

6 Basics of Mechanical Ventilation

Abstract: Mechanical ventilation is administered primarily in patients unable to maintain adequate alveolar ventilation. It is useful to remember that its role is supportive and is used to buy time, as we address ourselves to the conditions that led to the respiratory failure.

The introduction in the modern era has revolutionized the standard of respiratory and critical care medicine by integrating microprocessor-controlled flow rate and pressure waveform dynamics to optimize gas exchange for the critical care patient.

Mechanical ventilation (MV) requires sound knowledge and skill together as there are potential dangers from ventilation itself. Therefore, the policy of “providing support, doing least harm” should guide ventilatory support.

Now-a-days Non-invasive ventilation (NIV) is preferred if indicated and there are no contraindications. It should be used only if there is enough evidence to support the utility of NIV in that condition. Mechanical ventilation is initiated when a patient’s ability to maintain gas exchange has failed. This could be either hypoxemic or hypercapnic respiratory failure.

Positive pressure ventilation has significant effects on hemodynamics as it decreases preload and afterload.

Several models of mechanical ventilators are available from the simple pneumatic system to the new generation microprocessor controlled systems. The modern ventilators have different software and each has one or more unique features. However, the basic function and applications of these remain common.

The vast majority of patients in the ICU are managed using one of four modes of mechanical ventilation. These modes are either volume-preset or pressure preset. In the volume-preset mode the clinician sets the rate and tidal volume and the ventilator delivers whatever pressure is required to achieve it. In the pressure-preset mode the clinician sets the maximal inspiratory pressure and inspiratory time the ventilator delivers whatever tidal volume is generated by that pressure.

It is important to monitor patients on ventilation closely to avoid harmful effects.

INTRODUCTION

Mechanical ventilation is administered primarily in patients unable to maintain adequate alveolar ventilation. It is useful to remember that its role is supportive and is used to buy time, as we address ourselves to the conditions that led to the respiratory failure.

Their introduction in the modern era has revolutionized the standard of respiratory and critical care medicine by integrating microprocessor-controlled flow rate and pressure waveform dynamics to optimize gas exchange for the critical care patient. This intervention should not be started without thoughtful consideration because intubation and positive-pressure ventilation are not without potentially harmful effects.

Therefore, the policy of “providing support, doing least harm” should guide ventilatory support.

Indications of Invasive Mechanical Ventilation

Now-a-days non-invasive ventilation (NIV) is preferred, if indicated, and there are no contraindications. It should be used only if there is enough evidence to support the utility of NIV in that condition. The indications of intermittent positive pressure ventilation (IPPV) are mentioned below:

Indications

Mechanical ventilation is initiated when a patient’s ability to maintain gas exchange has failed. This could be either hypoxemic or hypercapnic respiratory failure.

1. Unprotected and unstable airways (e.g., coma). Intubations and IPPV allows :
 - To secure the airways.
 - Reduce the risk of aspiration.
 - Maintain adequate alveolar ventilation.
2. Hypercapnic respiratory acidosis
 - IPPV reduces the work of breathing and thus prevents respiratory muscle fatigue or speeds recovery when fatigue is already present
 - Maintains adequate alveolar ventilation (prevent or limit respiratory acidosis as needed).
3. Hypoxic respiratory failure IPPV helps correct hypoxemia as it allows to
 - Deliver a high FiO_2 (100% if needed during IPPV)
 - Reduce shunt by maintaining flooded or collapsed alveoli open.
4. Circulatory Disorders:
 - Cardiopulmonary arrest -Apnea
 - Refractory or unresuscitated shock.
5. Elevated intracranial pressure requiring hyperventilation.

Clinical Indices of the Need for MV

Inadequate Ventilation

- $\text{RR} > 30$ breaths/min (Normal 10-20)
- $\text{VT} < 5$ ml/kg (Normal 5-7)
- $\text{VC} < 15$ ml/kg (Normal 65-75)
- $\text{PaCO}_2 > 60$ mm Hg
- $\text{RR}/\text{VT} > 100$
- VD/VT ratio > 0.6 (Normal < 0.3)
- Paradoxical breathing.

