Basics of Mechanical Ventilation

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KEY POINTS

- A ventilator delivers a set volume of gas to a patient based on volume, pressure, or flow.
- Mechanical ventilators can be classified according to their input power, pressurised gas source, and drive mechanism.
- Gas flows into the lungs down a pressure gradient between the airway and the alveoli. This pressure gradient is known as the transairway pressure.
- Phases of a ventilatory breath are determined by trigger, limit, and cycling.

INTRODUCTION

A ventilator delivers a set volume of gas to a patient based on volume, pressure, or flow as set by the operator. It does this by generating a flow of gas into the breathing circuit and this flow is determined by settings as discussed below.

Physics of Mechanical Ventilators

A mechanical ventilator either fully or partially supports a patient's work of breathing.

The basic build of a mechanical ventilator can be described according to (1) input power, (2) source of pressurised gas, (3) drive mechanism, or (4) control circuit.

(1) Input power
  (a) Pneumatic: Compressed medical gases are used as the energy source.
  (b) Electrical: AC or DC current is used to drive the pistons and compressors that generate pressure.
  (c) Combined: Most intensive care unit ventilators are combined with pneumatic power used to deliver the breath whilst an electronically controlled microprocessor controls the valves that regulate the characteristics of the breath.
(2) Source of pressurised gas: Clearly, both oxygen and air are required. These may be provided via a hospital's central manifold supply with a blender mixing them to achieve the desired oxygen concentration (FiO_2). Alternatively, some machines may use an oxygen cylinder alongside an air compressor, whilst others will have an inbuilt turbine as a source of compressed air.
(3) Drive mechanism: This is the system used by the ventilator to convert input power into ventilatory work; there are 3 types: pistons, bellows, and pneumatic circuits. The most commonly used is the pneumatic drive mechanism. Pneumatic drive mechanisms use microprocessor controls and a proportional solenoid valve that converts electrical energy to mechanical energy. The microprocessor controls the solenoid (electromechanically operated valve) to open and close valves according

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to the desired flow or pressure pattern. Solenoid valves are control units which, when electrically energized or de-energized, either shut off or allow fluid or gas flow. The actuator takes the form of an electromagnet. When energized, a magnetic field builds up which pulls a plunger against the action of a spring. When de-energized, the plunger is returned to its original position by the spring action.

(4) Control circuit: The system that controls the ventilator drive mechanism and the inspiratory and expiratory valves is the control circuit. A control circuit can be classified as open or closed loop.
    (a) Open-loop control circuits achieve the set desired output without responding to changing conditions such as a circuit leak. Open control circuits are not controlled by a microprocessor.
    (b) Closed-loop control circuits adjust the input to match the desired set output as a result of the ventilator measuring flow, pressure, or volume, allowing compensation for changing conditions.

Control circuits can also be classified based on their underlying mechanism (mechanical, pneumatic, electronic, or fluidic).

(a) Mechanical control circuits are open-loop systems used in older mechanical ventilators that use levers and pulleys to control the drive mechanism.
(b) Pneumatic control circuits use valves, nozzles, ejectors, and diaphragms to control the drive mechanism.
(c) Electronic control circuits use resistors, diodes, circuits, and microprocessors to control the drive mechanism of the ventilators.
(d) Fluidic control circuits work similarly to electronic control circuits but control the direction of gas flow and perform logic functions based on fluidics (or fluidic logic) instead. Fluidics uses fluid dynamics to perform the functions otherwise controlled by electronics (for example, the Coanda effect).

Humidification and Warming

The gas at source is dry and may be cold. In addition, the endotracheal tube bypasses the natural humidification mechanisms of the nose and pharynx. Breathing dry cold gas will lead to mucociliary dysfunction and retention of secretions so artificial humidification of inspired gas is necessary (Figure 1).

Humidification can be achieved passively using standard heat and moisture exchange filters (Figure 2). This method is less efficient and suitable only for short-term ventilation as the filter needs to be changed regularly to mitigate the risk of it getting blocked with secretions. This incidentally increases the risk of aerosolisation and infection spread.

Active water-bath humidification, which passes the inspiratory gas over a heated water bath, is a more efficient method of humidification (Figure 3). Other methods of active humidification (eg ultrasonic nebulisers) exist but are less commonly used.

Airway Resistance

Airway resistance is the obstruction to airflow in the airways, normally 0.5 to 2.5 cm $H_2O/L/s$[1] in health. It is affected by 2 main factors: the velocity of gas flow and the airway radius.

(1) Velocity of gas flow: Flow can be turbulent or laminar. Transition from laminar to turbulent flow occurs when the Reynold number is greater than 2000. The Reynold number is a dimensionless number that increases with gas flow

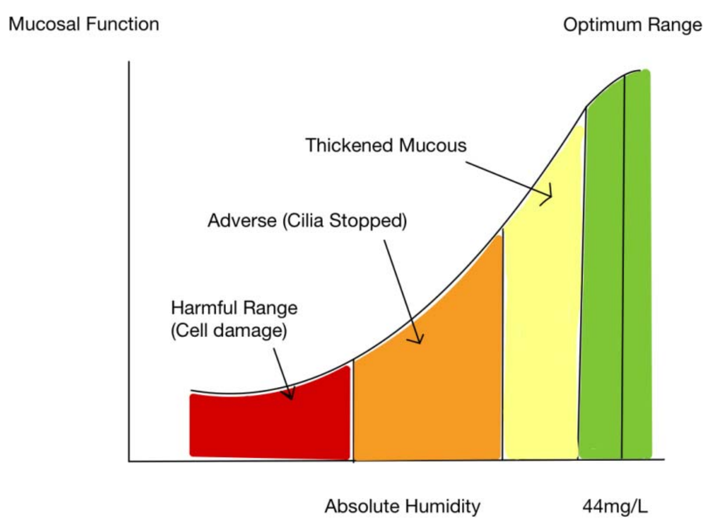


Figure 1. The effects of humidity and mucosal function.

