Guide to Understand Mechanical Ventilation Waveforms

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Mazen Kherallah, MD, FCCP
http://www.mecriticalcare.net
Email: info@mecriticalcare.net
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Introduction

In the past few years there has been an increase in the number of methods by which positive pressure ventilation can be delivered. The increasing number of methods available to deliver mechanical ventilation has made it difficult for clinicians to learn all that is necessary in order to provide a safe and effective level of care for patients receiving mechanical ventilation. Despite the method by which mechanical ventilation is applied the primary factors to consider when applying mechanical ventilation are:

- The components of each individual breath, specifically whether pressure, flow, volume and time are set by the operator, variable or dependent on other parameters
- The method of triggering the mechanical ventilator breath/gas flow
- How the ventilator breath is terminated
- Potential complications of mechanical ventilation and methods to reduce ventilator induced lung injury
- Methods to improve patient ventilator synchrony; and
- The nursing observations required to provide a safe and effective level of care for the patient receiving mechanical ventilation

If you are relatively inexperienced in the application of mechanical ventilators, you may find this and later sections challenging. Keep in mind as you work through this guide; that the intended aims of this package are to provide you with resource material and introduce you to topic areas that will form the basis for your understanding of mechanical ventilator waveforms.

How a Breath is delivered?

A ventilator mode is a description of how breaths are supplied to the patient. The mode describes how breaths are controlled (pressure or volume), and how the four phases (trigger, limit, cycle, and baseline) of the respiratory cycle are managed. Each of these phases has a set of variables associated with it. Some of the variables are set by the clinician, some are calculated by the ventilator’s internal programming, and others vary with the patient’s respiratory rate, pulmonary compliance and airway resistance.

Control Variables:

To deliver inspiratory volume, the operator most commonly sets either a volume or a pressure, the primary variable the ventilator adjusts to achieve inspiration is called the control variable. Mechanical ventilators can control four variables, but only one at a time (Pressure, Volume, Flow,
or Time). Because only one of these variables can be directly controlled at a time, a ventilator must function as either one of the following:

- Pressure controller
- Volume controller
- Flow controller
- Time controller

**Pressure Controller**

When the ventilator maintains the pressure waveform in a specific pattern, the breathing is described as *pressure controlled* (also *pressure limited* or *pressure targeted*). The pressure waveform is unaffected by changes in lung characteristics. The pressure waveform will remain constant but volume and flow will vary with changes in respiratory system mechanics (airway resistance and compliance). (Figure 1)

![Figure 1: Pressure control ventilation, a decrease in lung compliance (1) results into a change in the delivered volume (2) and flow (3) with no change in the delivered pressure (4).](image_url)
**Volume Controller**

When the ventilator maintains the volume waveform in a specific pattern, the delivered breath is *volume controlled* (*volume limited, volume targeted*). The volume and flow waveforms remain unchanged, but the pressure waveform varies with changes in lung characteristics (resistance and compliance). (Figure 2)

![Diagram showing Volume Control Ventilation](image)

Figure 2: Volume (or flow) control ventilation, a decrease in lung compliance (1) results into a change in the delivered pressure (2) with no change in the delivered flow (3) or volume (4).

**Flow Controller**

A flow controller ventilator directly measures flow and uses the flow signal as a feedback signal to control its output. Most new ventilators measure flow and are flow controllers; volume becomes a function of flow as follows:

\[
\text{Volume (L)} = \text{Flow (L/sec)} \times \text{Inspiratory Time (sec)}
\]
Flow and volume waveforms will remain constant, but pressure will vary with changes in respiratory mechanics (airway resistance and compliance) (Figure 2).

**Time Controller**
A time controller ventilator measures and controls inspiratory and expiratory time. Pressure and volume waveforms vary with changes in resistance and compliance. High frequency ventilation is an example of a time controller ventilator.

**Phase Variables:**
During mechanical ventilatory support, there are four phases during each ventilatory cycle: the trigger phase (breath initiation), the flow delivery phase (limit or target variable), the cycle phase (breath termination), and the expiratory phase (baseline phase). Mechanically delivered breaths can be described by what determines the trigger, flow delivery, and cycle parameters for that breath.