Inadequate Gas Exchange

- $\text{PaO}_2 < 60 \text{ mm Hg}$ on $\text{FiO}_2 > = 0.6$.

Although all these indices are mentioned but most of the time the decision to ventilate is clinical, based on the trends and the condition of the patient at that time.

Physiological Effects of Mechanical Ventilation

Positive pressure mechanical ventilation has many effects on the lung and heart as mentioned below:

Important Effects of PPV on Hemodynamics

Positive pressure has significant effects on hemodynamics as it decreases preload and afterload.

- Decreased preload
 - Positive alveolar pressure \uparrow lung volume \rightarrow compression of the heart by the inflated lungs \rightarrow the intramural pressure of the heart cavities rises (e.g., \uparrow RAP) \rightarrow venous return decreases preload is reduced \rightarrow stroke volume decreases \rightarrow cardiac output and blood pressure may drop. This can be minimized with i.v. fluid, which helps restore adequate venous return and preload.
 - Patients who are very sensitive to change in preload conditions (e.g. presence of hypovolemia, tamponade, PE, severe air trapping) are particularly prone to hypotension when PPV is initiated.
- Reduced afterload
 - Lung expansion increases extramural pressure (which helps pump blood out of the thorax) and thereby reduces LV afterload.
 - When the cardiac performance is mainly determined by changes in afterload than in preload conditions (e.g, hypervolemic patient with systolic heart failure), IPPV may be associated with an improved stroke volume. IPPV is very helpful in patients with cardiogenic pulmonary edema, as it helps to reduce preload (lung congestion) and afterload. As a result stroke volume tends to increase. All other changes are summarized in Figure 1.

MECHANICAL VENTILATION

Several models of mechanical ventilators are available from the simple pneumatic systems to the new generation microprocessor controlled systems. The modern ventilators have different software and each has one or more unique features. However, the basics functions and applications of these remain common.

Each ventilator has the following 3 panels:

1. Ventilator setting (controls)
2. Monitoring
3. Alarms and messages.

Now we shall discuss the various controls and their functions on a critical care ventilator.

Ventilator Control Panel

Common modes of MV: Traditional modes of invasive mechanical ventilation use volume, pressure, flow and time to cycle from the inspiratory to the expiratory phase and can be administered as full or partial ventilator support. Full support provides the patient with adequate ventilatory requirements to meet metabolic demands without supplementation by the patient. Partial support provides partial ventilator assistance but requires patients to actively participate in their own spontaneous ventilation.^{1,2}

The vast majority of patients in the ICU are managed using one of four modes of mechanical ventilation. These modes are either volume-preset or pressure preset. In the volume-preset mode the clinician sets the rate and tidal volume and the ventilator delivers whatever pressure is required to achieve it. In the pressure- preset mode the clinician sets the maximal inspiratory pressure and inspiratory time, the ventilator delivers whatever tidal volume is generated by that pressure.

Both pressure- and volume- presets ventilation can provide full ventilatory support. Volume preset ventilation assures minute ventilation that is set for the patients, even if lung mechanics change. Pressure preset ventilation purports to minimize ventilator induced lung injury, but changes in respiratory resistances or compliance may lead to significant decreases in ventilation.

Volume Preset Modes

Assists control (ACMV) or Controlled Mandatory Ventilation (CMV): The Tidal Volume (VT) and the minimum respiratory rate are set. The ventilator then delivers the set VT each time a breath is triggered by the patient. If the patient's spontaneous respiratory rate is low, then the ventilator delivers independently at the set rate and when the respiratory effort does not occur within a preselected time. Again, if the patient is paralyzed the ventilator delivers at the set rate- this is the so-called CMV (Fig. 2).

ACMV is used when the goal is to minimize the patient's work of breathing. However, an airway obstruction increase in patient's minute ventilation can lead to airtrapping or PEEPi.