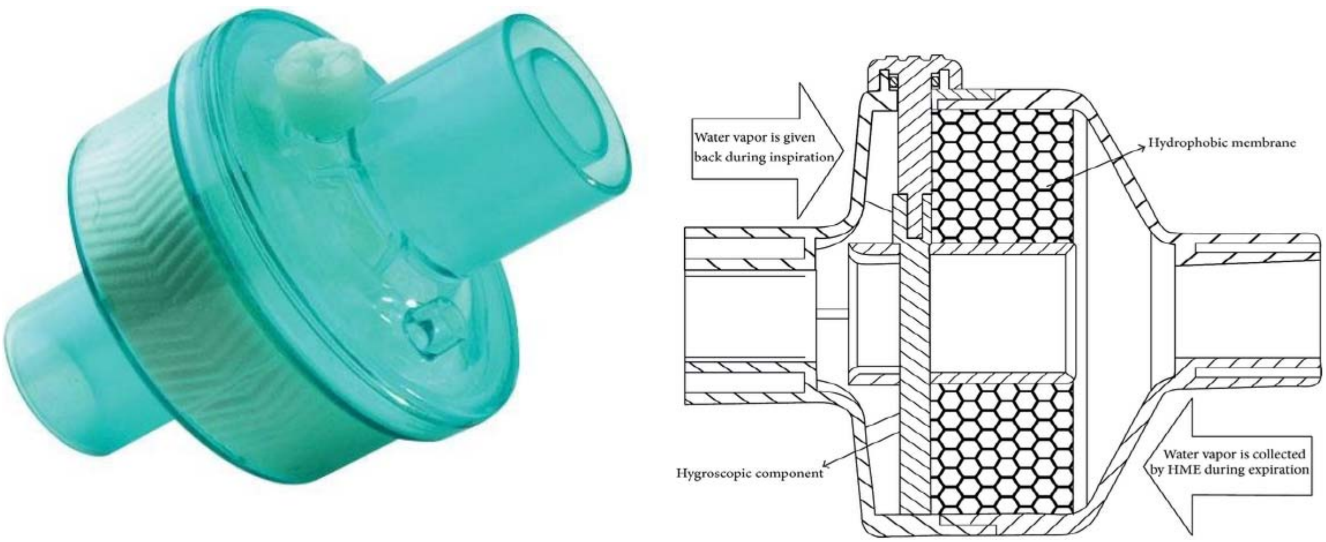


Figure 2. Heat and moisture exchange filter: construction and functioning.[1]

velocity (amongst other variables). Turbulent gas flow results in much higher airway resistance than laminar gas flows.

(2) Airway radius: Airway resistance is inversely proportional to r^4 (r = airway radius), as per the Hagen-Poiseuille equation. Thus, a small reduction in airway radius can lead to a large increase in the airway resistance. Hagen-Poiseuille equation:

$$\text{Airway resistance } (R) = 8nl/\pi \Delta P r^4,$$

where n = viscosity of the liquid (gas), l = length of the tube, ΔP = change in driving pressure, r = radius of the airway.

It can be seen from the equation that airway resistance also varies directly with the length of the airway or endotracheal tube and the viscosity of the gas. Airway resistance can also be calculated in the following way:

$$\text{Change in pressure/change in volume or Peak pressure} - \text{plateau pressure/flow.}$$

Changes in airway resistance can be visually observed on a ventilator system using the pressure–volume (P-V) loop display.[2] An increase in the bowing (suggestive of increased inspiratory or expiratory flow resistance [or both] depending upon the direction of the bowing) of the pressure-volume loop suggests an overall increase in airflow resistance (Figure 4).

Compliance

Lung compliance is the measure of distensibility of the lungs—it is the change in volume per unit change in transpulmonary pressure (Figure 5), and is calculated in the following way:

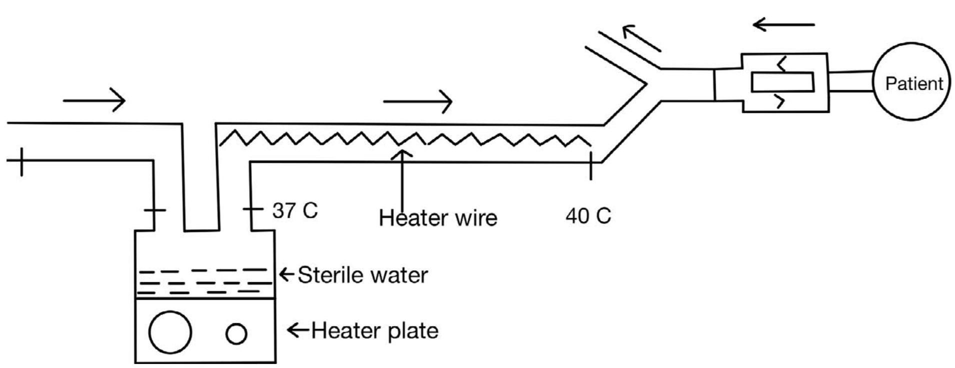


Figure 3. Scheme of a heated humidifier.

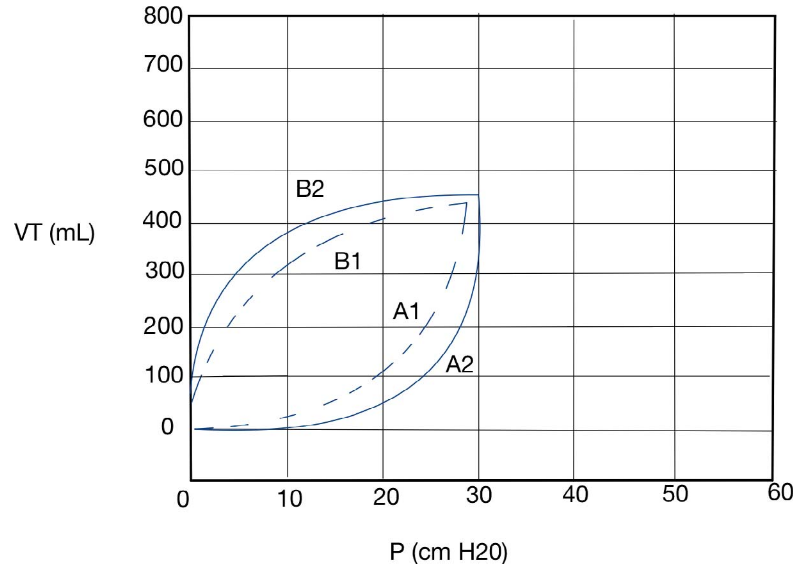


Figure 4. Increased bowing (from dotted to solid line) of the pressure-volume loop suggests an increase in airflow resistance. Bowing of inspiratory limb (from A1 to A2) may be caused by excessive inspiratory flow. Bowing of the expiratory limb (from B1 to B2) may be caused by an increase in expiratory flow resistance such as bronchospasm.

$$C = \Delta V / \Delta P,$$

where C is compliance, ΔV is change in volume, and ΔP is the change in transpulmonary pressure).

Low compliance means the lungs are stiff or noncompliant, making lung expansion difficult and increasing the work of breathing (eg acute respiratory distress syndrome).

High compliance means that there is incomplete exhalation, air trapping, and reduced CO_2 elimination due to a lack of elastic recoil in the lung (eg emphysema).

For a typical lung at functional residual capacity, compliance is 200 mL/cm H_2O.

The total compliance of the respiratory system includes both lung compliance and thoracic cage compliance:

$$1/\mathrm{RC} = 1/\mathrm{LC} + 1/\mathrm{TCC},$$

where RC is respiratory compliance; LC, lung compliance; and TCC, thoracic cage compliance.

