49 Invasive Mechanical Ventilation

Mechanical ventilators are devices that serve to support the patient's inadequate respiratory effort until improvement in respiratory function occurs either spontaneously or after intervention.

The common indications for mechanical ventilation[1] are given below:

	Condition	Manifestation or criteria
1.	Correction of hypoxemia	FiO2 requirement > 40-60% or failure of non-invasive respiratory support
2.	To reverse acute respiratory acidosis	pH <7.2 and, Pco2 >65 mm Hg
3.	To relieve respiratory distress	Marked retractions, severe tachypnea >100/min
4.	To treat apnea or poor respiratory efforts	Poor efforts or apnea requiring bag and mask ventilation
5.	To prevent or treat lung atelectasis as in postoperative setting or neuromuscular disease	
6.	To maintain patent airway	Altered sensorium, sedation, anesthesia, neurological and neuromuscular illnesses
7.	To decrease systemic or myocardial oxygen consumption as in shock	Septic shock, congestive cardiac failure, necrotizing enterocolitis etc
8.	To stabilize chest wall	Flail chest, diaphragmatic palsy

The goals of mechanical ventilation are to achieve acceptable gas exchange (alveolar ventilation and oxygenation) with minimum adverse effects and maximum patient comfort and to wean the patient off the ventilator support as soon as the underlying condition for initiating mechanical ventilation becomes passive.

The choice of ventilator modes for a neonate depends on various factors like equipment available in the NICU, underlying pathophysiology as well as familiarity and comfort level of the physician with a particular mode. Although there cannot be a universal protocol for the use of mechanical ventilation in the neonatal unit, availability of a protocol that delineates a basic approach for initiation and weaning ensures uniformity in its application. Ventilation strategies and settings need to be modified as and when the disease process evolves.

Modes of mechanical ventilation: The different modes of ventilation and their relative advantages and disadvantages are listed in Table 49.1. Among the various modes, the patient triggered ventilatory modes namely, SIMV, AC or PSV are preferred because they are associated with reduction in air leak and a shorter duration of ventilation.[2] Among these modes, AC mode seems to be associated with shorter duration of weaning than SIMV.[2]

Table 49.1: Modes of mechanical ventilation

Mode	Description	Disadvantages
Intermittent mandatory ventilation (IMV)	All breaths are mandatory. Unloads the respiratory muscles	Patient ventilator asynchrony
Synchronized intermittent mandatory ventilation (SIMV)	Breaths are delivered in synchrony with the patient's spontaneous effort. Allows spontaneous breathing in between the mandatory breaths, which are unsupported. Allows patient comfort and at the same time keeps respiratory muscles active.	Work of breathing can be high if spontaneous breaths are not supported adequately. Expiratory asynchrony can happen.
Assist control (AC)	All breaths are assisted and delivered in synchrony with the patient's spontaneous effort. Unloads the respiratory muscles. Useful in acute phase of illness.	If the spontaneous respiratory rate is high, all breaths would be assisted and this can lead to hyperventilation and respiratory alkalosis. There is also a risk of patient-ventilator

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		asynchrony and air trapping at higher rates. Expiratory asynchrony can happen.
Pressure support ventilation (PSV)	Patient controls the rate, inspiratory time and flow rate. Eliminates expiratory asynchrony. Better patient comfort and less need for sedation	Cannot be used in patients with poor respiratory drive or apnea. Pressure support needs to be adjusted based on changing lung mechanics

Based on the primary control variable, one can choose pressure controlled ventilation (PCV) where inflation pressure is set or volume controlled ventilation (VCV) where preset tidal volume is set. Until recently, pressure controlled, time-cycled, continuous-flow ventilation has been the standard of care in the NICU because delivery of small tidal volumes was unsuccessful with older ventilators; also endotracheal tube leaks are greater in neonates. However, the advent of newer ventilators has made this possible and studies have shown that VCV or volume guarantee ventilation may offer greater advantages as compared to PCV. Table 49.2 describes the various parameters that are either set or determined by ventilator (V) in PCV, VCV, volume guarantee (VG) and pressure support ventilation (PSV).