Synchronized intermittent mandatory ventilation (SIMV): The clinician sets the RR and VT and the ventilator delivers exactly that volume every minute. These mandatory breaths are synchronized with patient's spontaneous breaths by the ventilator. To allow the patient to take spontaneous breaths between the mandatory breaths, the machine creates a "time window" which is the only time when the ventilator will trigger in response to spontaneous breath. If the patients triggers outside this time window, then spontaneous breath is allowed to occur. If the patient fails to initiate a breath, after the time window, the ventilator delivers a controlled breath at the preset rate (Fig. 3).

Thus, in this mode 3 different kinds of breath can occur: patient- initiated assisted ventilation, ventilator generated controlled ventilation, and unassisted spontaneous breath. The last can also be separately boosted by pressure support.

Pressure Preset Modes

Pressure control ventilation (PCV): The clinician sets the inspiratory pressure above PEEP, the back up rate and the inspiratory time. Thus here, in contrast to volume controlled ventilation, the pressure is constant while the tidal volume is variable with changes in lungs mechanics.

Since in this mode the alveolar pressure cannot exceed the set pressure this is being increasingly used in patients with ARDS. The disadvantages are that minute ventilation is not guaranteed and air trapping may occur with prolonged inspiratory times.

Pressure support ventilation (PSV): The clinician sets only the inspiratory pressure above PEEP in a spontaneously breathing patient. Whenever the patient triggers a breath, the ventilator delivers this pressure. When a threshold decrease in inspiratory flow is reached, the inspiratory boost is terminated (Fig. 4). This mode of ventilation allows for titration of patient effort during the process of weaning. The disadvantages are that there is no guarantee of tidal volume with changing respiratory mechanics, and as with ACMV, airtrapping can occur. This mode has no back up ventilation in the event of apnea.

Continuous positive airway pressure (CPAP): Positive end expiratory pressure applied to a spontaneously breathing patient is referred to as CPAP. This is not a mode of ventilatory support.

It is the setting on which spontaneous breathing trials may be applied while the ventilator's monitoring function are in place. CPAP may also increase the FRC and decrease work of breathing in patients of COPD with PEEP_i.

Fraction Inspired Oxygen (FiO₂)

When the patient is attached to the ventilator, initially the FiO₂ is set at 1.0 (100%) and once the patient is stabilized, it is gradually reduced to below 0.6 generally believed to represent the threshold value for the risk of oxygen toxicity.

Positive End Expiratory Pressure (PEEP)

This increases FRC and helps recruit collapsed alveoli in ARDS. PEEP is also now believed to protect alveoli against ventilator- induced lung injury (VILI). PEEP needs to be titrated according to the patient's needs in ARDS. Even at this point of time there is no consensus on how to select optimum PEEP in ARDS.

Inspiratory Flow Rate

Patients are uncomfortable when the flow rate is low. Breathless patients generally need an inspiratory flow rate of 60 L/min, otherwise they experience "air hunger" or "flow deprivation". Patient's ventilator asynchrony may often be corrected by adjusting the inspiratory flow rate or tidal volume. While ventilating patients of status asthmaticus, flow rates of 60-100 L/min are needed to avoid airtrapping, consequent barotrauma and hemodynamic impairment.

Tidal Volume (TV)

Traditionally, the tidal volumes were set at 12-15 ml/kg, but there is increasing evidence that "Volutrauma" can cause lung injury. Therefore, lower tidal volumes (8 to 10 ml/kg) are now recommended especially in ARDS where tidal volumes of 5-7 ml/kg have been shown to have better outcomes than higher volumes. It is important to limit the plateau pressure to 30 cm H₂O, even if it means accepting low tidal volume and minute ventilation.

Respiratory Rate

RR upto 30/ min can be set where airtrapping is not a problem. In severe airflow limitation, however it is imperative that the rate is set low -8-12/min, while monitoring Auto PEEP (PEEP_i). For the occurrence of PEEP_i the respiratory rate appears to be the most important determining factor.

I: E Ratio

Where inspiratory flow rate cannot be adjusted directly, I: E ratio can be set. In obstructive airways diseases the expiration should be prolonged i.e. I: E should be 1: 4 or longer. In case of ARDS, where inverse ratio is desired it should be set at 1: 1, 2: 1 or more while monitoring PEEP_i.