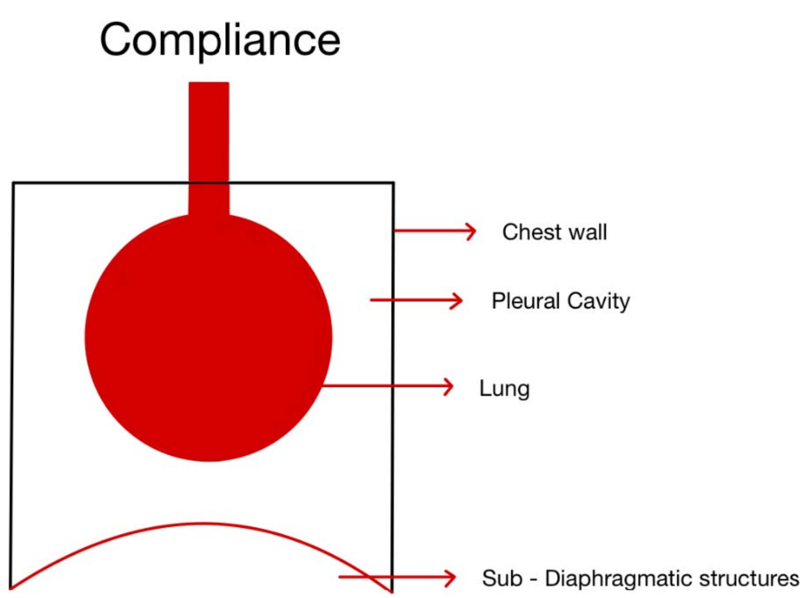


Figure 5. Factors determining compliance of the respiratory system.

Typical values for lung and thoracic cage compliance are 200 mL/cm H_2O; therefore, a typical value for respiratory compliance would be 100 mL/cm H_2O.

Compliance can be divided into static and dynamic compliance.

Static compliance

This is measured when there is no gas flow in the lungs. It relates to the elastic resistance of the lung and the chest wall. It can be represented graphically by the pressure-volume graph, which shows that the pressure-volume relationship between lung volume and intrathoracic pressure is not linear (Figure 6). Conditions causing decrease in static compliance are as follows:

- Acute respiratory distress syndrome

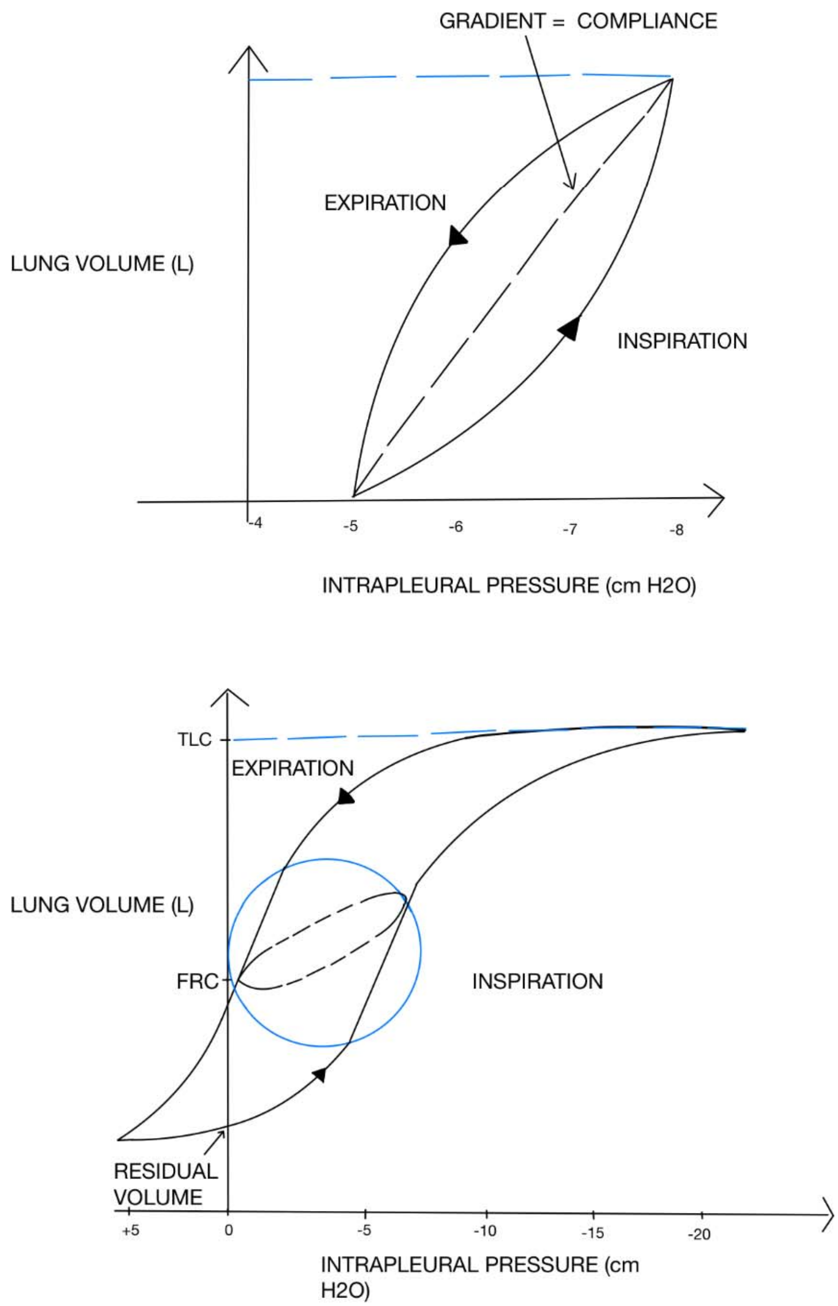


Figure 6. At both ends of the tracing, the pressure volume curve is flat, so the lung compliance is low. In the range of –5 to –10 cm H_2O, the pressure volume curve is the steepest and a small change in transpulmonary pressure will lead to a larger change in lung volume. Thus, the lung compliance is maximum at functional residual capacity.

- Atelectasis
- Abdominal distension
- Consolidation
- Obesity
- Pleural effusion
- Pneumothorax
- Retained secretions

Conditions causing increase in static compliance are as follows:

- Emphysema
- Flail chest
- Sternotomy

Dynamic Compliance

Dynamic compliance is measured when airflow is present. It includes both airway resistance and the elastic resistance of the lung and the chest wall. By including airway resistance, it is therefore always lower than static compliance.

Figure 6 also shows the different courses of the inspiratory and the expiratory curves followed during a normal breath. These different courses give rise to a loop, the area within which represents the amount of energy used in overcoming the resistive forces in the airway. The straight line joining them represents the dynamic compliance and the loop effect is called hysteresis.

Conditions causing decrease in dynamic compliance are as follows:

- Bronchospasm
- Kinking of endotracheal tube
- Airway obstruction

The method to measure static and dynamic compliance (Figure 7) is as follows:

- Obtain correct tidal volume.
- Obtain plateau pressure, by applying inspiratory hold.
- Obtain peak inspiratory pressure.

Static compliance is calculated as tidal volume/(plateau pressure − positive end-expiratory pressure [PEEP]). Dynamic compliance is calculated as tidal volume/(peak inspiratory pressure − PEEP).

