. If the patient has no other injuries that contraindicate them being placed prone, the therapist may want to discuss placing the patient prone with the physician prior to initiating HFOV.

Patients who are left supine may benefit from having the head of the bed raised slightly to help keep the contents of the abdominal cavity from placing pressure on the diaphragm. Again, make sure that there are no contraindications for raising the head of the bed.

Weaning from High Frequency Oscillatory Ventilation
The goals for using HFOV when treating patients with acute lung disease is to minimize ventilator induced lung injury while achieving nontoxic oxygen levels. Weaning from high frequency is a slow process that allows sufficient time for the changes to be representative of the patient's pulmonary status. Weaning from HFOV should be done in a systematic manner that prevents the lung from de-recruiting. The following steps for weaning from HFOV are guidelines only. They represent the practice of Critical Care Services at CMCD, information found in a review of current professional articles, and recommendations found in various research studies.

Weaning FiO2
Attempt to wean the FiO2 to a nontoxic level (<50%) while maintaining a SpO2 of >90%. If the patient does not maintain an adequate saturation at an FiO2 of < 60%, no additional attempts at weaning should be made until the patient can tolerate them.

Weaning Paw
If the patient is able to maintain a SpO2 >90% on an FiO2 ≤50%, obtain a physician’s order and start a gradual reduction in Paw of .5 - 3 cmH2O Q4-6 hours as tolerated. If weaning is overly aggressive, lung volumes may drop below closing pressures and desaturation may occur. Increasing the Paw 1 - 2 cmH2O above the previous Paw level may not be sufficient to re-recruit collapsed alveoli.

Weaning Power
When the pH is normalized and the PaCO2 is within acceptable limits, the power/Delta P should be weaned before the frequency. There seems to be no agreed upon value or amount to decrease the power by. Remember that small changes in the power can make a significant change in ventilation. Close attention should be paid to the patient's blood gas values. Note: When weaning the power, ensure there is adequate chest wiggle with the changes.

Weaning Frequency
When adequate chest wiggle is achieved with reduction of power, the frequency may be weaned. The clinician must remember that frequency is inversely related to tidal volume. To wean the tidal volume, increase the
frequency. This will reduce the size of the tidal volume. Close attention should be paid to the patient's blood gas values.

As with weaning conventional ventilation, it is advisable to wean one parameter at a time. Multiple changes may cloud the issue and the clinician may not be able to distinguish which change lead to the clinical change.

HFOV weaning difficulties are usually evidenced by restlessness, increased work of breathing, fluctuations in mean airway pressure, and a decrease in saturation.

Once a patient has demonstrated that he is ready to convert to conventional mechanical ventilation, the following settings may be considered as a starting point. These are merely suggested settings. The final decision for ventilator settings is either the PICU fellow or attending.

**Transitioning to Conventional Ventilation**

When a patient is ready to transition to conventional ventilation, many of the same precautions taken when placing a patient on HFOV need to be employed.

Much like weaning power, there seems to be no firm agreement on what the Paw needs to be on conventional ventilation. The literature varies from as low as 8 cmH₂O to a high of 24 cmH₂O. The physicians at CMCD will determine what level of Paw they want.

A suggested mode of ventilation is SIMV Pressure Control. Current literature suggest setting the pressure control level to achieve a delivered tidal volume of 6 – 8 ml/kg of ideal body weight. The same literature also suggest that a pressure support level be set to achieve a delivered tidal volume on a spontaneous breath of 3 – 5 ml/kg of ideal body weight.

A respiratory rate of 20 – 25 is a good suggested starting rate when transitioning to conventional ventilation.

An arterial blood gas should be obtained 30 to 60 minutes after transfer to conventional ventilation to further guide ventilator adjustments.

Keep in mind that different CCS attending physicians at CMCD have different philosophies of how to manage patients requiring HFOV. The information provided in the above sections is meant to be used as clinical guidelines only.
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