Evidence: Pressure controlled versus volume controlled or volume guarantee mode

Two recent meta-analyses [3,4] have concluded that volume control/ guarantee mode is associated with a significant decrease in the combined outcome of death or bronchopulmonary dysplasia (BPD), pneumothorax, hypocarbia, severe intraventricular hemorrhage/ periventricular leukomalacia, and shorter duration of mechanical ventilation.

Table 49.2: Modalities of mechanical ventilation

Modality	Description	Mode	Settings						Remarks
			PIP	V_T	PEEP	Ti	Rate	FiO_2	
Pressure controlled ventilation (PCV)	Traditional neonatal ventilators are continuous flow, time-cycled, pressure-limited ventilators	IMV SIMV AC	✓	Vari able	✓	✓	✓	✓	Simple design, easy to operate. Can ventilate despite a large ET leak. The major disadvantage is that the VT varies with changes in lung compliance and excessively large VT can lead to inadvertent hyperventilation and lung injury.
Volume controlled ventilation (VCV)	Delivers a constant tidal volume	IMV SIMV AC	Vari able	✓	✓	✓	✓	✓	The benefits of VCV include consistent V_T delivery, less volutrauma (avoiding high V_T), less atelectotrauma (avoiding low V_T) and more stable $PaCO_2$
Volume guarantee (VG)	The operator sets a target expired V_T and the ventilator adjusts the PIP for the next inflation based on the measurement of the expired V_T of the previous breaths.	SIMV AC PSV	Set Pmax	✓	✓	✓	✓	✓	The set Pmax is different from the delivered PIP because the ventilator adjusts the delivered PIP to achieve the target V_T. The PIP max should be set high enough to allow fluctuations around the working PIP

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Pressure support ventilation (PSV)	Following detection of spontaneous patient effort, the ventilator delivers a breath that is flow-cycled.		✓		✓	for SIMV back up	for SIMV back up	✓	The clinician has control over the inspiratory pressure and time limit and the synchronized intermittent mandatory ventilation (SIMV) rate which provides a safety back up in case of apnea. Volume guarantee can be added to PSV mode.

PIP: peak inspiratory pressure,
PEEP: peak end expiratory pressure,
V_T: tidal volume,
Ti: inspiratory time,
FiO_2: fractional inspired oxygen concentration

The preferred ventilator modes followed in our unit for various disease conditions are depicted in Table 49.3. We prefer AC mode during the acute phase of ventilation and PSV during weaning from the ventilator. Whenever possible, volume guarantee (VG) option is used. However, VG is avoided if the leak displayed is >30-40%.

Table 49.3: Preferred modes of ventilation in different lung conditions

Underlying condition	Acute phase	Weaning	Comments
Respiratory distress syndrome	A/C, use VG option to tailor PIP	*Choice 1:* PSV *Choice 2:* SIMV+PSV	1. Look for auto-triggering while using A/C or PSV modes (use SIMV if auto triggering occurs) 2. Ensure that the leak is <30 40% while using VG
Broncho pulmonary dysplasia	A/C or PSV Use VG option to tailor PIP	*Choice 1:* PSV *Choice 2:* SIMV+PSV	
Meconium aspiration syndrome	SIMV	*Choice 1:* PSV *Choice 2:* SIMV+PSV	Avoid using A/C if the baby's spontaneous breathing rate is >80 per minute
Pneumonia	A/C or PSV	*Choice 1:* PSV *Choice 2:* SIMV+PSV	
Transient tachypnea of newborn	A/C or PSV	*Choice 1:* PSV *Choice 2:* SIMV+PSV	Avoid A/C if the baby's spontaneous rates are very high (> 80-90 per min) –expiratory time (Te) might get compromised; in these situations, use either PSV or SIMV
Apnea/shock /asphyxia (conditions with normal lung or minimal lung disease)	SIMV (rates usually kept low)	SIMV	Avoid using A/C or PSV-chances of hypocarbia if the back-up rate is kept inadvertently high.
Failure of conventional ventilation, CDH, Air-leaks	HFO	*Choice 1:* PSV *Choice 2:* SIMV+PSV *Choice 3:* Direct weaning to CPAP/oxygen by hood	

