VENTILATOR BASICS

KEY POINTS

- Invasive mechanical ventilation assists or replaces spontaneous breathing to deliver oxygen and remove carbon dioxide from the lungs through an endotracheal tube or tracheostomy tube.

- The SARS-CoV-2 virus causes diffuse pneumonia that can progress to acute respiratory distress syndrome (ARDS), requiring invasive mechanical ventilation with protective ventilator mode strategies. Implementing these strategies can decrease mortality.

- Essential parts of a mechanical ventilator include fresh gas supply lines, one-way valves, filters, humidifier, pressure and flow sensors, O2 and CO2 sensors, breathing circuit tubing, safety alarms, and a control unit.

- Mechanical ventilation, if not carefully controlled, can be harmful and cause damage to lung tissue via barotrauma (too much pressure), volutrauma (too much volume), and atelectotrauma (collapse of small airways due to too little volume or pressure).

- Key ventilator settings are set by the health care provider (respiratory therapist, physician): FiO2, PEEP, tidal volume, respiratory rate, I:E ratio, and ventilator mode.

- Patients with SARS-CoV-2 associated ARDS require personally tailored tidal volumes, pressures, and FiO2 for safe ventilation.

ABBREVIATIONS

ARDS  Acute respiratory distress syndrome
CO2   Carbon dioxide
EtCO2  End tidal CO2
FiO2  Fraction of inspired oxygen
MV    Minute ventilation or minute volume
O2    Oxygen
PEEP  Positive end expiratory pressure
PIP   Peak inspiratory pressure
PPV   Positive pressure ventilation
SIMV  Synchronized intermittent mandatory volume
RR    Respiratory rate
Vt    Tidal volume, single breath volume
WHAT IS VENTILATION?

Ventilation refers to the movement of air in and out of the lungs, and functions to supply the body with oxygen and remove carbon dioxide, the waste product of metabolism.

What is a mechanical ventilator?

- A machine that supports breathing for people who are unable to sustain gas exchange to their organs. The extra support gives the lungs time to rest and heal.
- Breaths are delivered through an endotracheal tube or tracheostomy, a tube placed directly into a patient's windpipe (trachea). This tube is sealed with a balloon below the vocal cords. It isolates the airway so that a ventilator can deliver air into the lungs while avoiding inflating the stomach.

Why do COVID-19 patients need ventilators?

- COVID-19 can cause severe pneumonia and Acute Respiratory Distress Syndrome (ARDS). In ARDS, the lung tissue becomes inflamed and is less compliant. These changes make it difficult for patients to take in enough oxygen to maintain vital organ function.
- The lungs interface with the blood at the level of the alveoli, a delicate structure made of single cell walls so that gases can pass across them easily (Figure 1). When the alveoli are damaged and inflamed (Figure 2), they are no longer able to exchange oxygen and CO2 with the blood. Special ventilation parameters are required to ventilate these stiff, non-compliant lungs (see Table 1).

![Figure 1. The respiratory cycle and gas exchange - Gas exchange occurs at the level of the alveoli (small air sacs at the terminal ends of the airway).](image-url)
How do ventilators help people breathe?

- During the polio epidemic, severe shortages of iron lungs (using negative pressure ventilation) led to the innovation of “positive pressure ventilation” (PPV). In order to use positive pressure ventilation, patients must have a tightly fitted mask or a breathing tube in place. Pressure is used to drive air into the lungs, and exhalation occurs passively through the natural recoil of the lungs.

- Modern ventilators are automated and allow us to adjust ventilation parameters to patients’ individual needs. Individualizing pressure, tidal volume, respiratory rate, and oxygen concentration for each patient is vital to treating those with ARDS due to COVID-19.

VENTILATOR SETTINGS

There are several ventilator parameters that can be set by the provider caring for the patient. They include the following:

- Fraction of Inspired Oxygen (FiO2) -- fraction of oxygen being delivered to the patient. FiO2 of atmospheric air is 21%; ventilators can provide up to 100% FiO2. As COVID-19 patients are weaned from the vent, having precise control over the FiO2 is important for ensuring adequate oxygenation. Too high of oxygen levels can be detrimental to the human body.

- Positive End-Expiratory Pressure (PEEP) -- a constant pressure applied to the lungs throughout inhalation and exhalation. This pressure helps to keep the alveoli open so that they can participate in gas exchange with the blood. Providing PEEP in a controlled fashion is essential as the alveoli are prone to collapse in SARS-CoV-2/ARDS.
- **Tidal Volume** -- the volume of air that enters the lungs during inspiration; typically it is desired to deliver between 6-8 cc/kg (ideal body weight) volumes to a patient during a given breath. Larger tidal volumes are associated with poor outcomes in patients with ARDS.