Mechanics of Ventilation

Gas flows into the lungs down the transairway pressure gradient:

Transairway pressure = airway pressure − alveolar pressure.

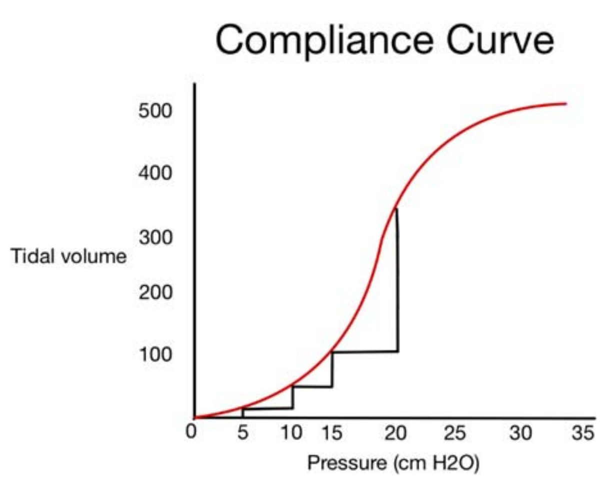
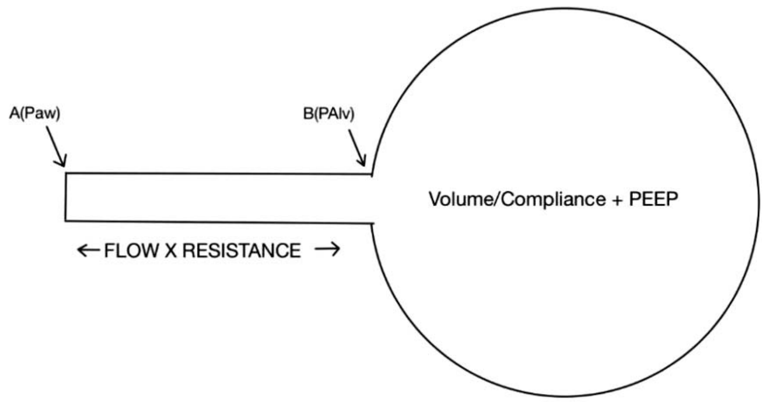


Figure 7. In the above graph, the compliance is measured for every 5-cm H_2O increase in the airway pressure. From a zero end-expiratory pressure, the airway pressure is increased in 5-cm H_2O increments and the corresponding change in volume is plotted. As you can see, the change in volume increases with every 5-cm H_2O pressure as we move to the right side of the graph, implying better compliance and reduced work of breathing.



$$P_{aw} = Flow \times Resistance + \frac{Volume}{Compliance} + PEEP$$

Figure 8. Lung-ventilator diagram.

This gradient can be generated via positive- or negative-pressure ventilation.

Negative-pressure ventilation (eg iron lungs) creates this pressure by applying a negative pressure to the chest wall which subsequently decreases alveolar pressure.

Positive pressure ventilation creates the pressure gradient by applying a positive pressure at the airways.

The lung-ventilator unit, shown in Figure 8, can be thought of as a tube (representing the ventilator tubing, the endotracheal tube, and the airways) with a balloon at one end (representing the alveoli).

Pressure at point B is equivalent to the alveolar pressure and can be determined by the volume required to inflate the alveoli divided by the compliance of the alveoli plus the baseline PEEP. Pressure at point A is equivalent to the airway pressure measured by the ventilator and is a product of flow and resistance added to the pressure at point B.

If considering this as an ideal pair of lungs, then flow, volume, and pressure are variables whilst resistance and compliance are constants. The figure shows the relationships between pressure, flow, and volume and by setting one, the other 2 become constants. It also shows that it is not possible to preset more than one variable at a time.

Thus, in volume and flow preset modes, the pressure becomes a dependent variable, and it is important to monitor pressure and minimise the risk of barotrauma. However, it is the alveolar (plateau) pressure and not the airway (peak inspiratory) pressure that is important. Alveolar pressure can be determined by measuring the airway pressure after an end-inspiratory

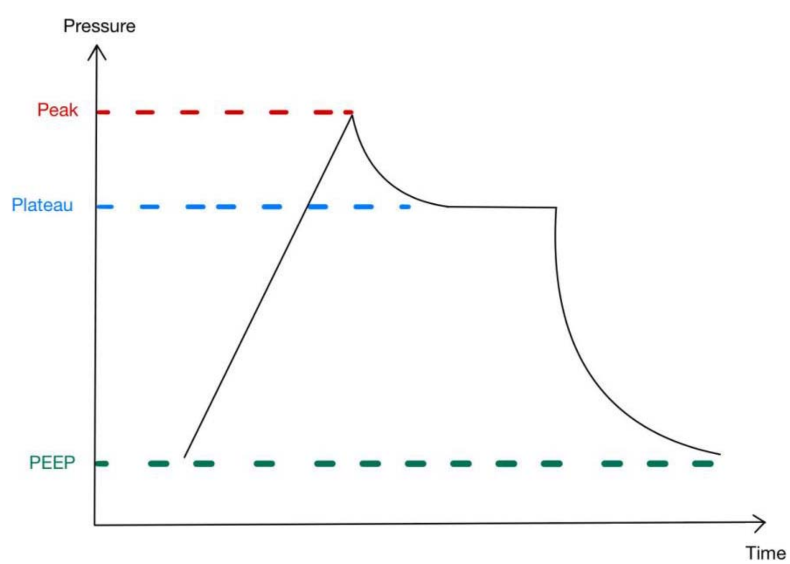


Figure 9. Peak airway pressure and plateau pressure.

pause (there is no air flow and therefore no resistance, thus $P_A = P_B$) as gas will have distributed throughout the lung units thereby achieving an equilibrium (Figure 8). However, the alveolar pressure can be higher than the measured pressure, for example, in bronchospasm if there is gas trapping.

The pressure at end of each lung inflation is the peak airway pressure; this is needed to overcome resistive and elastic forces in the lungs and chest wall. The pressure in the alveoli at the end of inspiration is the plateau pressure (Figure 9).

Determinants of Ventilation

The underlying principles behind the different modes of ventilation are relatively simple and are governed by 3 parameters (Figure 10):

(1) What initiates inspiration? The trigger.
(2) What target or limit is achieved during inspiration? The limit.
(3) What ends inspiration? Cycling.