Triggering Sensitivity

This is the degree of negative pressure required to be generated by the patient to initiate a ventilator breath. The greater the negative pressure required the higher the threshold load on the patient. Generally, the triggering sensitivity is set at -2 cm H₂O.

A lower sensitivity may sometimes lead to "auto triggering" by the ventilator, requiring the sensitivity to be set at a higher level.

The practice of gradually increasing the threshold load to train the respiratory muscles during the process of weaning is no longer popular.

Flow triggering employs directly the negative inspiratory flow generated by the patients as opposed to pressure, which is more sensitive and imposes less inspiratory threshold load.

ALARM LIMITS

Airway pressure limit: the peak airway pressure should be set at generally 50 cm H₂O except in cases of status asthmaticus where high P_{pk} values are acceptable. In the latter the P_{lat} should be < 30 cm H₂O as this reflects truly the transalveolar pressure. The pressure alarm is set 5-10 cm H₂O above the normal peak pressure.

Exhaled volume and minute ventilation limits: This alarm provides extra safety to detect early any leaks in the system. These should be set 15 to 20% below the set tidal volume and minute ventilation.

Inspiratory Rise Time

The normal inspiratory rise time is set at 5%. During inverse ratio ventilation, we want an instant rise and it should, therefore, be set at zero. In partial modes or if the patient is alert during controlled modes, increased patient comfort can be accomplished by increasing inspiratory rise time, as it may make the start of inspiration gentle.

Flow Wave Form

'Square' 'Decelerating' or 'Sine wave' forms can be set. Change from a square to a decelerating flow may nearly halve the inspiratory flow rate and may lead to airtrapping. There is no evidence that setting the wave form changes outcome in ventilated patients.

Summary of Initial Ventilator Setup

Initial settings for ventilation may be summarized as follows:

- Assist-control mode
- Tidal volume set depending on lung status
 - Normal = 10-12 mL/kg ideal body weight
 - COPD = 8 mL/kg ideal body weight
 - ARDS = 6-8 mL/kg ideal body weight
- Rate of 10-12 breaths per minute
- FIO₂ of 100%
- PEEP 4 cm H₂O
- Peak flow rate 60 lt/mt.
- Alarms.

MONITORING PANEL

Feedback from the ventilator is used to assess the respiratory mechanics of the patient. This information, together with the clinical information about⁵ the patient then guides further adjustment of the ventilatory settings.^{3,4}

Peak Airway Pressure

This represents the airway pressure generated in the trachea and the proximal airways during inspiration. This is the maximal pressure obtained during positive pressure ventilation and

presents the total pressure needed to overcome resistances related to the circuit, endotracheal tube, airway and lung tissue as well as impedance due to elastic recoil of the lung and chest wall. Patients with airway obstruction may have a very high peak pressure without any increase in plateau. The gradient Ppk to Pplat is directly related to the airway resistances. Precipitously increasing Pk should alert us to the possibility of bronchospasm, pneumothorax, ARDS or retained secretions.⁴⁻⁷

Plateau Pressure (Pplat)

Upon applying an inspiratory hold of 0.5 secs, the pressure waveform reveals the plateau pressure, which represents the elastic recoil pressure of the respiratory system at end inspiration.

This also represents the transalveolar pressure. In the presence of high airway resistance or high inspiratory flow rate, there is a wide gap between Ppk and plat. In ARDS or interstitial lung diseases the difference is small. The risk of baro or volutrauma and adverse hemodynamic effects are related to Pplat rather than Ppk.

The target Pplat is 30 cm H₂O. In the presence of PEEP_i or airtrapping there is also elevation of Pplat. In patients with stiff chest wall or obesity Pplat may exceed 35 cm H₂O without alveolar distension.^{8,14}

Expiratory Tidal Volume (Vexp)

Expiratory tidal volume gives information about the tidal volume generated in the lung when pressure targeted ventilation is applied. In volume targeted ventilation the gap between set tidal volume (VT) and the expired tidal volume (VExp) represents leak from the tubing, pneumothorax or airtrapping.