Note: Choice 1 indicates the preferred mode of ventilation

The usual settings on a mechanical ventilator are shown in Table 49.4. These settings are basic guides and need modification based on the disease condition and acuity of the illness.

Table 49.4: Ventilatory parameters and their initial settings

Parameter	Description	Setting	Remarks
Tidal volume	Alveolar ventilation = RR X (VT- dead space). Increasing either RR or VT will increase alveolar minute ventilation, but increasing VT has a greater impact than increasing rate, because of the effect of dead space.	4-6 mL/kg; maximum – 8 mL/kg	Volutrauma if VT 8 mL/kg Atelectotrauma if 3 mL/kg
Peak inspiratory pressure (PIP)	The optimal PIP setting is one that results in just adequate chest rise, audible breath sounds, and results in an adequate tidal volume (between 4 and 6 mL/kg). The PIP setting will also depend on the age and size of the infant and the underlying disease condition.	Start at 12-16 cm H_2O. Can increase to 20-25 in poorly compliant lungs as in severe RDS/pneumonia etc	The exhaled VT for a set PIP in pressure controlled ventilation and conversely, the PIP required to deliver a set VT in volume controlled ventilation should be constantly evaluated and monitored.
Positive end expiratory pressure (PEEP)	PEEP is an important determinant of mean airway pressure and therefore of adequacy of oxygenation. Optimum PEEP ensures that the functional residual capacity (FRC) is maintained.	Initial PEEP setting depends on underling lung condition and in diseases with poor lung compliance, level of 5 to 6 cm H_2O is reasonable while in diseases with risk of air trapping like meconium aspiration syndrome, 3-4 cm H_2O should be adequate. PEEP	Inadvertently high PEEP or failure to reduce PEEP as lung compliance improves, leads to over-distension of the lung, hypercarbia, increased pulmonary vascular resistance, and impairment of venous return and decreased cardiac output.

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		can be titrated upward if FiO_2 remains above 40%.	
Inspiratory time (Ti)	Ti depends on the time constant of the respiratory system Smaller neonates have shorter time constants and diseases with poor lung compliance like RDS have shorter time constants compared to diseases with higher airway resistance like BPD and MAS. In flow cycled modes like PSV, Ti is patient determined and inflation is terminated when inspiratory flow declines to a preset value, usually 15% of peak flow. Here, the set Ti value is only an upper limit that comes into play when flow cycling fails to occur.	Ti is set around 0.4 to 0.5 second for term neonates and 0.25 to 0.35 seconds for preterm neonates.	The flow time scalar graph is a useful adjunct to adjust Ti should be sufficient enough to allow completion of inspiratory flow before the ventilator cycles off into expiration and also avoid a significant inspiratory hold that increases patient–ventilator asynchrony.
Rate	Depends on the lung condition and infant	40 (range of 30-60 per min)	In RDS, with shorter time constants, a higher rate is preferred. In MAS, a lower rate with adequate Ti and Te is preferred.
Expiratory time (Te)	Disease conditions with greater airway resistance need adequate Te to allow complete emptying of lungs during exhalation. Te can be either directly set or altered using Ti and rate.		Insufficient Te is depicted in the flow time scalar as failure of the expiratory flow to return to zero before the next inflation
FiO_2	FiO_2 should be adjusted to achieve a SpO_2 target of 90-95%	Begin at 30-50% and optimize based on SpO_2	Excessive oxygen can lead to oxygen toxicity. If FiO_2>

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	by optimizing FRC (increasing the PEEP in increments of 0.5-1 cm H_2O until FiO_2 is below 30%.)	and underlying condition.	60%, rule out PPHN or inadequate MAP
Trigger sensitivity	Trigger sensitivity helps to optimize patient–ventilator interaction.	Trigger should be set at the most sensitive value to provide a rapid ventilator response and minimize work load to trigger an inflation.	Auto triggering can occur if there is ET tube leak or water condensate in the circuit.