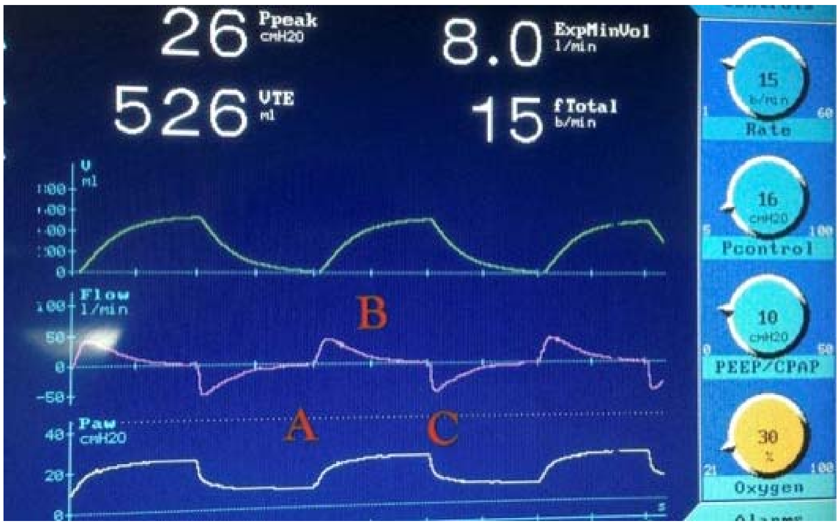


Figure 10. Phases of a ventilatory breath are determined by trigger, limit, and cycling. A represents the trigger; B, the limit; and C, the end of inspiration or otherwise beginning of expiration.

Triggers

A *trigger* is the event that initiates each mechanical breath. The following can be triggers:

(1) Time: A ventilator initiates a breath according to a set respiratory rate, independent of patient effort. So for a respiratory rate of 15/min, each respiratory cycle lasts 4 seconds so the ventilator initiates a breath on every fifth second (Figure 11).
(2) Pressure: A spontaneous breath effort drops the airway pressure below the set PEEP and when the drop reaches the set trigger pressure, a breath is initiated (Figure 12).
(3) Flow: A spontaneous breath effort can also cause an inspiratory flow of gas that is detected by the ventilator and this initiates inspiration.
(4) Neural assist: Neurally adjusted ventilatory assist is a mode where the ventilator is able to sense electrical diaphragmatic activity and it therefore initiates an assisted breath (Figure 13).

A ventilator can be also be falsely triggered by many factors. Common scenarios might be fluctuations in pressure and flow causes by water accumulating in the expiratory limb of the breathing circuit or a high cardiac output similarly leading to fluctuations that trigger the ventilator (Figures 14–17).

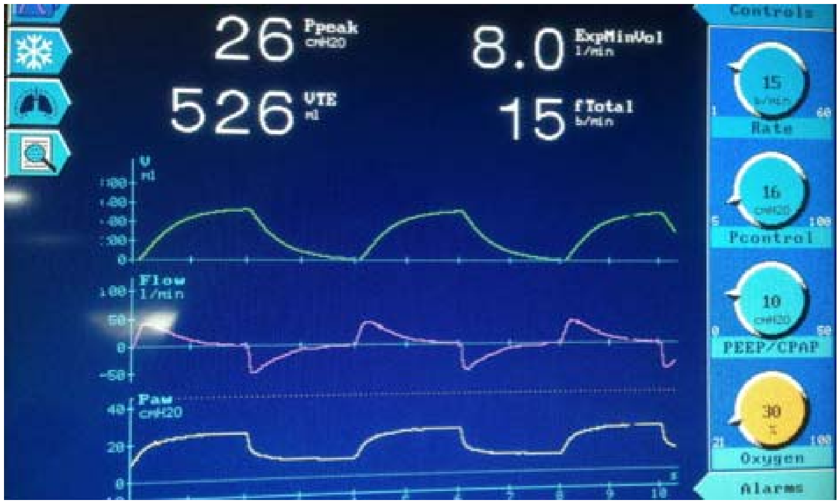


Figure 11. Respiratory rate for ventilator-initiated breath.

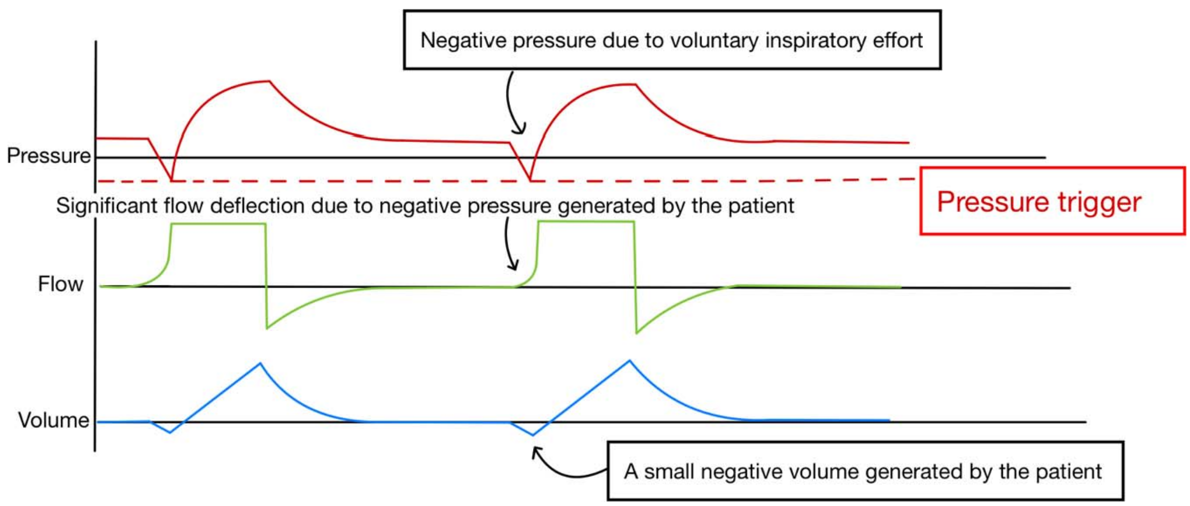


Figure 12. Pressure trigger set to initiate breath.

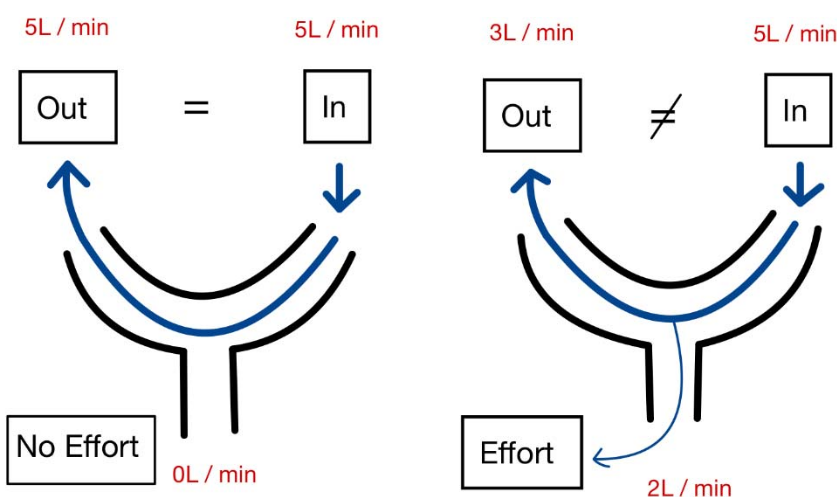


Figure 13. In flow triggering, a change in the flow of gas during an inspiratory effort is sensed by the ventilator. This initiates inspiration. There is a constant flow of 5 L/min at the end of expiration which is measured as the gas emerges in the expiratory limb. In the figure above, when the patient does not take a breath, there is no change in the flow and therefore a breath is not initiated. In contrast, when the patient takes a spontaneous breath, some of the gas in the circuit is diverted into the patient. This reduces the flow of gas emerging in the expiratory limb and this will trigger the ventilator.