- **Respiratory Rate/Frequency** -- the number of breaths that are delivered in a given time, usually measured in breaths per minute (BPM).

- **Inspiratory to Expiratory Time (I/E)** -- ratio of time spent in inspiration versus expiration. Inspiring a given volume in too short of time will cause higher peak airway pressures and driving pressures (see below). Expiring over too short of a time can leave residual air in the patient’s lungs. Over time residual air can build up and overinflate the lungs, which is referred to as “breath stacking.”

![Airway Pressure Tracing](image)

**Figure 3. Airway pressure tracing during inspiration and expiration.** 1 - peak airway pressure. 2 - Plateau pressure. 3 - Driving Pressure. 4 - PEEP (during both inspiration and expiration)

The settings on the ventilator control the following variables:

- **Peak Inspiratory Pressure (PIP)** -- the highest pressure measured within the breathing circuit during the peak of inspiration when the lungs are the fullest.

- **Plateau Pressure** -- the pressure measured in the breathing circuit after a patient has been given a breath that is then held. When inspiration is paused in a breath holding maneuver like this, the pressure equilibrates between the large and small airways, giving us the ability to indirectly measure the pressure in the alveoli. Elevated plateau pressures (above 30 mmHg) is associated with worse outcomes.

- **Driving pressure** -- difference between the plateau pressure and PEEP. Driving pressure needs to be carefully controlled since high driving pressures can damage the delicate lung tissue.

- **End-tidal CO2** -- “capnography” or measurement of CO2, provides a noninvasive, continuous monitoring of inhaled and exhaled CO2, commonly referred to as EtCO2. A capnograph depicts the measurement in two formats: a numeric value, measured in mmHg, and a waveform tracing of the measured value over time.

- **Minute Ventilation** -- Minute ventilation or minute volume is the amount of air the patient moves in one minute; product of the ventilatory rate and tidal volume.  \( MV = RR \times V_T \)
Typical ranges for the above items can be found in the table below (Table 1), which compares ranges for normal patients with desired ranges for patients with ARDS (COVID-19 patients).

Table 1.

<table>
<thead>
<tr>
<th></th>
<th>Non-ARDS</th>
<th>ARDS</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>FiO2 (fraction of inspired oxygen)</td>
<td>0.21-1</td>
<td>0.21-1</td>
<td>Titrating FiO2 and PEEP to PaO2 and SpO2 For ARDS, SpO2 target 88-95%. Avoid hyperoxia.</td>
</tr>
<tr>
<td>PEEP (positive end expiratory pressure)</td>
<td>0-12 cm H2O</td>
<td>5-24 cmH2O</td>
<td>Higher levels of PEEP appropriate in patients with recruitable alveoli.</td>
</tr>
<tr>
<td>Vt (tidal volume, ml/kg)</td>
<td>6-15 ml/kg</td>
<td>6-8 ml/kg</td>
<td>Based on ideal body weight</td>
</tr>
<tr>
<td>RR (respiratory rate, bpm)</td>
<td>8-15 bpm</td>
<td>20-35 bpm</td>
<td>Titrating RR to normal acid-base status</td>
</tr>
<tr>
<td>Plateau Pressure</td>
<td>&lt;25-30 cmH2O</td>
<td>&lt;25-30 cmH2O</td>
<td></td>
</tr>
<tr>
<td>I:E ratio (inspiratory: expiratory)</td>
<td>4:1 to 1:4; generally, recommend 1:2</td>
<td>1:2</td>
<td>Inverse I:E ratio (prolonged inspiratory time) has largely fallen out of favor. Adjust to avoid auto-PEEP and asynchrony</td>
</tr>
</tbody>
</table>

References:

BREATHING SYSTEM AND ITS COMPONENTS

A breathing system is defined as a gas pathway that extends from the source of the gas delivered (i.e. fresh gas from a pipeline or gas from atmosphere) to the point where gas escapes (i.e. back into atmosphere or into a scavenging system), delivering oxygen to the patient and removing carbon dioxide.

Some breathing systems have the patients rebreathing recycled gases, ICU ventilators are typically designed to prevent rebreathing of gases. Air and oxygen are connected through a high-pressure gas source (i.e. pipeline supply) or low-flow inlet.
A standard ICU ventilator includes the following:

- **Unidirectional valves**-- prevent back-flow of exhaled gases, avoiding mixing of CO2 with inspired gas.