Once mechanical ventilation is initiated, the settings need to be titrated based on clinical evaluation and supported by blood gases and/ or chest x-ray as the disease condition evolves. Relying solely on blood gases may lead to late detection of worsening or delay in weaning leading to lung injury. The various parameters that need to be monitored in neonates on mechanical ventilation are listed in Table 49.5.

Table 49.5: Parameters to be monitored in ventilated neonates

Clinical Parameters	• Patient comfort and synchrony • Color, perfusion and capillary refill • Chest rise with spontaneous breaths and ventilator inflations • Respiratory rate including spontaneous breaths • Retractions or work of breathing • Breath sounds audible symmetrically in all lung areas, adventitial sounds and ET leak • Heart sounds and murmur • Others: sensorium (activity), blood pressure, perfusion and urine output (*Agitation or patient- ventilator asynchrony often reflects inadequate ventilator support rather than lack of sedation*)
Ventilatory parameters	• Exhaled tidal volume in PCV and measured PIP in VCV/VTV • Spontaneous respiratory rate • Mean airway pressure • Percentage ET leak

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	• Flow–time scalar to evaluate the adequacy of inspiratory and expiratory time, inspiratory hold
Pulse oximetry	Oxygen saturation between 90% and 95%
Blood gas analysis	Blood gases are usually indicated 30 minutes after initiation of mechanical ventilation and 30 minutes after making significant changes in setting. Blood gases may be needed frequently (4-6 hourly) during acute illness and less often (12 hourly or once in 24 to 48 hours) in chronically ventilated neonates. The usual targets are pH 7.25, PCO_2 45-55 (permissive hypercapnia- PCO_2 55-60 mm Hg), PaO_2 50-70 mm Hg, base excess -5 to +5 and HCO_3 in normal range
Chest radiograph	After first intubation, chest radiograph should be performed to confirm the position of ET tube and to evaluate lung expansion. Flattening of diaphragm and greater than 8 posterior rib spaces on CXR indicates over expansion of lungs. Adequacy of PEEP is best determined on the basis of oxygen requirement rather than lung expansion on CXR.
Condition	**Suggested Settings**
Respiratory distress syndrome Poorly compliant low volume lungs with shorter time constants	Initial settings: • PIP 14-18 cm H_2O or VT of 5-6 ml/kg • PEEP 5-6 cm H_2O • Rate 50-60/min • Ti 0.35 seconds
Transient tachypnea of newborn (TTN)	Initial settings: • PIP 12-16 cm H_20 or VT of 4-5 ml/kg • PEEP 4 to 5 cm H_2O • Rate 40-60/min • Ti 0.35 - 0.4 seconds
Apnea of prematurity (AoP) Asphyxia	• PIP 12-14 cm H_2O or VT of 4-5 ml/kg • PEEP 3 to 4 cm H_2O • Rate 20-40/min • Ti 0.4-0.45 seconds
Meconium aspiration syndrome	The clinical features of MAS may be quite variable depending on the pathophysiology- surfactant inactivation and chemical pneumonitis leading to atelectasis versus airway obstruction.