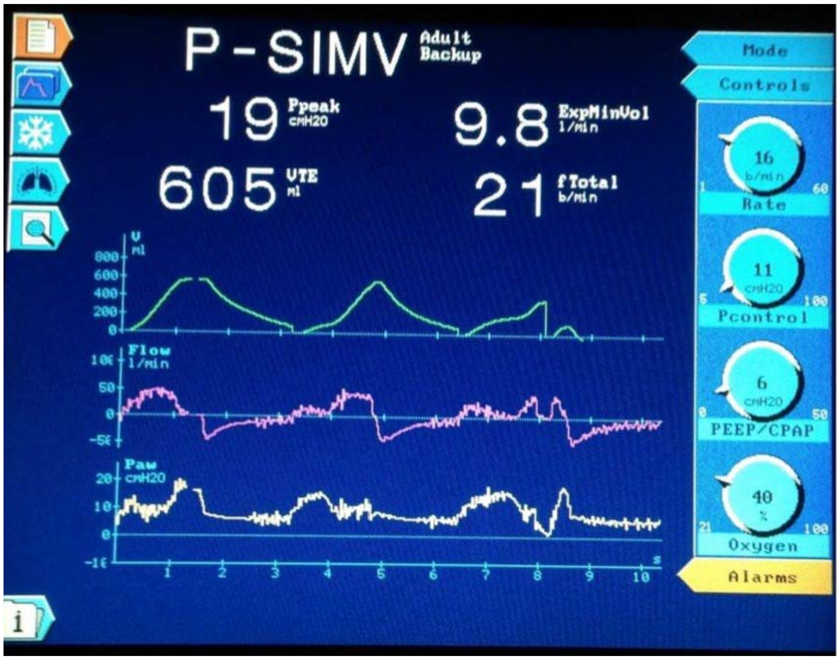


Figure 14. Ventilator display showing fluctuations in pressure and flow.

Figure 15. Water accumulation in the expiratory limb of the breathing circuit.

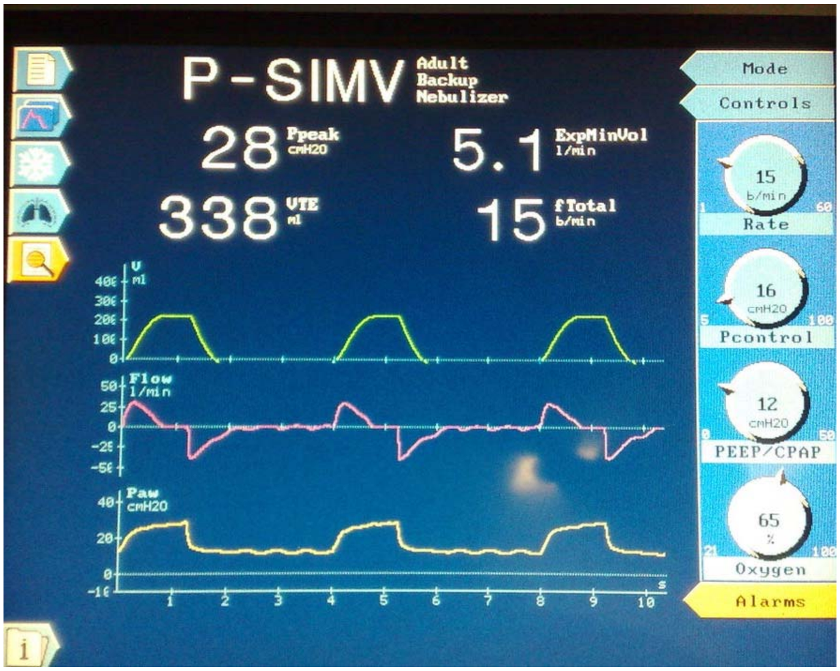


Figure 16. Ventilator display showing fluctuations.

Figure 17. Display on patient monitor.

Limits

A *limit* is the mechanism that determines how the breath is delivered to the patient rather than the factor that brings inspiration to an end. It can be one of the following:

(1) Flow limited: A fixed flow is delivered over a set time interval so that a known tidal volume will be delivered to the patient.
(2) Pressure limited: A fixed pressure is set with a fixed time interval and the volume delivered varies with patient characteristics such as lung compliance.

Cycling

Cycling is the factor that governs the changeover from inspiration to expiration. Inspiration ends on attaining a preset parameter. This preset parameter can be one of the following:

(1) Volume: Cycling occurs once the preset volume is delivered.
(2) Time: Cycling occurs after preset time is achieved. This can be set directly (inspiratory time) or indirectly (inspiration:expiration [I:E] ratio).

Figure 18 shows time cycling where respiratory rate is set as 15 with inspiratory time as 2 seconds. In this case the I:E ratio is set indirectly and is 1:1.

