

Mechanical Ventilation

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Caring for a mechanically ventilated neonate continues to unnecessarily strike fear in the heart of many a resident. This fear is only amplified by the fact that we nursery folk speak a language all our own, rich with three and four letter acronyms. By reviewing the physiology, and understanding the ventilator manipulations available, the task becomes much less intimidating, even manageable. After reading this chapter, I hope you'll find yourself more comfortable managing ventilated babies and talking the talk; and should a child not play by the rules, as premies have been known to do, give your fellow a call. They will be happy to give you a hand.

There are three main indications for the initiation of mechanical ventilation, and fortunately they're self-explanatory:

- A.** Apnea
- B.** Inability to oxygenate
- C.** Inability to ventilate

The goal of mechanical ventilation is simply to assist the infant to maintain “physiologic normalcy”; to keep arterial blood gas values in a desired range while minimizing iatrogenic lung injury. Desired ranges are provided in the section titled “desired blood gas ranges.”

I. CPAP

- A.** The simplest form of mechanical assistance (besides nasal cannula) is nasal CPAP (continuous positive airway pressure). CPAP is of benefit to children who have lungs prone to collapse, such as stiff lungs with RDS and pneumonia. By keeping the lung inflated, CPAP helps the lung to function in a happier part of the compliance curve. Using the analogy of the lung as a balloon, the hardest part of inflating it is overcoming the initial opening pressure (the first blow on the balloon), we usually start with a CPAP of 4-6 cm H₂O. Once it's open, distension becomes much easier. CPAP provides the opening pressure in a lung prone to collapse, decreasing the work of breathing for the infant and increasing functional residual capacity, improving both oxygenation and ventilation.

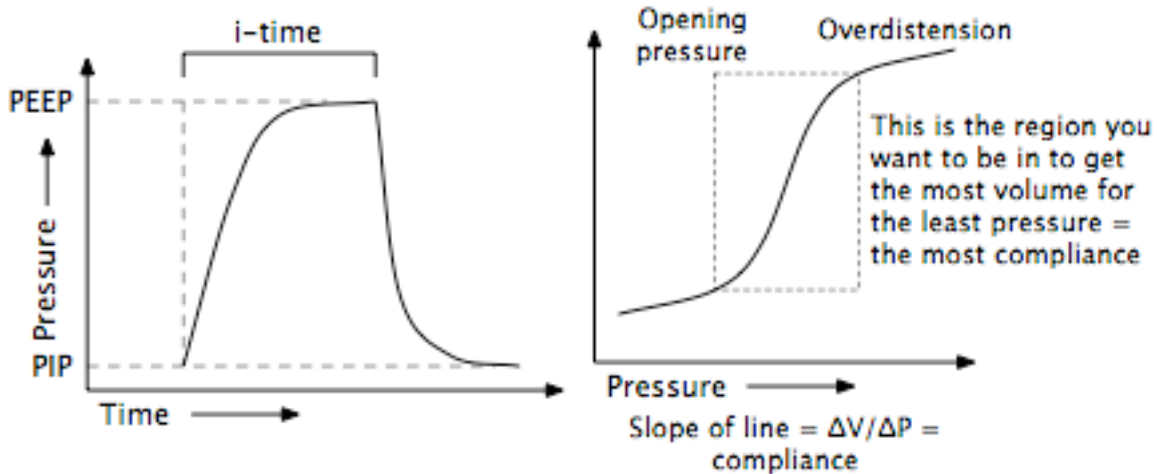
II. Conventional Mechanical (Tidal) Ventilation

- A. Conventional mechanical ventilation** is the primary mode of assisted ventilation used. Children on conventional ventilators look as though they are breathing, and as such are easily distinguished from their high-frequency ventilated counterparts. There are several modes of conventional ventilation; they differ primarily in how they interact with the infant's spontaneous respiratory efforts.
- B. IMV (intermittent mandatory ventilation):** The set rate is delivered in a time-cycled manner regardless of where the baby is in their respiratory cycle. A child on an IMV rate of 30 gets a breath every two seconds, whether the infant is inhaling or exhaling.
- C. SIMV (synchronized IMV):** The set rate is delivered in a time-cycled manner; however, the ventilator times breaths to coincide with baby's inspiratory effort. At a ventilator rate of 30 the ventilator assists a breath every two seconds. Should the infant not initiate a breath, the ventilator delivers an IMV breath. This is the primary mode of conventional ventilation used in the NICU.