**Triggers**
Triggering is what causes the ventilator to cycle to inspiration. Ventilators may be time triggered, pressure triggered or flow triggered. With **time-trigger** system; the ventilator cycles at a set frequency as determined by the controlled respiratory rate, the clinician sets a rate and a machine timer initiates mechanical breaths, for example; a rate of 12 breaths per minute will initiate a breath every 5 seconds (60 seconds/12 breaths). (Figure 3-A) The **flow-triggered** system has two preset variables for triggering, the base flow and flow sensitivity. The base flow consists of fresh gas that flows continuously through the circuit and out the exhalation port, where flow is measured. The patient’s earliest demand for flow is satisfied by the base flow. The flow sensitivity is computed as the difference between the base flow and the exhaled flow. Hence the flow sensitivity is the magnitude of the flow diverted from the exhalation circuit into the patient’s lungs. As the patient inhales and the set flow sensitivity is reached the flow pressure control algorithm is activated, the proportional valve opens, and fresh gas is delivered. The flow triggering is indicated by the initial positive deflection of the flow above baseline bias flow. (Figure 3-B) **Pressure-trigger** system is where the ventilator senses the patient’s inspiratory effort by way of a decrease in the baseline pressure, the patient effort pulls airway/circuit pressure negative and mechanical breaths are initiated when pressure exceeds the set negative pressure threshold (pressure sensitivity), the pressure triggering is indicated by a negative pressure deflection at the initiation of the breath. (Figure 3-C)
The time taken for the onset of inspiratory effort to the onset of inspiratory flow is considerably less with flow triggering when compared to pressure triggering. At a flow triggering sensitivity of 2 liters per minute, for example, the time delay is 75 milliseconds, whereas the time delay for a pressure sensitivity of 1 cm H₂O is 115 milliseconds - depending on the type of ventilator used. The use of flow triggering decreases the work involved in initiating a breath.

**Flow Delivery (Limit or Target Variable)**

The second phase variable is the flow delivery governed by a clinician set target or limit for the ventilator during inspiration. In other words; it means how the machine delivers the set target. There are two commonly used targets/limits. A limit variable is the maximum value a variable (pressure, flow, volume) can attain. This limits the variable during inspiration but *does not end the inspiratory phase*. **Pressure target** where the clinician sets inspiratory pressure (Pi); therefore the flow/volume varies with pulmonary mechanics and patient’s effort (Figure 4-A); and **flow target** where the clinician sets the flow magnitude and pattern; therefore the pressure varies according to pulmonary mechanics and patient’s effort in order to deliver that flow (Figure 4-B and C).
Breath Termination (Cycling):

Cycling which means termination of inspiration and changing to expiration can be set to pressure, flow, volume or time. **Time cycling** terminates inspiration when the set inspiratory time is achieved. (Figure 5-A and C) **Volume cycling** terminates inspiration once the set target volume is achieved. (Figure 5-B) **Flow cycling** terminates inspiration when the flow has fallen to a set level (25% of peak inspiratory flow as an example). (Figure 5-D) **Pressure cycling** terminates the breath when a set pressure is achieved (Figure 5-E). Note that the pressure cycling can be the primary cycle variable (e.g. older “IPPB” devices) or can be a “backup” cycle variable with other cycling mechanism to prevent over-pressurization.

Figure 4: Flow delivery (limit or target variable; pressure targeted (A) and flow targeted (B and C).
Figure 5: Cycling variable, time cycled breath (A and C), volume cycled breath (B), flow cycled breath (D), pressure cycled (E), and flow cycled with backup time cycled breath (F).
Expiratory Phase (Baseline Variable):
The variable that is controlled during the expiratory phase, most commonly is the pressure. Positive end expiratory pressure (PEEP) is applied to the circuit above ambient pressure at the end of exhalation to improve oxygenation.

Flow Waveforms
In volume targeted ventilation inspiratory flow is controlled by setting the peak flow and flow waveform. The peak flow rate is the maximum amount of flow delivered to the patient during inspiration (for example 30 liters per minute), whereas the flow waveform determines the how quickly gas will be delivered to the patient throughout various stages of the inspiratory cycle. There are four different types of flow waveforms available. These include the square, decelerating (ramp), accelerating and sine/sinusoidal waveform, as illustrated in figure 6.

Square waveform:
The square flow waveform delivers a set flow rate throughout ventilator inspiration. If for example the peak flow rate is set at 60 lpm, then the patient will receive a flow at a speed rate
of 60 lpm throughout ventilator inspiratory flow time and will take 0.5 second to deliver a set tidal volume of 0.5 L. (figure 6-B)

**Decelerating waveform:**
The decelerating flow waveform delivers the peak flow at the start of ventilator inspiration and slowly decreases until a percentage of the peak inspiratory flow rate is attained or the flow reaches a zero point. (Figure 6-A)

**Accelerating waveform:**
The accelerating flow waveform initially delivers a fraction of the peak inspiratory flow and steadily increasing the rate of flow until the peak flow has been reached. (Figure 6-C)