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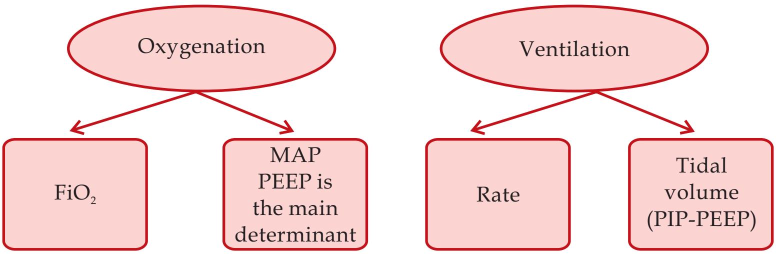
	The choice of ventilator setting depends on the underlying pathology: • PIP 14 to 18 cm H_2O or VT 5 to 6 ml / kg • PEEP 3.5 to 4 cm H_2O • Rate 30 to 40 min • Ti 0.35-0.5 seconds Target SpO_2 92-95% to avoid PPHN; PEEP 4-6 cm H_2O if predominant atelectasis.
BPD	BPD is a heterogeneous lung disease with regions of atelectasis and airtrapping. There is increased airway resistance and increased functional residual capacity and functional dead space. **BPD early stages: strategy similar to ventilation in RDS (except for rates)** Volume-targeted: VT 5-8 mL/kg Rate 20-40 bpm Ti: 0.35-0.45 seconds PEEP 5-6 cm H_2O **Severe BPD:** VT: May need higher VT of 6-10 mL/kg. Rate 20-30 bpm Ti: 0.5-0.7 seconds (adequate Ti is needed to overcome airway resistance and adequate Te to ensure complete emptying) PEEP: Variable. Chronic BPD patients may have trache-bronchomalacia and higher PEEP of 8-12 cm H2O may be needed to prevent airways from collapsing
Congenital diaphrag-matic hernia (CDH)	CDH is characterized by pulmonary hypoplasia and significant PPHN. Gentle ventilation, permissive hypercarbia and maintaining a pre-ductal SpO2 of >85% are key principles in initial stabilization. PIP <25 cmH_2O. Tolerate PaCO2 up to 60 mm Hg as long as pH >7.25, adequate perfusion and normal lactate. If PIP > 25 cm H2O, consider initiating HFO. Other settings: PEEP 4-5, Rate 30-40/min, Ti 0.35, FiO2 50-100%, VT of 4 ml/kg.

Subsequent ventilator adjustments should be tailored to meet adequate oxygenation and ventilation.



Target: SpO_2 90-95%

Adjustment in hypoxia

- Optimize functional residual capacity by increasing PEEP. Increase PEEP in small steps of 0.5-1 cm H_20 until FiO_2<30% or results in no further drop in FiO_2.
- When FiO_2>60% suspect PPHN or right to left shunting
- Increasing PIP and Ti will also increase MAP, but these steps are less effective and can potentially cause lung over-distension and injury

Adjustment in hyperoxia

- Wean FiO2 below 60% and then decrease MAP. Adjustments in PIP and PEEP should be proportional and go hand in hand. Decreasing PEEP below 5 can lead to atelectasis

Target: $PaCO_2$ of 40-45 mmHg in acute stage and up to 45-60 mm Hg as long as pH > 7.25 in chronic setting.

Adjustment in hypercarbia

- Alveolar minute ventilation depends on tidal volume and rate.
- Dead space should be minimized by cutting short the ET tube and avoiding the use of ET CO_2 monitors in extremely small preterm neonates.
- Watch out for hypercarbia that is secondary to lung over expansion (increased AP diameter of chest, decreased chest rise with ventilator breaths, lung hyper expansion in CXR).

Adjustment in hypocarbia

- $PaCO_2$ values 25 mm Hg can lead to cerebral vasoconstriction and PVL and should be avoided. Wean VT first followed by rate.
- In SIMV mode, ventilator rate should not be reduced below 15 to 20 inflations/min before extubation
- In AC mode, if infant has sufficient drive, weaning is accomplished by decreasing the PIP/PEEP.

Acute deterioration on mechanical ventilator: Mechanically ventilated neonates can have episodes of acute deterioration manifesting as desaturation, apnea, bradycardia or poor perfusion. This can be secondary to an acute event like endotracheal tube displacement or obstruction, pneumothorax, equipment failure (DOPE), worsening disease or onset of new pathophysiological process like PDA, sepsis, intraventricular hemorrhage, etc.