a

b

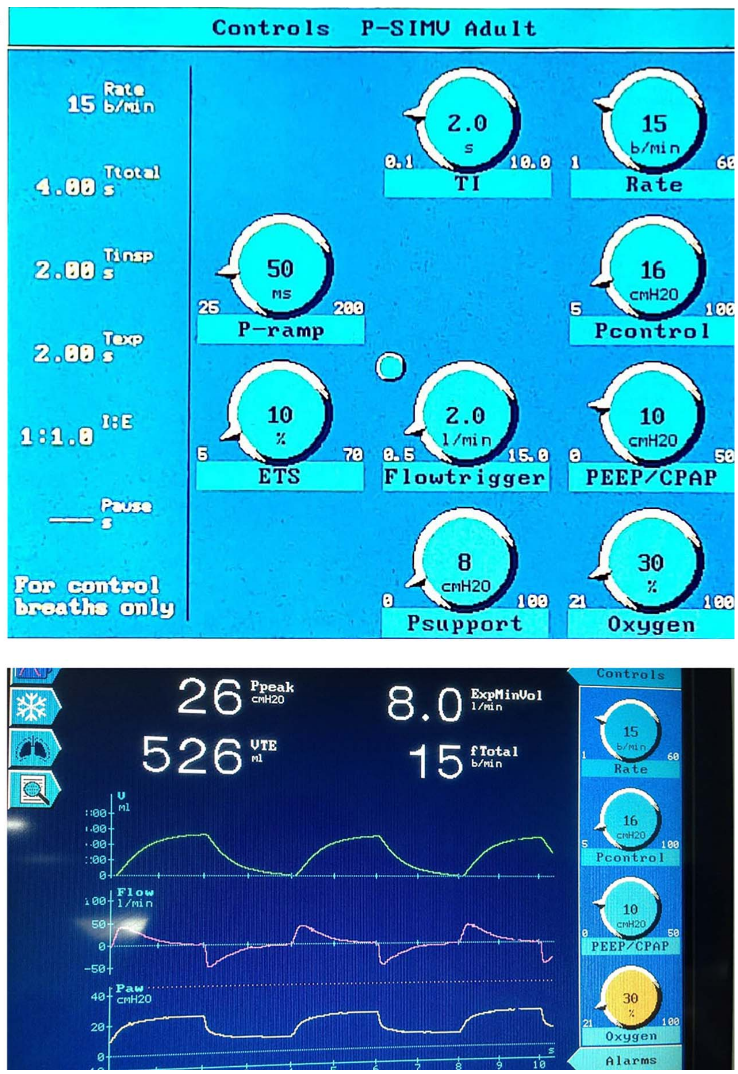


Figure 18. (a) Time cycling where respiratory rate is set as 15 with inspiratory time as 2 seconds. In this case inspiration:expiration (I:E) ratio is set indirectly and is 1:1. (b) Time cycling where respiratory rate is set as 15 with an inspiratory time of 2 seconds. In this case I:E ratio is set indirectly and is 1:1.

(3) Flow: During a pressure-supported breath, inspiratory flow increases and then declines after reaching a peak inspiratory flow rate. Once this flow declines to a preset expiratory flow rate, usually described as a percentage of the peak inspiratory flow rate, cycling occurs to expiration. In the 2 examples shown, (Figure 19), the peak inspiratory flow rateis 80 L/min. Expiratory trigger sensitivity (ETS) of 50%, 25%, and 10% results in cycling at 40, 20, and 8 L/min flow, respectively. The inspiratory time and tidal volume are inversely proportional to the ETS. If there were to be a leak in the system, cycling would not occur as the decelerating flow could be prevented from reaching the ETS setting, resulting in prolonged inspiration. To prevent this, a maximum inspiratory time can be set, which is particularly valuable in a noninvasive ventilation mode, where leakage is almost certain.
(4) Pressure: Cycling occurs after a preset pressure is reached (Figure 20). This reduces the risk of barotrauma. If the airway pressure exceeds the set maximum, the ventilator will cycle to expiration, regardless of the tidal volume being delivered. Thus, high airway pressures may lead to premature termination of inspiration, causing a degree of hypoventilation.

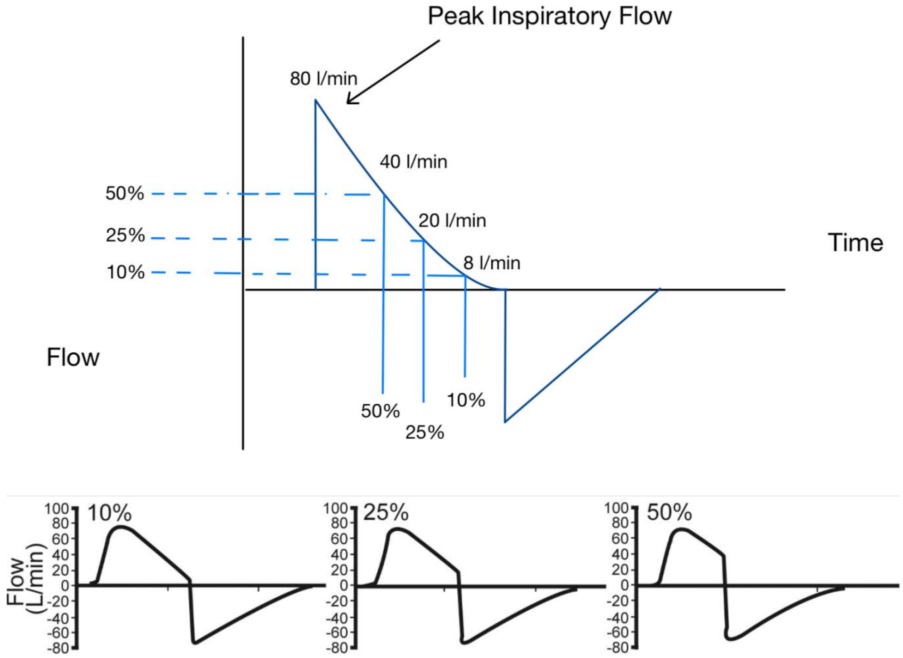


Figure 19. Flow cycling at 10%, 20%, and 50% expiration trigger sensitivity (ETS).

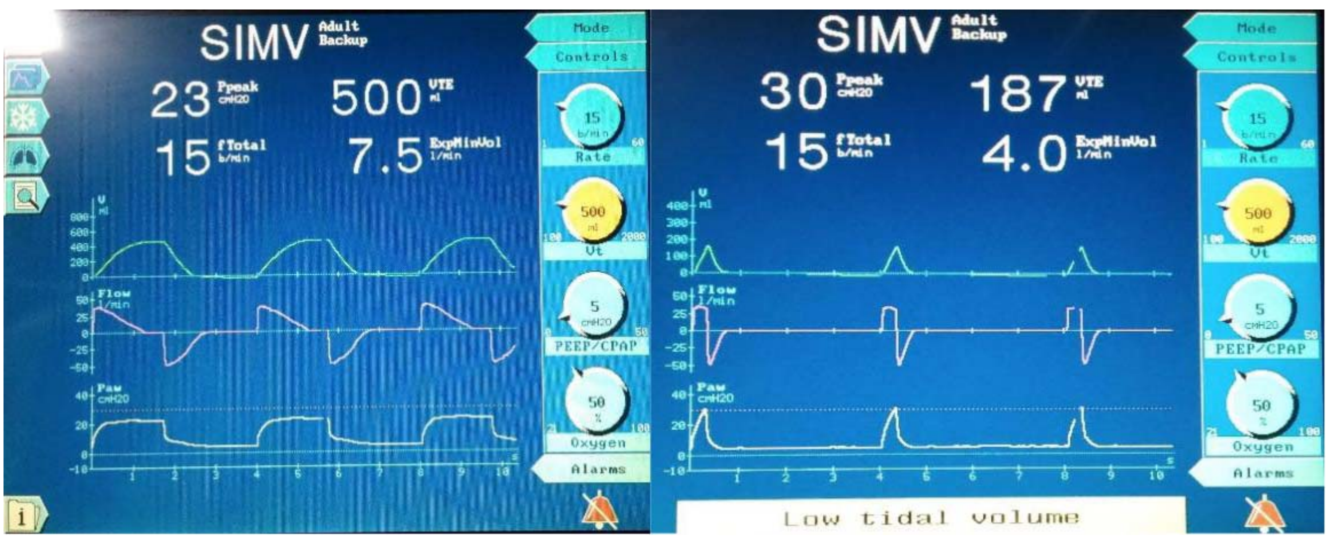


Figure 20. Pressure cycling with peak pressures set at 30 cm H_2O.

Ventilator Breath Types

Ventilator-delivered breaths can be controlled or assisted.

