

MECHANICAL VENTILATION IN THE NEONATE

I. GENERAL PRINCIPLES

A. NEONATAL VENTILATORS

We use three types of neonatal ventilators in the NICU:

1. SIMV (Synchronized intermittent mandatory ventilation)
2. CPAP (Continuous positive airway pressure)
3. High Frequency Oscillatory Ventilator (HVOF)

B. RESPIRATORY MINUTE VOLUME (V_m)

1. Tidal Volume (V_t) is normally approximately 6-10 mL/kg and 4-6 ml/kg in the preterm. Respiratory rate (RR) is usually 30-60 BPM. Tidal volume and respiratory rate are related to respiratory minute volume as follows:

$$V_m(\text{mL}/\text{min}) = V_t \times \text{RR}$$

2. The PaCO₂ level is inversely proportional to the minute volume. The higher the minute volume is, the lower the PaCO₂ will be.
3. During pressure ventilation, tidal volume (V_t) is proportional to Peak Inspiratory Pressure (PIP) and to Dynamic Lung Compliance.
4. Respiratory minute volume can be altered by changing Ventilatory Rate or PIP (V_t).

C. OXYGENATION (PaO₂) is directly proportional to:

1. Delivered oxygen (FiO₂)
2. Mean airway pressure (MAP)

II. PRESSURE VENTILATION

A. DESCRIPTION

The ventilator will rapidly reach the preset peak pressure limit and then hold the pressure for the remainder of the chosen inspiratory time. A pressure ventilator will deliver different tidal volumes with changes in lung compliance and airway resistance.

B. CONTROL

1. PEAK INSPIRATORY PRESSURE (PIP)

High PIP is a major contributor to barotrauma in the lung. PIP is controlled and closely monitored.

2. INSPIRATORY TIME (I_t)

- a. The normal newborn breathes with an I:E ratio of 1:1.5 to 1:2. This same ratio is used in infants with normal lung compliance and those with obstructive lung disease.

- b. A 1:1 I:E ratio is commonly employed for infants with impaired Dynamic Compliance in order to maximize alveolar recruitment.
- c. Mean airway pressure (MAP) is directly proportional to I:E ratio. Higher I:E ratio's and MAP promote improved alveolar recruitment.
- d. At rates less than 40 BPM, inspiratory time is maintained at 0.3 - 0.6 sec. An attempt will normally be made to use the shortest I_t to minimize the MAP.
- e. It should be considered that different inspiratory times might have significant effects on tidal volume. Long inspiratory times may contribute to excessive alveolar distention in compliant lungs.

3. WAVE-FORM

- a. A sine wave produces a slow gentle rise to peak pressure, useful in limiting barotrauma in infants with relatively normal compliance.
- b. A square wave produces a rapid rise in airway pressure, useful in infants with poor lung compliance.
- c. Wave-form will normally be adjusted by the respiratory therapist based upon the infant's ventilatory requirements.

4. FLOW RATE

- a. Standard flow rates are 6-10 L/min. Much of this flow is not delivered to the infant but rather is used to drive the ventilator.
- b. Infants on PIP greater than 20 cmH₂O and rates in excess of 60 BPM may benefit from flow rates of 12-16 L/min in order to reach peak pressure more rapidly and deliver a larger tidal volume. This may be tested by using a pneumotachograph.

C. MONITORING

- 1. The pressure ventilator automatically calculates and displays Rate and I:E.
- 2. PIP and PEEP and MAP are monitored by a Mean Airway Pressure monitor, which is far more accurate than an analog gauge.

D. GENERAL PROCEDURE

- 1. Mechanical ventilation is initiated for respiratory failure and apnea. Hand bagging is a good way to test settings.
- 2. Inspiratory times are usually 0.3 - 0.6 second.
- 3. For RDS, I:E ratio should be 1:1. For obstructive lung diseases, use 1:1.5 or 1:2.
- 4. The Neonatal Respiratory Therapist will be responsible for calculating and monitoring I:E changes that result from rate changes and informing the physician as needed.

5. A complete pressure ventilator order NEO RESP includes flow rate FiO_2 , rate, I:E ratio or I_t , PIP and PEEP. After initial settings, only changed parameters need to be ordered. Each morning, the complete current ventilator settings are clarified in NEO RESP.
6. Blood gas results are communicated to the physician/NNP by RT. A joint management decision is made and an order written.
7. It is very important that CLINICAL ASSESSMENT be performed after initiating respirator therapy. You should note:
 - a. Color change, SaO_2 , HR, and RR
 - b. Chest expansion
 - c. Quality of breath sounds
8. The FELLOW OR ATTENDING NEONATOLOGIST is NOTIFIED of ANY SIGNIFICANT DETERIORATION.
9. Our preferred aim of management is to minimize MAP and FiO_2 .
10. Bedside tidal volume checks or pulmonary function tests are useful monitoring techniques.