**Sine / sinusoidal waveform:**
The sine waveform was designed to match the normal flow waveform of a spontaneously breathing patient. (Figure 6-D)

The decelerating flow waveform is the most frequently selected flow waveform and it is the waveform of the pressure-targeted ventilation as it produces the lowest peak inspiratory pressures of all the flow waveforms. This is because of the characteristics of alveolar expansion. Initially a high flow rate is required to open the alveoli. Once alveolar opening has occurred a lower flow rate is sufficient to procure alveolar expansion. Flow waveforms which produce a high flow rate at the end of inspiration (ie. square and accelerating flow waveforms) exceed the flow requirements for alveolar expansion, resulting in elevated peak inspiratory pressures.

**Breath Types**
Phase variables with trigger, limit, and cycle criteria can be used to characterize breath types during mechanical ventilation, four different breath types can be generated based on different phase variables; spontaneous, supported, assisted and controlled breaths.

**Spontaneous Breath**
Spontaneous breath is completely regulated by the patient with no contribution of the ventilator. The breath is triggered and cycled by the patient with no set target on the ventilator. The baseline variable can be set with positive pressure (Continuous Positive Airway Pressure: CPAP) (Figure 7-A)

**Supported Breath**
Supported breath is triggered by the patient (pressure or flow trigger), the target (limit) is set as pressure and the cycle variable being a percentage of the peak inspiratory flow (patient-triggered, pressure-limited and flow-cycled breath) (Figure 7-B)
**Assisted Breath**
Assisted breath is initiated by the patient, but all other aspects of the breath are controlled by the ventilator. The breath is triggered by the patient (pressure or flow trigger), the target is set as pressure or volume, and the cycle variable is a volume or a set time (patient-triggered, pressure- or volume-targeted and time-cycled breath). (Figure 7-C)

**Controlled Breath (Mandatory)**
A breath that is time triggered, with a set target being a pressure or volume and the cycle variable is a set volume or time (time-triggered, pressure- or volume-targeted and time-cycled breath) (Figure 7-D)

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**Breath Sequence**
The sequence of same or different types of breaths makes the mode of mechanical ventilation. A mode with sequence of breaths that are all of controlled type would be controlled mode ventilation; in contrast to spontaneous mode of ventilation where all the breaths are of
spontaneous type. A mode can have two or more different types of breaths such as intermittent mandatory ventilation where controlled breaths are mandatory at a set rate and the patient can breathe with spontaneous breaths in between (Figure 8)

Basic Modes of Mechanical Ventilation

In general, modes of mechanical ventilation are essentially made of breath sequences. The description of all modes of mechanical ventilation can be made based on what type of control variable is controlled by the mode (volume, pressure, or dual) and what are the different types of ventilatory breaths that compose the mode (spontaneous, supported, assisted or controlled). It is thus essential that the clinician is well acknowledged with basics of control variables, phase variables and breath types. Other specific settings of each mode can be described with each mode of ventilation.

Continuous Positive Airway Pressure (CPAP)

Continuous positive airway pressure (CPAP) is the use of continuous positive pressure to maintain a continuous level of positive airway pressure in a spontaneously breathing patient. It is functionally similar to positive end-expiratory pressure (PEEP), except that PEEP is an applied pressure against exhalation and CPAP is a pressure applied by a constant flow. The ventilator
does not cycle during CPAP, no additional pressure above the level of CPAP is provided, and patients must initiate all of their breaths above the level of CPAP (Figure 9). The breath types are all spontaneous with a sinusoidal flow waveform.

**Figure 9: Continuous Positive Airway Pressure (CPAP)**

**Pressure Support Ventilation (PSV)**

Pressure support is only applied to spontaneous breaths, the trigger of the breath could be either pressure or flow (sensitivity). In pressure support ventilation, all the breaths are supported breath type and are initiated by the patient. once the breath is triggered, the ventilator will deliver the pressure support at the limit of the set level above the CPAP/PEEP and the breath will be cycled off when the patient's inspiratory flow declines to a value determined by the clinician (for example; 25% of peak inspiratory flow). In PSV the volume and the flow are both variable and determined by the resistance, compliance, inspiratory effort and level of pressure support; in addition the inspiratory time is variable as well.
Pressure support ventilation is a pressure preset mode in which each breath is patient triggered and supported. It provides a means of a positive pressure that is synchronized with the inspiratory effort of the patient.

The trigger is either pressure or flow depending on the ventilator used; the set level for the trigger (sensitivity) can be determined by the clinician.