(1) Controlled breath: initiated by the ventilator
   (a) Preset volume
   (b) Preset pressure
(2) Assisted breath: initiated by the patient and assisted by the ventilator

Preset volume breaths can deliver a constant flow pattern with a resultant airway pressure that will depend on the resistance and compliance of the patient's respiratory system. The breaths can either be controlled or assist controlled, depending upon patient's respiratory effort.

Preset pressure breaths use a high initial inspiratory flow rate that decreases over the course of inspiration. The resultant tidal volume will depend upon inspiratory time plus the resistance and compliance of the patient's respiratory system.

Modes of Ventilation

Below, we describe the 3 most common conventional modes of ventilation:

(1) Continuous mandatory ventilation
(2) Synchronous intermittent mandatory ventilation (SIMV)
(3) Pressure-support ventilation

Continuous Mandatory Ventilation

In continuous mandatory ventilation, the ventilation will be controlled if there are no spontaneous breaths but can be assisted if there are spontaneous breaths. The breath type is always a mandatory breath (preset volume or pressure).

Volume Control

Here, the trigger is time, which depends on the set frequency. When the patient is making spontaneous efforts, the trigger is either flow or pressure. The user sets the tidal volume, respiratory rate, I:E ratio, and PEEP.

Volume-control ventilation maintains a constant minute ventilation but there is no compensation for leaks and airway pressures may vary with changing lung compliance/resistance which can contribute to barotrauma[3].

Pressure Control

Again, the trigger is time. In this mode, the inflation pressure is set by the operator and the ventilator delivers an inspiratory flow in order to reach this set pressure. The resultant tidal volume depends upon the compliance and resistance of the respiratory system. The user sets the inspiratory airway pressure, respiratory rate, I:E ratio, and PEEP.

There is greater control over peak airway pressures as well as some degree of compensation for leaks. There may also be a more homogenous distribution of ventilation through the lungs, as all areas are subject to the same pressure. However, variation in lung compliance can cause an unintended variation in minute ventilation.

Pressure-Regulated Volume Control

Pressure-regulated volume control is a hybrid of the above 2 modes of ventilation that can help deliver a guaranteed tidal volume with a pressure-control waveform. This is done by combination of alteration in inspiratory time and peak flow in response to the breath-by-breath changes in airway or compliance characteristics.

It combines the advantages of the above 2 modes of breath delivery.

Synchronous Intermittent Mandatory Ventilation

SIMV allows spontaneous breathing between ventilator breaths.[4] The ventilator is set to deliver a certain set number of breaths. If the patient is apnoeic, the ventilator will deliver these breaths as mandatory breaths. The mandatory ventilator breaths during SIMV can be volume controlled or pressure controlled as with the above descriptions for continuous mandatory ventilation whilst the spontaneous breaths will be synchronised[5] to mandatory breath if it falls on the SIMV period or pressure-supported when it falls in the spontaneous period triggered by pressure or flow.

This mode can allow for some spontaneous respiratory effort and aid weaning[6] from a ventilator (Figure 21).

Pressure-Support Ventilation

Pressure-support ventilation is a spontaneous mode of ventilation. The operator sets the inspiratory pressure which supports the patient's effort. A backup ventilation setting is used in case of apnoea. The ventilator delivers a high initial flow rate (peak inspiratory flow) until the set airway pressure is reached. Cycling from inspiration to expiration occurs when the inspiratory flow rate during the deceleration phase of inspiratory flow falls to the set expiration trigger sensitivity (ETS), which is set as a percentage of peak inspiratory flow.

The tidal volume will be directly proportional to set pressure-support level and inversely proportional to the ETS.

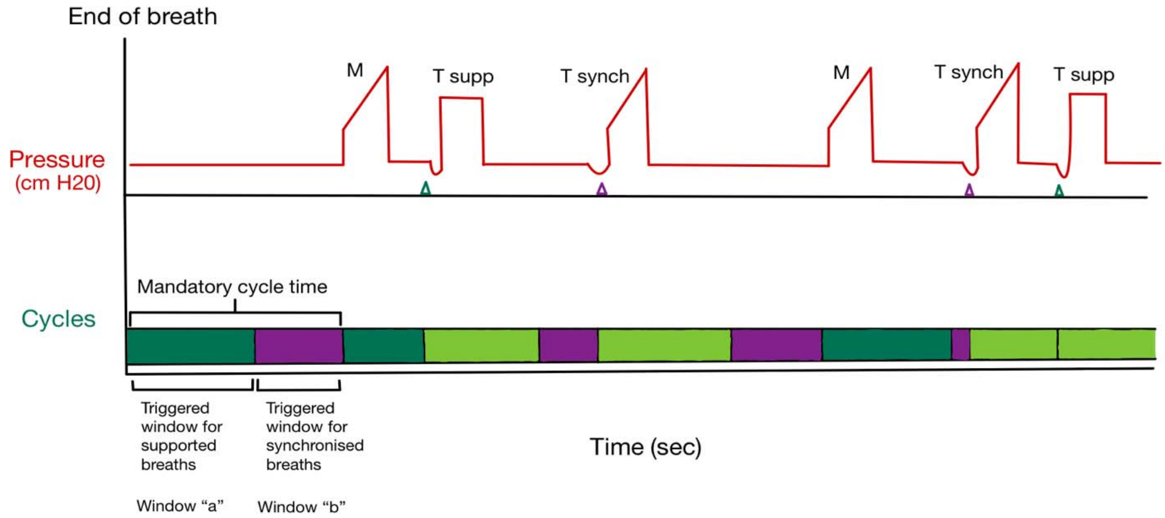


Figure 21. Pressure-time scalar in synchronous intermittent mandatory ventilation, volume-controlled mode. Spontaneous breaths will be synchronised during the expiratory phase, also called the mandatory cycle time. Mandatory cycle time is divided into 2 windows: window "a" for synchronised supported breaths, which is closer to the just concluded breath; window "b" for synchronised mandatory breath, which is closer to the oncoming breath. As you can see, a breath triggered in window "a" will be synchronised into a pressure-supported breath and that triggered in window "b" will be synchronised into a mandatory breath. The total breath will depend on timing of triggering. For example, if the set rate is 12 and there are 8 spontaneous breaths, the rate could be between 12 to 20 breaths per minute. M = mandatory breath; T = triggered breath by a spontaneous effort.

This mode can be used to aid weaning from mechanical ventilation with good patient-ventilator synchrony but the tidal volume and minute ventilation are heavily dependent upon the patient. Cycling will not happen or is delayed in the presence of air leaks, which is more common in noninvasive ventilation with a poor mask fit.

SUMMARY

A mechanical ventilator fully or partially substitutes the ventilatory work done by the patient. All modes of mechanical ventilation help to ventilate and oxygenate patients, supporting gas exchange until the underlying abnormality resolves.
The main indications for mechanical ventilation are to support decreased ventilatory drive, increased ventilatory workload, and inadequate respiratory muscle function.
The underlying principles behind the different modes of ventilation are governed by 3 parameters: what initiates inspiration, what target or limit is achieved during inspiration, and what ends inspiration.

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