E. FOR ELEVATED PaCO_2

1. Verify ET tube position and patency. Verify ABG.
2. Transilluminate, rule out pneumothorax, chest x-ray.
3. Increase rate in increments of 5 - 10 BPM.
4. Increase PIP in 2 cm H_2O increments to achieve adequate chest expansion and tidal volume.
5. Decrease I_t in 0.1 sec increments until I:E = 1:1.5
6. Reduce PEEP if lungs are hyperventilated.
7. Increase rate further in 5 - 10 BPM increments as needed.
8. Consider muscle relaxation and/or volume ventilation with fellow/attending supervision.

F. FOR REDUCED PaO_2

1. Verify ET tube position and patency. Verify ABG.
2. Transilluminate, rule out pneumothorax, chest x-ray.
3. Increase FiO_2 up to 60%-100%.
4. Increase I_t to 0.4 - 0.6 sec, I:E = 1:1.
5. Increase PEEP.
6. Increase PIP in 1-2cm H_2O increments to deliver an optimal tidal volume.
7. Notify Fellow/Attending if no improvement.

G. WEANING

There are many ways of weaning from the respirator; the patient's condition dictates the rate and method. Remember, changes are accomplished in small increments. (PIP 2 cm H₂O, FiO₂ 5%, Rate 5 BPM). SaO₂ and TcPCO₂ monitoring are used to facilitate weaning.

1. Reduce FiO₂ to 80% before changing PIP, I:E or PEEP.
2. Reduce PIP as clinically indicated.
3. Reduce FiO₂ to less than 60%
4. Reduce I_t
5. Reduce PIP to 10-14 cm H₂O (Larger babies may be extubated with PIP 14-18)
6. Reduce rate to 20 BPM

H. DETERIORATION

1. Anytime the infant suddenly deteriorates: remove from ventilator, stabilize by hand ventilation with NRPR bag, and notify fellow/attending.
2. Inadvertent extubation, malposition of ET tube (right mainstem), ET tube occlusion, must be quickly investigated. Auscultation, laryngoscopy, arterial blood gases and chest roentgenogram may be necessary. Emergency reintubation may be needed.
3. Pneumothorax may be diagnosed by auscultation, transillumination or chest x-ray. An emergency thoracentesis may be required.
4. Reset ventilator by stabilization settings used during hand ventilation.

III. VOLUME VENTILATION

A. DESCRIPTION

1. Volume ventilators deliver a preset tidal volume to the patient. The amount of pressure it takes to deliver that volume depends upon the airway resistance and the lung compliance of the patient.
2. Ventilator operates in eight possible modes of ventilation. The two modes we most commonly employ are:
 - a. Volume control (vol) will be used in the acute, paralyzed patient. The volume control mode delivers regular mechanical breaths with a set V_t regardless of spontaneous breathing.
 - b. Synchronized IMV (SIMV) with pressure support, used in the alert infant. SIMV guarantees a minimum minute volume while allowing the patient to "trigger" spontaneous breaths at a rate and volume determined by the patient. Extra breaths are boosted with pressure support.

B. MONITORING

1. PIP and MAP are monitored by a transducer and displayed by the ventilator.

2. PEEP can be measured only by the analog gauge.

C. INITIAL VOLUME VENTILATOR SETTINGS

Two examples of expiratory Tidal Volume calculation follow:

1. A 3 kg infant requires a PIP of 40cm H₂O:
$$V_E = 3 \text{ kg} \times 10 \text{ mL/kg} + (1.8 \times 40)\text{mL}$$
$$= 102 \text{ mL}$$

2. A 3.6 kg post-op cardiovascular surgery patient requiring 25cm H₂O:

$$V_E = 3.6 \text{ kg} \times 15 \text{ mL/kg} + (1.8 \times 25)\text{mL}$$
$$= 99 \text{ mL}$$

IV. HIGH FREQUENCY OSCILLATORY VENTILATION

Definition

HFOV is a method of mechanical ventilation that employs supra-physiological breathing rates and tidal volumes frequently less than dead space. Because conventional ventilation relies on the production of large pressure changes to induce mass flow of gas in and out of the lungs, it may be associated with deleterious consequences of volume and pressure changes at alveolar level. These include air leaks, such as PIE and pneumothorax, and bronchiolar-alveolar injury leading to chronic lung disease.

Indications

Rescue: This is the most established role for HFOV

Prophylactic: In animal experiments HFOV causes less lung injury than conventional ventilation.

