

Introduction to Mechanical Ventilation



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Introduction

Mechanical ventilation is a procedure often performed in patients in respiratory failure, which is defined broadly as the inability to meet the body's needs for oxygen delivery or carbon dioxide removal. A ventilator delivers air, usually with an elevated oxygen content, to a patient's lungs via an endotracheal tube to facilitate the exchange of oxygen and carbon dioxide. The indications for mechanical ventilation include airway protection, treatment of hypoxemic respiratory failure (low blood oxygen), treatment of hypercapnic respiratory failure (elevated carbon dioxide in the blood), or treatment of a combined hypoxic and hypercapnic respiratory failure. On some occasions, patients are also intubated and placed on mechanical ventilation for procedures. However, intubation and

initiation of mechanical ventilation require a great degree of vigilance, as committing to this therapy can affect the patient's overall course of treatment.

Mechanical ventilation is managed by Respiratory Therapists (RTs), highly-trained medical professionals who specialize in the care of respiratory illnesses. In addition to managing ventilators, RTs have expertise in other forms of oxygen administration and respiratory support, provide medications for respiratory disorders, and assess patients for extubation readiness. RTs are essential for the appropriate care of mechanically ventilated patients. Conversely, mechanical ventilation traditionally has not been taught as a core component of many medical and nursing practices outside of Critical Care and Anesthesiology. As such, to collaborate effectively with RTs in the care of ventilated patients, additional education is warranted. Ventilator management can seem intimidating due to varied and confusing terminology (with many clinicians using synonyms for the same modes or settings), slight variation among brands of ventilators, unfamiliarity, or ceding management to others.

For COVID-19 patients, ventilators are often crucial, given the nature of the illness. But note that intubation and initiation of mechanical ventilation require a great degree of vigilance. The data supporting the importance of good ventilator management continues to increase, and appreciating the fundamental principles of ventilation is essential for all clinicians involved in the care of these patients.

VENTILATOR BASICS

Control (target) variables are the targets that are set, based on the mode of mechanical ventilation chosen. For example, there are pressure-controlled and volume-controlled modes of ventilation. In pressure-control, the clinician sets a designated pressure that is delivered with every breath. In volume-control, they set a designated tidal volume instead.

Conditional variables are the dependent variables in mechanical ventilation. For example, in volume controlled modes of ventilation, the tidal volume is a set parameter, while the pressure is a conditional variable, and can vary from breath to breath.

Trigger - the factor that initiates inspiration. A breath can be pressure-triggered, flow-triggered, or time-triggered.

Cycle - the determination of the end of inspiration, and the beginning of exhalation. For example, the mechanical ventilator can be volume, pressure, or time cycled.

PHYSIOLOGY TERMS

Airway resistance refers to the resistive forces encountered during the mechanical respiratory cycle. The normal airway resistance is ≤ 5 cm H₂O.

Lung compliance refers to the elasticity of the lungs, or the ease with which they stretch and expand to accommodate a change in volume or pressure. Lungs with a low

compliance, or high elastic recoil, tend to have difficulty with the inhalation process, and are colloquially referred to as “stiff” lungs. An example of poor compliance would be a patient with a restrictive lung disease, such as pulmonary fibrosis. In contrast, highly compliant lungs, or lungs with a low elastic recoil, tend to have more difficulty the exhalation process, as seen in obstructive lung diseases.

Atelectasis is a complete or partial collapse of the entire lung or area (lobe) of the lung. It occurs when the tiny air sacs (alveoli) within the lung become deflated or possibly filled with alveolar fluid.

Derecruitment is the loss of gas exchange surface area due to atelectasis. Derecruitment is one of the most common causes of gradual hypoxemia in intubated patients and can be minimized by increasing PEEP.

Recruitment is the restoration of gas exchange surface area by applying pressure to reopen collapsed or atelectatic areas of the lung.

Predicted Body Weight is the weight that should be used in determining ventilator settings, (*never* use actual body weight). Lung volumes are determined largely by sex and height, and therefore, these two factors are used to determine predicted body weight.

The formula for men is: **PBW (kg) = 50 + 2.3 (height (in) - 60)**

The formula for women is: **PBW (kg) = 45.5 + 2.3 (height (in) - 60)**

PHASES of MECHANICAL BREATHING

Initiation phase is the start of the mechanical breath, whether triggered by the patient or the machine. With a patient initiated breath, you will notice a slight negative deflection (negative pressure, or sucking).

Inspiratory phase is the portion of mechanical breathing during which there is a flow of air into the patient’s lungs to achieve a maximal pressure, the peak airway pressure (PIP or Ppeak), and a tidal volume (TV or VT).