Respiratory Rate

The total respiratory rate is the set control rate + additional patient initiated breaths.

The total rate should be less than 30, if higher, it indicates that the patient requires greater support. The respiratory rate and the VExp are used to assess the patient's readiness to be weaned expressed as the f/Vt ratio, which should be less than 105.

Inspiratory Hold

An inspiratory hold of 0.3 to 0.5 secs is used to measure Pplat. The static compliances can be calculated using the formula

$$\text{Compliance} = \frac{\text{Inspired tidal volume}}{\text{Pplat} - \text{PEEP}}$$

Expiratory Hold

An intrinsic PEEP may be detected by occluding the airway at the end of expiration and measuring the equilibrium airway pressure after 3 or 4 seconds.

Intrinsic PEEP or PEEP_i

This is the concealed volume of air above FRC left in the alveoli at the end expiration. When an expiratory hold is applied, the deflection on the pressure gauge measures the PEEP_i. In the new generation ventilators, this maneuver is automatically done and the PEEP_i value is digitally displayed. PEEP_i represents airtrapping, but it may underestimate its degree. It is best seen on flow vs time graphics (Fig. 5).

Airtrapping also elevates Plat, therefore, the latter can be taken as a reliable marker that indicates the volume of air trapped especially while ventilating patients of bronchial asthma and COPD. PEEP_i may lead to hemodynamic compromise, barotraumas or increased work of breathing as the negative pressure required to initiate a ventilator breath is increased. When the P_{plat} is rising, measures to reduce PEEP_i should be taken - viz. reduce RR, reduce TV and/ or increase peak flow rate.

Graphics

The visual representation of the relationship between volume, of pressure flow and time gives a ready and breath-to-breath assessment of lung mechanics. This can effectively guide ventilator management.

ALARMS AND MESSAGE PANEL

Alarms limits are set as the outset to protect the patient from complications through high airway pressure, air trapping, air leak or system failure. Most of the alarms are self explanatory:

- Airway pressure too high
- High continuous pressure
- O₂ concentration
- High respiratory rate
- O₂ sensor
- Exp minute volume too high
- Exp minute volume too low
- Apnea alarm
- Gas supply
- No battery capacity left
- Checking tubing

Appropriate action should be taken for each alarm.

WEANING FROM MECHANICAL VENTILATION

Since ventilation itself, when not required can be life threatening so should be discontinued at the earliest. It takes up a considerable portion of the time of workstaff in the ICU. There are two components of weaning - discontinuation of ventilation and removal of the airway.

Weaning should be attempted when the following conditions are fulfilled:

Every day in the morning we should assess patient for weaning by DAILY SCREEN –

- Alert, cooperative patient
- Acute phase of the disease process has resolved
- Acceptable pattern and depth of spontaneous breathing
- Patient coughs when suction catheter is passed, intact gag reflex
- Patients not receiving any vasopressor or sedative infusion drip. Dopamine allowed if dose ≤ 5 mcg/kg/min, and intermittent dosing of sedatives allowed.
- PEEP set ≤ 5
- $\text{PaO}_2/\text{FiO}_2 \geq 200$, e.g., PaO_2 of 100/ FiO_2 of 0.5 = 200
- $f/\text{VT} \leq 105$. This is also known as the Rapid Shallow Breathing Index (RSBI) Measured after 1 minute of spontaneous breathing with ventilator rate set to 0 and pressure support set to 0. The f/VT ratio is currently regarded as the most reliable predictor of weanability. A ratio of 105 best discriminates between successful and unsuccessful attempts at weaning (less than 105 predicts successful weaning).

Predictors of Successful Weaning on SBT

- Tidal volume > 5 ml/ kg.
- Vital capacity > 10-15 ml / kg.
- Respiratory rate < 30 /min.
- PaO₂ > 60 mm Hg.
- pH > 7.3.

However, the sensitivity of these traditional predictors of weaning is inadequate.

Mostly the decision to wean off is taken on the basis of daily screen.