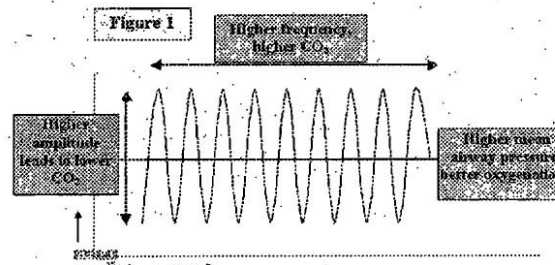
Principles of HFOV

The use of high frequency ventilation at low tidal volumes allows the primary goals of ventilation, oxygenation and CO₂ removal, to be achieved without the costs of pressure-induced lung injury.

HFOV has been described as “CPAP with a wiggle”. This reflects the two physical goals:

- CPAP: Sustained inflation and recruitment of lung volume by the application of distending pressure (mean airway pressure [MAP]) to achieve oxygenation.

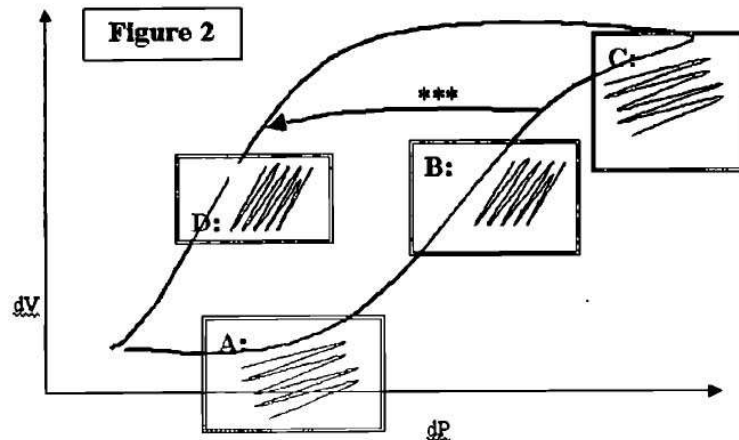
- Wiggle: Alveolar ventilation and CO₂ removal by the imposition of an oscillating pressure waveform on the MAP at an adjustable frequency (Hz) and an adjustable amplitude (delta P).



The ‘art’ of HFOV relates to achieving and maintaining optimal lung inflation. Optimal

oxygenation is achieved by gradual increments in MAP to recruit lung volume and monitoring the effects on arterial oxygenation. The aim is to achieve maximum alveolar recruitment without causing over-distension of the lungs.

Optimizing lung inflation with MAP: It is useful to conceptualize HFOV as like taking the lung around on sustained pressure volume hysteresis loop. (Figure 2).



Point A in figure: Under-inflation: At this point, the lung is under-inflated, PVR will be high and relatively large amplitude will produce only small changes in volume. Clinically, this manifests as a high oxygen requirement with limited chest vibration.

Point B in figure: Optimal inflation: Once the lung has opened up with higher MAP, the PVR will fall and a smaller amplitude will produce a larger change in volume. Clinically, this manifests as falling oxygen requirements and good chest vibration.

Point C in figure: Over-inflation: Again, more amplitude will be needed to produce volume changes and over-inflated lung will compromise the systemic circulation. This is the most dangerous point in HFOV and is to be avoided at all costs! It is difficult to pick up clinically because the oxygen requirement stays low, although they will eventually rise and the reduced chest vibration is easy to miss. Chest X-ray is currently the best diagnostic tool for this.

Point D in figure: Optimal inflation weaning: The goal should be to move the baby's lungs from point B to point D avoiding point C. Having achieved optimal lung inflation by slowly reducing MAP, it should be possible to maintain the same lung inflation and ventilation at a low MAP. If MAP is lowered too far, oxygen requirements will start to rise.

Optimizing the ventilation

This is controlled by adjusting delta P to achieve optimal PCO_2 (40-50 mmHg). Although the delta P of each breath appears large by comparison to conventional ventilation pressures, the attenuation of oscillation through the endotracheal tube means that the transmitted amplitude at the level of the alveolus is very small. Higher delta P will increase tidal volume and hence CO_2 removal.

With increasing ventilator frequency, lung impedance and airway resistance increases so the tidal volume delivered to the alveoli decreases. This leads to the apparent paradox that increasing ventilator frequency may reduce CO_2 elimination, leading to raised $PaCO_2$ and vice-versa.

Practical Management

Preparation:

1. If there is any significant leak around the ET tube, a larger one should be inserted.
2. Oxygen saturation, BP monitoring and arterial access should be used, if possible.
3. A pre-oscillation x-ray should be taken as a baseline.
 4. Blood pressure and perfusion should be optimized prior to HFOV; any volume replacement contemplated should be completed and inotropes commenced, if necessary.
5. Muscle relaxants are not indicated unless previously in use.

HFOV Adjustments

Oxygenation and ventilation are best considered separately; however, adjusting the ventilator for one parameter will also alter other settings and so, after making a change, always check the other settings.