- **Y-Piece**-- merges the inspiratory and expiratory limb.

- **Inlet gas monitor**-- monitors concentration of oxygen delivered to the patient. A low oxygen concentration alarm must be associated with the device and must activate within 30 seconds of an oxygen concentration drop below the set limit.

- **Flow sensors**-- used to measure the volume of exhaled gas; the location of the flow sensor can vary.

- **Breathing circuit pressure sensors**-- the continuous measurement of airway pressure in the patient’s breathing circuit is critical to the patient’s safety and protection of lung tissue; high peak airway pressures can result in barotrauma to the lungs. The location of a pressure sample site can be variable.

- **Heat moisture exchangers**-- heat and moisture exchangers replace the normal warming and humidifying function of the upper airway. It is important to prevent dehydration of the respiratory tract to avoid damaging the airway and lung tissue.

- **Filter**-- prevents contamination of the ventilator, which is crucial considering SARS-CoV-2 contagiousness. The disposable filter goes in series with the tubing on the inspiratory and expiratory limbs of the breathing circuit. Viral filters should be 0.22µm or smaller.

- **Alarms**-- circuit disconnect and abnormal O2/CO2 alarms should be present to alert the provider if there is a circuit failure.

- **PEEP valve**-- PEEP can be applied to the system by the ventilator or by a PEEP valve, which is simply a spring-loaded valve that can be adjusted to apply pressure to the circuit.
MODES OF VENTILATION

Ventilators have multiple modes that control how breaths are delivered to the patient. The best mode depends on each individual patient’s specific needs for breathing support.

**Continuous Mandatory Ventilation/Assist Control (CMV/AC) (Figure 5)**

- Breaths are delivered and controlled by the ventilator. Breaths can be triggered by the patient, either by changes in pressure (as shown in the figure) or changes in flow. In the absence of patient triggering, a mandatory breath will be triggered based on elapsed time (determined by the set respiratory rate).
- In response to a trigger, the ventilator will deliver a set volume or pressure based on the primary mode setting (volume or pressure target, as explained below) over a time based on the respiratory rate and I:E. See “volume control” and “pressure control” below.

**Volume Control (VC-CMV) (Figure 6)**

- Provider sets: breath volume (Vt), respiratory rate
- Ventilator delivers a fixed, predetermined tidal volume regardless of the pressure required (up to a maximum pressure setting).
- Flow is determined by the machine using the inspiratory time and tidal volume.
- If the patient initiates a breath before the set time, then the set volume will be delivered.
Pressure Control (PC-CMV) (Figure 7)

- Provider sets: inspiratory pressure, respiratory rate
- Ventilator delivers a breath with a fixed, specified pressure over a period determined by respiratory rate and I:E ratio.
- If the patient initiates a breath before the set time, then the set pressure is delivered over the set inspiratory time.

Pressure Support (PS) (Figure 8)

- Patients initiate their own breaths, and the machine delivers a pre-set inspiratory pressure to help overcome airway resistance.
- The patient controls the rate, and the tidal volume is variable depending on patient effort, lung compliance, and set pressure.
- This differs from CMV/AC in that there are no scheduled or “mandatory” ventilator-delivered breaths, so if a patient stops breathing, no breaths will be delivered.
Figure 9 Synchronized intermittent mandatory ventilation (SIMV) (Figure 9)

- With this mode, regular series of breaths are scheduled based on set volume and respiratory rate. It will deliver these breaths whether the patient has spontaneous breaths or not.
- If a patient takes a spontaneous breath prior to scheduled breath, then the patient will determine the volume of the breath, it is not supported by the ventilator.
- The ventilator will wait for the patient to exhale their spontaneous breath before delivering another scheduled breath, thus being “synchronized.”

SUMMARY

COVID-19 patients require ventilators with:

1. Adequate fresh gas delivery for the exchange of oxygen and removal of CO₂ in predictable tidal volumes at safe pressures for the lungs, with appropriate safety alarms to designate failure in any of these components.

2. Features to humidify and filter the circuit.

3. Ability to support both CMV and SIMV modes.

4. Titratable amounts of PEEP - an important parameter for intensivists to control while caring for ICU patients.

References:

Disclaimer: This document was compiled and written by medical trainees without full medical licenses to provide CoVent-19 Challenge participants with a general understanding of ventilators and respiratory physiology. The CoVent-19 Challenge team does not take any liability for any misinformation that may be included in this document.