The inspiratory pressures in pressure supported breath are set by the operator. The peak pressure is determined by the addition of the level of pressure support to the level of CPAP/PEEP (i.e. peak pressure = pressure support + CPAP/PEEP). There are no plateau pressures in pressure supported breaths as it is impossible to achieve an inspiratory pause. The speed of pressurization may be fixed by the ventilator or adjustable by setting the rise time.

The flow in pressure support must vary so that the preset level of pressure support is achieved and maintained throughout the breath. Flow cannot, therefore, be set by the operator. Likewise
the flow waveform cannot be set but tends to be decelerating in nature. Initially a high flow rate is delivered to the patient in order to distend the alveoli and overcome the resistance of the endotracheal tube. Once the alveoli opening occurs and the preset pressure has been obtained the rate of flow decreases - producing a decelerating flow waveform.

**The termination** of the pressure support breath is based on the decline of inspiratory flow. Inspiration cycles off when inspiratory flow falls to a preset value. This value may be a percentage of peak inspiratory flow (e.g. 25%) or a fixed amount of flow (e.g. 4 liters / min). The decline of inspiratory flow suggests that the patient’s inspiratory muscles are relaxing and that the patient is approaching the end of inspiration. At this point the inspiratory phase is cycled off. The ventilator terminates the pressure support and opens its exhalation valve. The expiratory phase is free of assistance, and returns to baseline pressure which may be level of CPAP/PEEP that is applied.

Pressure support ventilation is thus defined as a mode of ventilation that is patient initiated with a preset pressure, variable flow, volume and inspiratory time, and is flow cycled. (Figure- 10)

**Synchronized Intermittent Mandatory Ventilation (SIMV)**

Intermittent mandatory ventilation (IMV) was an earlier version of the more advanced SIMV. In this mode of ventilation a preset respiratory rate is delivered at a specified time interval. For a patient receiving 10 breaths per minute, a breath is delivered every six seconds regardless of the patient's efforts. The theoretical disadvantage of this form of ventilation is that the patient may take a spontaneous breath and could receive a machine delivered breath at the same time or during expiration, causing hyperinflation and high peak airway pressures. SIMV is said to avoid this problem by monitoring the patient's respiratory efforts and delivering breaths in response to the patient's inspiratory efforts. The patient can breathe spontaneously in between the mandatory breaths and those breaths can be pressure supported.

**SIMV** is similar to IMV in that it will still deliver a minimum number of breaths, despite the potential lack of inspiratory effort from the patient. If the ventilator is set to deliver 10 bpm the patient will receive these breaths whether he is breathing or not. SIMV utilizes a window of time in which the circuit is open for the patient and can breathe spontaneously. During this window, any spontaneous breath can be supported with pressure support (triggered window for supported breaths). In addition; SIMV utilizes another window in which a mandatory breath is due and will look to deliver this breath within a specified time frame, if the patient makes a sufficient inspiratory effort (governed by sensitivity) the machine will sense this effort and give the patient the breath during this time, synchronized to his own effort (triggered window for synchronized breaths). (Figure 11).
Figure 11: Synchronized Intermittent Mandatory Ventilation (SIMV): M: mandatory, $T_{\text{supp}}$: Patient triggered and supported, $T_{\text{synch}}$: patient triggered and synchronized

**Continuous Mandatory Ventilation (CMV)**

CMV is a mode of mechanical ventilation where all breaths are delivered based on set variables. The ventilator is set to deliver a breath according to parameters selected by the operator. "Assist control" or "controlled mechanical ventilation" are outdated terms for CMV, which is now accepted standard nomenclature.

**Volume-controlled CMV**

Breaths in volume-controlled CMV are patient-triggered, volume targeted and time-cycled (assisted breath) or time-triggered (machine), volume targeted and time-cycled (controlled breath). The operator will set tidal volume, flow rate, respiratory rate ($f$), FiO2, inspiratory time ($T_{\text{insp}}$), PEEP, and Slope. If the patient is not breathing, all breaths will be controlled and the trigger timer is set based on the set rate (60 sec/rate). (Figure12)
Figure 12: Volume-controlled CMV, all breaths are time triggered every 5 seconds (1), flow (volume)-targeted (2), and time-cycled (3).