- 1) Ventilation: Changing the delta P or occasionally the frequency may effect changes in PaCO₂. Raising the delta P of oscillation and vice versa may increase ventilation.

Start at a delta P 1-2 cmH₂O higher than conventional ventilation. Adjust the delta P in 1-2 increments until the chest wall is seen to “wiggle” down the point of the umbilicus.

The optimal frequency of oscillation may be different in different disease states. Small infants with RDS may be managed at 15 Hz, term infants are often best managed at 10 Hz, although with very non-compliant stiff lungs, lower frequencies may be necessary.

Note: If adjustment of frequency is needed, decreasing the frequency increases CO₂ removal (opposite to CMV).

- 2) Adjusting the MAP and FiO₂ controls oxygenation. The high lung volume strategy allows the use of low FiO₂ levels (<35%) and the MAP should be adjusted to achieve this.

For air leaks: A low volume strategy may help. Reduce MAP 1-2 cmH₂O below MAP on CMV and tolerate higher FiO₂.

For rescue HFOV: Starting MAP should be 2 cmH₂O above that used on CMV.

For prophylactic HFOV: Starting MAP will need evaluation based on assessment of lung disease severity derived during resuscitation. Generally, start at 8 cmH₂O, but use of 10-12 cmH₂O if the lungs seem unusually stiff.

MAP should be increased in 1 cmH₂O increments until the FiO₂ is less than 30%.

Over inflation (point C) can be assessed clinically or by x-ray. Arrange for a chest x-ray 1-2 hours after patient has been on HFOV.

Normal inflation should allow the right hemi-diaphragm to be at the 8th or 9th rib. It may be necessary to perform chest x-rays every 6-12 hours if difficulties are encountered.

Over-inflation is occurring if: diaphragm is at 10+ ribs, intercostal bulging of lungs presents, or sub-cardiac air is visible as a crescent under the apex. A high diaphragm indicates under-inflation. When managing RDS, there will also be clearing of the lung fields as atelectasis resolves.

Once the baby is stable in an $FiO_2 < 30\%$, the MAP should be cautiously reduced in 1 cmH_2O increments as allowed by the oxygenation (to get to point D). FiO_2 rising above .30 suggests you have dropped MAP too much.

CASE STUDY

Baby Boy B was a 27 week, 800 gram male infant born to a 31 year old gravida 4, para now 4, female with a history of incompetent cervix and premature labor. Baby Boy B's Apgar scores were 5 and 7.

Baby Boy B had respiratory distress from birth. He was taken to the neonatal intensive care unit and placed on assisted mechanical ventilation.

Baby Boy B Initial Settings

Parameter	Setting
PIP	20 cmH_2O
PEEP	4 $cm H_2O$
IMV	40 BPM
I-Time	.4 seconds
MAP	8 cmH_2O
FiO_2	60%

Umbilical arterial catheter was placed. Chest x-rays were taken and showed a moderate reticulogranular pattern with air bronchograms, right hemidiaphragm T-7

Baby Boy B Arterial Blood Gas

Parameter	Reading
$PaCO_2$	68
PaO_2	35
pH	7.18
Bicarbonate	17
Base Deficit	-7

Baby Boy B was placed on high frequency oscillatory ventilation to optimize lung volume, equalize air distribution within the lung, and minimize pulmonary injury by reducing tidal volume breathing.

HFOV Baby Boy B Initial Settings

Parameter	Setting
MAP	10
Frequency	10
Delta P	20
FiO_2	60%

FiO_2 decreased to 28%. Chest x-ray indicated the right hemidiaphragm at T9 and there was a significant reduction in the reticulogranular pattern.

HFOV Baby Boy B Arterial Blood Gas

Parameter	Reading
PaCO ₂	41
PaO ₂	64
pH	7.35
Bicarbonate	20
Base Deficit	-3
MAP was decreased to 9 cmH ₂ O.	

The initial ABG demonstrated a mixed respiratory and metabolic acidosis. The PaO₂ of 35 mmHg is trending towards hypoxemia.

What are some conventional ventilator adjustments to improve oxygenation aside from increasing FiO₂?

- ↑ PIP*
- ↓ PEEP
- ↑ PEEP*
- ↑ I-Time*

What are some strategies to improve ventilation with a conventional ventilator in a neonate?

- ↓ PEEP*
- ↑ PEEP
- ↑ PIP*
- none

How can oxygenation be improved with HFOV in a neonate?

- ↑ MAP*
- ↓ Δ P
- ↑ Hz
- ↑ FiO₂*

How can ventilation as defined by a pure respiratory acidosis be improved with HFOV?

- ↑ Δ P*
- ↓ MAP
- ↓ Hz *
- ↓ Δ P

The physiologic effects of CPAP include:

- Increased FRC*
- Decreased intrapulmonary shunting*
- Increased respiratory rate
- Decreased PaO₂

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