Appropriate action would include quick clinical assessment, disconnection from ventilator and manual bagging to rule out equipment failure, verifying ET position and patency and a bed-side trans-illumination of chest to rule-out pneumothorax. Appropriate action would avert a potentially serious or life threatening disaster. After initial stabilization, chest radiograph, blood gas and other ancillary tests can be done to diagnose worsening or new disease condition.

Weaning from ventilator[5]: In order to decrease ventilator induced lung injury and other adverse effects, the duration of ventilation should be as short as possible. Weaning should be attempted as soon as the underlying condition begins to improve, the neonate is clinically stable and blood gases are acceptable. The various parameters that can be weaned in a ventilator are described below:

1. Tidal volume: Wean VT in volume controlled mode to maintain PCO_2 <50 mm Hg. Dropping VT <4mL/kg will lead to atelectasis and should be avoided
2. Peak inspiratory pressure (PIP): Wean PIP based on delivered tidal volumes. PIP can be dropped gradually as compliance improves which is reflected in higher VT for the same set PIP. In volume guarantee mode, the PIP is automatically weaned as compliance improves
3. PEEP: Wean as indicated when FiO2 < 30%. Oxygenation is the best guide to wean PEEP rather than lung inflation on CXR. In conditions with high risk of air trapping, one can lower PEEP while accepting higher FiO_2. Generally, weaning PEEP to < 5 cm H_2O should be avoided to prevent atelectasis

4. Rate: Wean as tolerated for PCO_2<50 mm Hg. Generally rate is weaned once PIP or VT has been weaned. Weaning rates when PIP is high (example 18-20 cm H_2O) can lead to increased work of breathing. In SIMV mode, rates should not be dropped below 15-20 bpm because it can lead to excessive work of breathing. In PSV and AC modes, the set rate represents the back-up rate and dropping rates does not lead to weaning. Typically Ti (inspiratory time) is not altered during weaning

Although there is no fixed protocol for weaning, some considerations should be kept in mind: 1 most potentially harmful parameter should be weaned first; 2 weaning should occur in small decrements with one parameter at a time to avoid flip-flop; and 3 ensure adequate support to decrease work of breathing during weaning process. All changes should be documented.

Extubation from mechanical ventilation: Once ventilatory parameters have been weaned sufficiently, the underlying condition is resolved and the neonate good spontaneous efforts, he/she can be considered ready for extubation. For example, a neonate ventilated for RDS in the pressure controlled SIMV mode on settings of PIP 16 cm H_2O, PEEP 5 cm H_2O, rate 20 and FiO_2 0.30 can be considered ready to be extubated to CPAP. Older infants ventilated for chronic conditions can be extubated from higher peak pressures or tidal volume. As adjuncts to extubation, caffeine therapy in preterm neonates <32 weeks' gestation is associated with 50% reduction in extubation failure.[6] This can be initiated early or peri-extubationally in same doses as recommended for apnea of prematurity. CPAP applied immediately after extubation reduces the incidence of respiratory failure and need for re-intubation in very preterm neonates.[7]

Despite successful extubation, up to one-third of neonates may require re-intubation. The common reasons for re-intubation are significant apnea, hypoxia, acidosis or hypercarbia, upper airway obstruction due to edema or stenosis or excessive work of breathing. While it is difficult to predict failures, a few common risk factors are listed below.

Risk factors for extubation failure
• Lower GA (≤26 weeks) • Prolonged ventilation (>10–14 days) • History of previous extubation failure • Use of sedatives and analgestics (e.g. morphine, fentanyl) • Multiple reintubations: upper airway problem • Evidence of residual lung injury: BPD, pulmonary interstitial emphysema • Extubation from high ventilatory settings or high FiO2 • Hemodynamically significant PDA • Hemodynamic instability, sepsis, NEC

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