Plateau phase does not routinely occur in mechanically ventilated breaths, but may be checked as an important diagnostic maneuver to assess the plateau pressure (Pplat). With cessation of air flow, the plateau pressure and the tidal volume (TV or VT) are briefly held constant.

Exhalation is a passive process in mechanical breathing. The start of the exhalation process can be either volume cycled (when a maximum tidal volume is achieved), time cycled (after a set number of seconds), or flow cycled (after achieving a certain flow rate).

VENTILATOR SETTINGS

Peak Inspiratory Pressure (PIP or Ppeak) is the maximum pressure in the airways at the end of the inspiratory phase. This value is often displayed on the ventilator screen. Since this value is generated during a time of airflow, the PIP is determined by both airway resistance and compliance. By convention, all pressures in mechanical ventilation are reported in “cm H₂O.” It is best to target a PIP < 35 cm H₂O.

Plateau Pressure (Pplat) is the pressure that remains in the alveoli during the plateau phase, during which there is a cessation of air flow, or with a breath-hold. To calculate this value, the clinician can push the “inspiratory hold” button on the ventilator. The plateau pressure is effectively the pressure at the alveoli with each mechanical breath, and reflects the compliance in the airways. To prevent lung injury, the Pplat should be maintained at < 30 cm H₂O.

Positive End Expiratory Pressure (PEEP) is the positive pressure that remains at the end of exhalation. This additional applied positive pressure helps prevent atelectasis by preventing the end-expiratory alveolar collapse. PEEP is usually set at 5 cm H₂O or greater, as part of the initial ventilator settings. PEEP set by the clinician is also known as extrinsic PEEP, or ePEEP, to distinguish it from the pressure that can arise with air trapping. By convention, if not otherwise specified, “PEEP” refers to ePEEP.

Intrinsic PEEP (iPEEP), or auto-PEEP, is the pressure that remains in the lungs due to incomplete exhalation, as can occur in patients with obstructive lung diseases. This value can be measured by holding the “expiratory pause” or “expiratory hold” button on the mechanical ventilator.

Driving pressure (ΔP) is the term that describes the pressure change that occurs during inspiration, and is equal to the difference between the plateau pressure and PEEP (Pplat – PEEP). For example, a patient with a Pplat of 30 cm H₂O and a PEEP of 10 cm H₂O would have a driving pressure of 20 cm H₂O. In other words, 20 cm H₂O would be the pressure exerted to expand the lungs.

Inspiratory time (iTime) is the time allotted to deliver the set tidal volume (in volume control settings) or set pressure (in pressure control settings).

Expiratory Time (eTime) is the time allotted to fully exhale the delivered mechanical breath.

I:E ratio, or the inspiratory to expiratory ratio, is usually expressed as 1:2, 1:3, etc. The I:E ratio can be set directly, or indirectly on the ventilator by changing the inspiratory time, the inspiratory flow rate, or the respiratory rate. By convention, decreasing the ratio means increasing the expiratory time. For example, 1:3 is a decrease from 1:2, just like 1/3 is less than 1/2.

Peak inspiratory flow is the rate at which the breath is delivered, expressed in L/min. A common rate is 60 L/min. Increasing and decreasing the inspiratory flow is a means of indirectly affecting the I:E ratio. A patient with a respiratory rate set at 20, who is not overbreathing, has 3 seconds for each complete cycle of breath. If you increase the inspiratory flow, the breath is given faster, and that leaves more time for exhalation. Thus, inspiratory flow indirectly changes the I:E ratio.

Tidal volume (TV or VT) is the volume of gas delivered to the patient with each breath. The tidal volume is best expressed in both milliliters (ex: 450mL) and milliliters/kilogram (ex: 6 mL/kg) of predicted body weight, much as one might describe a drug dosage in pediatrics. Clinicians can choose to set the ventilator in a volume control mode, where the tidal volume will be constant for each breath. In pressure control modes, the pressure is constant, but the tidal volume is an independent variable, and will vary slightly with each breath. Regardless, every mode of ventilation delivers a tidal volume.

Respiratory rate (RR or f, for “frequency”) is the mandatory number of breaths delivered by the ventilator per minute. However, it is important to be mindful that the patient can breathe over this set rate, and therefore one must report both your set RR and the patient’s actual RR; both of these values can found on the ventilator screen. In addition, it is important to remember that the RR is a key factor in determining time for exhalation. For example, if a patient has a RR of 10 breaths per minute (bpm), he will have 6 seconds per breath; $((60 \text{ seconds/min}) / 10 \text{ bpm} = 6 \text{ sec/breath})$. A RR of 20 bpm, only allows 3 seconds for the entire respiratory cycle.