- D. Assist control (A/C):** In this mode, every breath the infant takes is assisted. The rate set is only an apnea backup rate. In this mode, you determine the size of the breath and the baby determines the rate.
- E. Pressure Support:**
1. This term is most commonly used to describe a ventilation mode in which an infant's spontaneous effort is augmented by supplemental inspiratory pressure (short of that required to deliver a full tidal volume) with every breath. This is often delivered in combination with SIMV delivering full tidal augmenting volumes at a rate substantially lower than the infant's spontaneous rate. For example, an infant might be supported with SIMV at a rate of 15 and PIP of 20 along with pressure support of 8 for all other spontaneous breaths. In this mode, the baby contributes to ventilator breaths and sets the rate.
 2. However, the “pressure support” mode on the Babylog ventilator does not provide that kind of pressure support. On the Babylog, “pressure support” simply means that the duration of inspiration is determined by the rate of gas flow into the lungs during inspiration, such that inspiration is terminated when the inspiratory flow rate drops below 15% of the peak inspiratory flow. For the Babylog, this mode is equivalent to A/C with patient-controlled or flow-terminated inspiration.
- F. Volume guarantee:**
1. In this mode the ventilator assesses the pressure required to deliver a breath of the specific size that you choose. It can be used in the SIMV, A/C, or pressure support modes. You set the maximum pressure the ventilator can deliver, and should it require less it delivers less. For example, if you set a PIP maximum of 20 and the baby only requires a PIP of 12 to achieve your desired volumes it only delivers a PIP of 12.
 2. If the maximum inspiratory pressure is not sufficient to deliver the desired tidal volume, the ventilator will display a “low tidal volume” alarm. Because the ventilator uses data from the last breath to set the pressure for the next one, which cannot “guarantee” delivery of the desired volume, this mode might be more accurately described as “volume targeted” ventilation.
 3. This mode may produce ventilator behaviors that appear anomalous to the uninitiated. The Babylog will shorten the inspiratory time if the desired volume has already been delivered and it will often reduce the inspiratory pressure to equal the end expiratory pressure as the baby's lung function and respiratory effort improve. The latter will result in placement of the infant on CPAP via the endotracheal tube, which is usually not desirable.

III. Settings

- A.** In any mode, conventional ventilation provides sustained inflation of the lung by delivering breaths of a set peak inspiratory pressure (PIP) above a baseline opening pressure (positive end expiratory pressure or PEEP) for an established inspiratory time (i-time). There are a number of variables you have at your disposal when ventilating an infant. The flow available to the ventilator (flow rate) determines how quickly you reach the PIP. The diagram to the right illustrates how these variables affect ventilator breaths.
- B. Ventilator changes:** From this point forward, consider oxygenation and ventilation to be completely separate entities. As such, there are different ventilator manipulations you can make to enhance either oxygenation or ventilation and sometimes both. The following pointers are provided with the caveat that they all assume that you're ventilating the baby in the “sweet spot” of the compliance curve, and may not hold true if the baby is hyperinflated or atelectatic. If this is the case, call your fellow or attending.



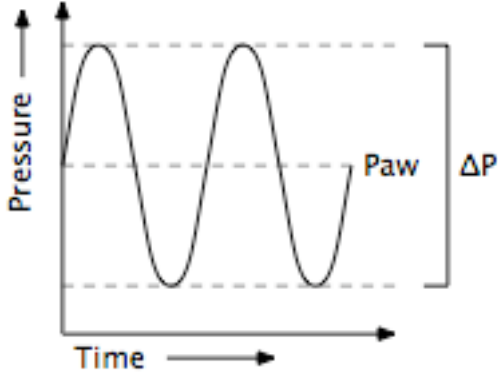
C. Oxygenation: For oxygenation to occur, you must provide lung expansion, particularly increasing the functional residual capacity, a by-product of your mean airway pressure. An easy way of remembering this is that any change that you make which increases the area under the curve above will increase oxygenation, assuming cardiac output can keep up. Considering the curve, the largest impact would be seen by changing the PEEP. Other maneuvers that would likely lead to an improvement in oxygenation include increasing PIP, increasing i-time, increasing the flow rate, or lastly increasing ventilator rate.