Spontaneous Breathing trials(SBT); When a patient fulfils the criteria of weaning he is subjected to spontaneous breathing trial. It is a trial of spontaneous breathing for 30 to 120 minutes with T-piece or 'pressure support set to 4-7cm H₂O.

It has been observed that rapid, shallow respiration occurs and a trial of spontaneous breathing results in and increases respiratory efforts by more than 4 times the normal value. There are certain subjective and objective criteria to assess tolerance or success of spontaneous breathing trial as mentioned below:

Subjective Criteria

- Absence of signs of increased work of breathing including thoracoabdominal paradox or excessive use of accessory respiratory muscles
- Absence of other signs of distress such as diaphoresis or agitation.

Objective Criteria

- SaO₂ > 90% or PaO₂ > 60mmHg on FiO₂ < 0.4-0.5
- Increase in PaCO₂ < 10 mmHg or decrease in pH < 0.10
- Respiratory Rate < 35 breaths/min
- Heart rate < 140 or an increase < 20% from baseline
- Systolic blood pressure > 80 mmHg or < 160 mmHg or change < 20% from baseline. Patient who tolerates spontaneous breathing trial for 30 or 120 mts should be extubated and put on oxygen.

Spontaneous breathing trial is terminated if the following criteria are met:

- Resp rate >35 for >5 minutes
- SaO₂<90% during >30 seconds of good quality measurement
- 20% increase or decrease in heart rate for >5 minutes
- Systolic blood pressure > 180 or < 90 during at least one minute of continuous recording or repeated measurements
- Agitation, anxiety, or diaphoresis confirmed as a change from baseline and present for >5 minutes.

What questions should we ask when a SBT fails?

- Can we identify the cause?
- Are the responsible factors reversible?
- How long should the patient rest?
- What technique should we apply to facilitate liberation?

If a spontaneous breathing trial fails, then one of the following 4 methods of gradual weaning can be adopted:

There are 4 methods of gradual weaning:

1. Single daily- T- Tube trial for up to two hours. If trial is successful the patient is extubated. If it fails the patient is given respiratory muscles rest with full ventilatory support for 24 hrs before another trial is performed.
2. Intermittent mandatory ventilation.
3. Pressure Support.
4. Trials of spontaneous breathing. Initially 5-10 mts in duration, the trials are extended and repeated several times a day until patient can sustain spontaneous ventilation for several hours.

During weaning trials watch for distress signs when the intervention should be discontinued and the patient is placed back on full support to provide adequate respiratory muscles rest. Weaning trials are again resumed the next day.

Recent randomized controlled trials have shown that the period of weaning is more prolonged with SIMV while it is similar with pressure support, multiple daily T- piece trials or single daily T- piece trials.

Complications of Mechanical Ventilation

Ventilator is not without side effects. It can result in the following:

- Ventilator-induced lung injury
- Barotrauma
- Volutrauma
- Oxygen toxicity
- Ventilator-associated pneumonia
- Cardiovascular effects.

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MULTIPLE CHOICE QUESTIONS

- 1. How much tidal volume should be used in patient of ARDS?**
 - A. 6 ml per kg of body weight
 - B. 8 ml per kg of body weight
 - C. 6 ml per kg of ideal body weight
 - D. 8 ml per kg of ideal body weight
- 2. IPPV can result in all of the following *except*:**
 - A. Decrease afterload
 - B. Increase preload
 - C. Increase afterload
 - D. Decrease work of breathing
- 3. Increase in peak airways pressure should alert us to the possibility of which of the following?**
 - A. Increase bronchospasm
 - B. Pneumothorax
 - C. Increase in secretions
 - D. ARDS
 - E. All of the above
- 4. What is the cycling mechanism in pressure support?**
 - A. Inspiratory time
 - B. Volume
 - C. Peak airways pressure
 - D. Threshold decrease in flow
- 5. In ARDS Plateau pressure should remain less than which of the following?**
 - A. 60 cm H₂O
 - B. 40 cm H₂O
 - C. 30 cm H₂O
 - D. 38 cm H₂O

1. C 2. C 3. E 4. D 5. C