Minute ventilation (\dot{V}_E , V_e , or MV) is the ventilation the patient receives in one minute, calculated as the tidal volume multiplied by the respiratory rate (TV x RR), and expressed in liters per minute (L/min). Most healthy adults have a baseline minute ventilation of 4-6 L/min, but critically ill patients, such as those attempting to compensate for a metabolic acidosis, may require a minute ventilation of 12-15 L/min, or even higher, to meet their demands.

Fraction of inspired oxygen (FiO₂) is a measure of the oxygen delivered by the ventilator during inspiration, expressed at a percentage. Room air contains 21% oxygen. A mechanical ventilator can deliver varying amounts of oxygen, up to 100%.

VENTILATOR MODES

Assist Control (AC) is a commonly used mode of ventilation, and one of the safest modes of ventilation in the Emergency Department. Patients receive the same breath, with the same parameters as set by the clinician, with every breath. They may take additional breaths, or over-breathe, but every breath will deliver the same set parameters. Assist control can be volume-targeted (volume control, AC/VC) where the clinician sets a desired volume, or pressure-targeted (pressure control, AC/PC) where the clinician selects a desired pressure.

Synchronized Intermittent Mandatory Ventilation (SIMV) is a type of intermittent mandatory ventilation, or IMV. The set parameters are similar to those in AC, and the settings can be volume controlled (SIMV-VC) or pressure controlled (SIMV-PC). Similar to AC, each mandatory breath in SIMV will deliver the identical set parameters. However, with additional spontaneous breaths, the patient will only receive pressure support or CPAP. For example, in SIMV-VC we can set a TV, and as long as the patient is not breathing spontaneously, each delivered mechanical breath will achieve this tidal volume. However, spontaneous breaths in this mode of ventilation will have more variable tidal volumes, based on patient and airway factors.

Pressure Regulated Volume Control (PRVC) is a type of assist-control that combines the best attributes of volume control and pressure control. The clinician selects a desired tidal volume, and the ventilator gives that tidal volume with each breath, at the lowest possible pressure. If the pressure gets too high and reaches a predefined maximum level, the ventilator will stop the air flow and cycle into the exhalation phase to prevent excessive airway pressure and resulting lung injury. In this mode of ventilation, the pressure target is adjusted based on lung compliance, to help achieve the set tidal volume.

Pressure Support is a partial support mode of ventilation in which the patient receives a constant pressure (the PEEP) as well as a supplemental, “supporting” pressure when the ventilator breath is triggered. In this mode, the clinicians can set the PEEP and the additional desired pressure over the PEEP. However, the peak inspiratory airflow, the respiratory rate, and the tidal volume are all dependent variables, and determined by the patient’s effort. The patient triggers every breath, and when the patient stops exerting effort, the ventilator stops administering the driving pressure, or the desired pressure over PEEP. Therefore, patients placed on this mode of ventilation must be able to take spontaneous breaths.

Non-invasive positive pressure ventilation (NIPPV) refers to two non-invasive modes of ventilation, in which the patient’s airway is not secured with an endotracheal tube. Rather, these modes of ventilation are delivered through a tight-fitting facemask or nasal prongs. There are several indications, and clear contraindications to these modes of ventilation, as discussed in the text. Both CPAP and BPAP are non-invasive modes of ventilation.

Continuous Positive Airway Pressure (CPAP) is a partial support mode of ventilation, in which the patient received a constant airway pressure throughout the respiratory cycle. The peak inspiratory airflow, respiratory rate, and tidal volume are all dependent variables and determined by the patient’s effort. Therefore, the patient must be awake, minimally sedated, and able to take spontaneous breaths during this mode of ventilation.

Bilevel Positive Airway Pressure (BPAP or BiPAP) is a partial support mode of ventilation, in which the patient receives two levels of airway pressure throughout the respiratory cycle. A high inspiratory pressure (iPAP), is similar to the peak airway pressure setting. The lower expiratory pressure (ePAP), similar to PEEP, is clinically apparent at the end of

expiration and helps maintain alveolar distention. The patient must be awake, minimally sedated, and able to take spontaneous breaths during this mode of ventilation.

Unconventional Modes of Ventilation

There are other modes of ventilation occasionally used in specific circumstances in ICUs, including Airway Pressure Release Ventilation (APRV), also referred to as Bi-Level or Bi-vent, High-frequency Oscillatory Ventilation, Proportional Assist Ventilation (PAV), and Neurally Adjusted Ventilator Assist (NAVA), but these modes are not appropriate to use without expert consultation.