1. A recap...to improve oxygenation:
 - a. increase PEEP
 - b. increase PIP
 - c. increase i-time
 - d. increase rate

D. Ventilation

1. **Minute ventilation** is the product of tidal volume and respiratory rate. Tidal volume tends to be proportional to PIP-PEEP or ΔP . So, to increase ventilation and lower your baby's PaCO₂, you want to increase minute ventilation, probably by increasing the ventilator rate. You can also increase tidal volume by increasing PIP, decreasing PEEP, or increasing the i-time.
2. A recap...to improve ventilation:
 - a. increase rate
 - b. increase PIP
 - c. decrease PEEP
 - d. increase i-time. Generally, lengthening your i-time increases your effective tidal volume. In some children, lengthening the i-time may lead to air trapping and a decrease in ventilation.
 - e. increase tidal volume
3. Some tidal volume targets to keep in mind:
 - a. Small baby (<1500 grams): 4-6 ml/kg
 - b. Average baby: 6-8 ml/kg
 - c. Big, sick PPHN types: 6-8 ml/kg

IV. High Frequency Ventilation:

- A.** At Packard, high frequency ventilation is used primarily as a rescue therapy, reserved for children in whom conventional mechanical ventilation has failed, or in whom ventilator pressures that are likely to result in significant lung injury are required. We use the high frequency oscillator (HFOV) exclusively, not the high frequency jet ventilator or high frequency flow interruptor. The mechanics of high frequency ventilation allow you to generate a higher mean airway pressure with a lower peak pressure than conventional ventilation (lower pressures, less lung injury). High frequency also allows for very effective ventilation with smaller tidal volumes than a conventional ventilator (lower volumes, less lung injury).
- B.** When to use it
1. Unable to ventilate despite high ventilator rates and adequate tidal volumes, when this is caused by poor lung compliance. High frequency ventilation is not effective for high resistance respiratory failure.
 2. Requiring very high mean airway pressures to oxygenate
 3. Air leak (pneumothorax or pulmonary interstitial emphysema)
- C. How does it work?** A high frequency ventilator provides a baseline distending pressure (mean airway pressure or P_{aw}), and then delivers hundreds of tiny breaths (less than the anatomic dead space) per minute. It may not make any physiologic sense but it does work and is very effective at both oxygenating and ventilating infants. There are only three settings on a high frequency ventilator, and only two that you'll usually adjust.
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- D. Ventilator changes:** Think of oxygenation and ventilation as separate entities. Adjusting the mean airway pressure changes oxygenation, while changing the amplitude or ΔP changes ventilation.
- E.** Again:
1. Mean airway pressure = oxygenation
 2. Amplitude (ΔP) = ventilation
- F.** Special considerations with high frequency ventilation:
1. As effective as high frequency ventilation can be, it is not without its problems. Because babies being ventilated with high frequency aren't ventilated tidally, it is very difficult to clinically assess the adequacy of support being provided. For this reason frequent CXRs are obtained to evaluate lung distension (every 6-12 hours) and $PaCO_2$ levels should be followed closely to avoid hypocarbia. It makes sense to have a transcutaneous CO_2 monitor on any infant on a high frequency ventilator, as high frequency is extremely efficient at ventilating and can drop $PaCO_2$ values to dangerously low levels very quickly.
 2. Another consequence of non-tidal ventilation is its impact on cardiac function. The heart is able to compensate during conventional ventilation by refilling when intrathoracic pressures are at their low point (PEEP). By providing a higher continuous mean airway pressure, a high frequency ventilator can decrease venous return requiring more aggressive cardiovascular support including volume and at times pressors. It may not be well tolerated in a term infant with septic shock.

V. Desired arterial blood gas ranges

- A.** These are some ball park values to aim for, as each child will have their own targets for any given day.
- 1.** Prematures:
 - a. pH: 7.25-7.35
 - b. PaCO₂: 45-59
 - c. PaO₂: 50-70
 - d. Sats: 88-92%
 - 2.** Terms:
 - a. pH: 7.35-7.45
 - b. PaCO₂: 35-50
 - c. PaO₂: 60-80
 - d. Sats: 92-97%
 - 3.** PPHN:
 - a. pH: 7.45-7.55
 - b. PaCO₂: 30-40
 - c. PaO₂: >100
 - d. Sats: >95%

VI. How to handle a bad blood gas (a systematic approach):**A. So, you've got a lousy blood gas:**

- 1.** Figure out what's going on (oxygenation, ventilation, or acid-base problem)
- 2.** Evaluate the baby
- 3.** Call for help if confused or unsure
- 4.** Make an intervention if necessary

B. As far as what's going on...

- 1.** Is there acidosis, and if so is it metabolic or respiratory?
- 2.** Look at the baby - Comfortable? Upset? Agitation is common in babies whose ventilation is sub-optimal.

C. If you have a metabolic acidosis (i.e. base deficit with normal PaCO₂)

- 1.** Is baby dry? If so, consider a bolus.
- 2.** Does baby need base? Some little babies do as their kidneys aren't very good at retaining base, consider acetate or sodium bicarbonate.
- 3.** Could baby be septic?
- 4.** You can make a ventilator change as respiratory compensation is faster than metabolic compensation, but you have to address the underlying metabolic acidosis.

D. If you're dealing with a respiratory problem, troubleshoot first.

- 1.** Tube's out
- 2.** Tube's at the carina
- 3.** Tube's occluded or needs suctioning
- 4.** Recent vent change — if you make a vent change and get a bad gas, undo that change!
- 5.** Atelectasis
- 6.** Pneumothorax - these kids will be sick
 - a. Listen for decreased breath sounds

- b. Consider transillumination
- 7. Pulmonary intestinal emphysema (PIE)

VII. Weaning Strategies

- A.** The primary determinant in deciding to implement ventilator weaning strategies is the status of the disease being treated and its time course. Specifically, weaning infants with pneumonia will not usually occur until day three to four of life, whereby those with hyaline membrane disease can be weaned sooner on day two to three of life. In addition, if circulatory instability secondary to sepsis is ongoing, extubation efforts are inappropriate even if pulmonary dysfunction is minimal.
- B.** Neonate must be in a state of physiologic homeostasis.
- C.** Nutritional support is especially critical for successful weaning for chronic ventilator-dependent babies.
- D.** When using conventional mechanical ventilation (CMV), gradual stepwise reductions in IMV should be instituted after FiO₂ and mean airway pressure have been somewhat normalized.
- E.** When using high frequency oscillatory ventilation (HFOV), FiO₂ should be weaned to 60% before the MAP is decreased in 1 cm H₂O increments. Lung expansion and PaCO₂ levels will also influence weaning PaCO₂. The lung inflation goal is 8-9 ribs. The amplitude is weaned as tolerated to keep PaCO₂ in target range. Expiratory time and Hertz usually remain constant. If HFOV is being employed for treatment of air leaks, MAP should be weaned first and foremost and a lower degree of lung inflation is desirable.

VIII. Suggestions for Weaning

- A. Weaning should be initiated after evidence that ventilatory support is decreasing. This evidence may include:**
 - 1. Improving compliance noted on your pressure/volume loops
 - 2. Reduction in FiO₂ requirements
 - 3. Increased urine output (diuretic phase seen in RDS)
 - 4. Low PaCO₂ allows you to decrease your PIP, IMV, PEEP or i-time.
- B.** Begin with the factors that are most toxic to the lung. Wean slowly, frequent small changes allow the infant to gradually assume responsibility for gas exchange.
- C.** In the LPCH NICU we are focusing on extubating babies from a mean airway pressure (PAW) of 7 or less. Always note what your baby's PAW is.
 - 1. Weaning off support from the ventilator can be approached in numerous ways. Consider extubation when the PAW is <7, and work toward achieving these additional settings as you move toward this MAP.
 - 2. These are suggestions. Your job as the baby's doctor is to carefully assess the changing compliance and to make suggestions to the team as to how they can improve your baby's outcome. Discuss your ideas with the respiratory therapists, senior residents, fellows, nurses, nurse practitioners, and attendings. By assuming responsibility for your patient, you can significantly reduce the damaging effects of positive pressure ventilation.

IX. Extubation

- A.** When your baby meets extubation criteria, discuss the plan with the team. Are you extubating to NCPAP, NC, or RA? Consider placing on NCPAP prior to extubation to avoid atelectasis.
- B.** At least four hours prior to extubation, feedings should be stopped or an NG tube should be inserted to evacuate the contents of the stomach in order to prevent aspiration.

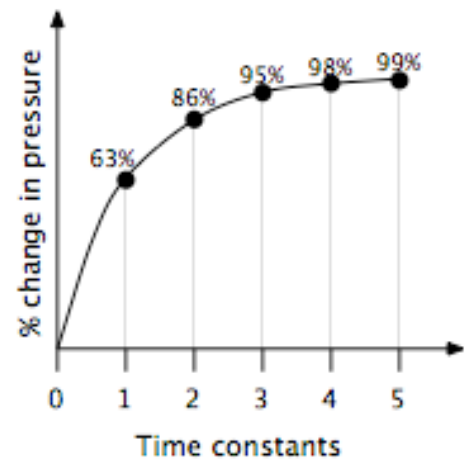
- C. At the time of extubation you should be present at the bedside with a respiratory therapist and the infant's nurse.
- D. Your intubation supplies (the red box) should be available at the bedside in the event that infant requires immediate reintubation. Suction and oxygen via a bag and mask should also be available.
- E. Follow up with a CXR if infant appears to be in distress to check for atelectasis.
- F. Consider a follow up ABG, transcutaneous and/or end tidal CO₂ monitoring, and follow oxygen saturations closely.
- G. Reassess throughout the following hours for signs of respiratory distress.
- H. Always sign out a recent extubation to the on call team.

X. Signs of Respiratory Distress

- A. Tachypnea, retractions, cyanosis, agitation, lethargy, pallor, stridor, grunting, apnea...

XI. Long Inspiratory Time Strategy

- A. **Time constants:** A time constant is the product of the airway resistance and the compliance. Simply put, it is a measure of how quickly the patient's lungs can inflate or deflate: how long it takes for the pressure of air in the alveoli to equal the pressure of air in the proximal airway.



- B. **Acute RDS:** Near complete equilibration of alveolar pressures occurs in 3-5 time constants. The surfactant deficient, premature lung has low compliance and normal airway resistance, resulting in a short time constant; meaning it takes a short amount of time for the pressure to be equal between the proximal airway and the alveoli. The time constant may be as short as 0.05 seconds; this would mean that 95% of the applied pressure to the airway was delivered to the alveoli in 0.15 seconds (three time constants).
- C. **Chronic Lung Disease:** As the lung is healing from RDS, the airways develop increasing inflammation which leads to decreased bronchiolar diameter and increased resistance. Therefore, chronic lung disease (CLD) is a high resistance disease: as the resistance increases, the inspiratory time must increase in order to sufficiently inflate the alveoli. The goal of using a long i-time (0.8-1.2 seconds) in a baby with high resistance disease is to allow ventilation of all lung units, even the alveoli connected to very inflamed, narrowed airways. We typically use low flow (<4 lpm) to create a slow ramp wave form. We also try to use the lowest flow that will meet the baby's own inspiratory flow demands.

- D.** Using long i-times in babies can be quite dangerous if used improperly, therefore as a resident you should always consult the fellow or attending if you have questions about the i-time. Improper application of a long i-time can result in auto-PEEP if sufficient time for exhalation is not allowed. The inadvertent PEEP can lead to rupture of the alveoli, air leaks, and cardiopulmonary compromise. On the other hand, by the time an ex-preemie has made his or her way to a state of CLD in which long i-times are necessary, abruptly changing this strategy can result in acute hypoxia and alveolar collapse. Respect the long inspiratory time in these babies and ask for help before changing the strategy.

XII. Ventilator Modes

Mode	Features	Benefits	Disadvantages	Target For
PSV	All breaths supported with ventilator-driven breaths to set PIP. Patient-controlled i-time and RR. Operator-selected backup rate.	WOB is lower for spontaneously breathing patients above operator-selected RR. Patient determines i-time and e-time; can vary from breath to breath based on patient demand. Patient can raise or lower V_{\min} as demand changes.	Patient may hyperventilate or develop auto-PEEP. Fluctuations in patient RR and/or i-time may cause P_{aw} to vary. Large ET air leaks may cause dysynchrony as breathing criteria may not be attainable. V_T varies with changes in C&R.	Patients who are spontaneously breathing. Patients who exhibit signs of raised WOB on non-vent supported breaths (e.g. SIMV)
SIMV	Patient can breathe spontaneously between set vent breaths. Fixed RR and I:E ratio for vent breaths. Set i-time.	Complete clinician control of vent breath perimeters and vent-supported RR. Consistent P_{aw} . Fixed i-time for infant unable to maintain adequate i-time in RR.	WOB increased for patients breathing at rates above fixed rate. Spontaneous breaths not vent supported. Dysynchrony possible during inspiratory phase if patient i-times do not match vent.	Patients who are not spontaneously breathing. Patients who develop uncorrectable respiratory alkalosis with PSV or A/C.

Mode	Features	Benefits	Disadvantages	Target For
A/C	All breaths supported with ventilator-delivered breath to set PIP. Patient-controlled RR. Operator-selected backup rate. Set i-time.	All patient breaths are vent supported. WOB is lower for patients spontaneously breathing above operator-selected RR. Patient can vary V_{\min} as demand changes. Fixed i-time for infants unable to maintain adequate i-time in PSV.	Dysynchrony possible during inspiratory phase if patient i-times do not match vent. Patient may hyperventilate or inverse I:E ratio. Patients may develop auto-PEEP. Fluctuations in patient RR may cause P_{aw} to vary. V_T varies with changes in C&R.	Patients who cannot maintain adequate i-times. Patients who exhibit signs of raised WOB on non-vent supported breaths (e.g. SIMV)
VG	Set V_T . PIP adjusts to achieve target V_T .	V_T constant with changes in C&R. PIP decreases as C&R improves.	P_{aw} may be affected when PIP varies.	Patients who require a steady V_T due to changes in C&R.