Once the patient starts to breathe and reaches the sensitivity level, the breath will be assisted with the set tidal volume and terminated after the set inspiratory time is elapsed. The set rate will function then as a backup rate, if the trigger timer is reached and the patient did not initiate a breath, the machine will deliver a mandatory breath. (Figure 13)
Figure 13: Volume-controlled CMV, all breaths are patient triggered (1), flow (volume)-targeted (2), and time-cycled (3)

**Pressure-controlled CMV**

Breaths in Pressure controlled CMV are patient-triggered, pressure targeted and time-cycled (assisted breath) or time-triggered (machine), pressure targeted and time-cycled (controlled breath). The operator will set inspiratory pressure (Pinsp), respiratory rate (f), FiO2, inspiratory time (Tinsp), PEEP, and Slope. The flow will be decelerating waveform. If the patient is not breathing, all breaths will be controlled and the trigger timer is set based on the set rate (60 sec/rate). Once the patient starts to breathe and reaches the sensitivity level, the breath will be assisted with the set inspiratory pressure and terminated after the set inspiratory time is elapsed. The set rate will function then as a backup rate, if the trigger timer is reached and the patient did not initiate a breath, the machine will deliver a mandatory breath. (Figure 14)
Closed-loop Mechanical Ventilation

Closed-loop mechanical ventilation encompasses a plethora of techniques, ranging from the very simple to the relatively complex. In the simplest form, closed-loop ventilation is the control of one output variable of the mechanical ventilator based on the measurement of an input variable. An example would be pressure support ventilation, in which flow (output) is constantly changing to maintain pressure (input) constant throughout inspiration. More complex forms of closed-loop ventilation involve measurement of multiple inputs (e.g., compliance, oxygen saturation, respiratory rate) to control multiple outputs (e.g., ventilator frequency, airway pressure, tidal volume). The latter type of control more closely mimics the ventilatory control and response of human physiology.

The following closed-loop systems are commercially available today: pressure regulated volume control (PRVC), volume support (VS), volume assured pressure support (VAPS) proportional assist ventilation (PAV), neurally adjusted ventilatory assistance (NAVA), the knowledge-based system (KBS), and adaptive support ventilation (ASV). Feedback may be within a breath such as in VAPS or from breath to breath such as PRVC, VS and ASV.
Pressure Regulated Volume Control (PRVC)

PRVC is based on the concept of adaptive control in which the ventilator automatically adjusts the pressure limit of a breath to meet an operator-set volume target over several breaths. PRVC is a control mode of ventilation with a dual control on the volume and pressure. All breaths are patient- or machine-triggered, volume-controlled with pressure regulation and time-cycled. The breaths delivered at preset tidal volume, minute volume and preset rate during preset inspiratory time. The ventilator automatically adjusts the inspiratory pressure control level to changes in the mechanical properties of the lung/thorax on a breath-by-breath basis. The pressure change is 2-3 cm H2O each time and the pressure does not exceed 5 cm H2O below the pressure alarm (limit) level set on the ventilator even if the targeted volume is not achieved, an alarm message is then displayed showing the target volume is not achieved.

The ventilator always uses the lowest possible pressure level to deliver the preset tidal and minute volumes. If an improvement in lung compliance occurred, the same pressure will deliver higher than the target volume, the pressure then will be gradually decreased 2-3 cm H2O each time to achieve the lowest level that assures delivery of target volume. The I:E ratio is controlled, and the inspiratory flow is decelerating (resembling a pressure controlled breath).

The patient can initiate breaths depending on the sensitivity setting, so it is important to adjust trigger sensitivity appropriately. The patient triggered breaths are delivered using the same preset parameters as the ventilator initiated breaths. This is a volume targeted (controlled) pressure-limited, time-cycled mode. The purpose of the PRVC mode is to deliver set tidal volumes at the minimum pressure level needed. Regular volume control ventilation has been a conventional mode of ventilation for decades. The main problem associated with regular volume control is the potentially excessive airway pressure that can lead to barotrauma, volutrauma, and adverse hemodynamic effects. Many of these problems can be minimized with PRVC. (Figure 15)
Figure 15: Dual-control CMV, the pressure is gradually increasing to achieve target volume.

The feedback loop starts once a breath is triggered (patient or time triggered); the ventilator delivers a pressure based on the VT/C and maintain this pressure limit as long as the set inspiratory time has not elapsed. Once the inspiratory time is elapsed; the ventilator will cycle off and terminate the breath. The respiratory system compliance will be calculated based on the required pressure and the delivered tidal volume of the previous breath. If the delivered volume is equal to the set tidal volume; the machine will do no changes and deliver the next breath with same parameters. In case the delivered volume was higher (improved compliance) or lower (worsened compliance); the machine will calculate a new lower or higher pressure limit respectively. (Figure 16)
Volume Support

In volume support ventilation; once the target volume is set by the operator, a test breath (5 cm H2O) is given initially and the pressure is increased slowly until target volume is achieved; the maximum available pressure is 5 cm H2O below upper pressure limit. If the delivered VT higher than set VT then the pressure will be decreased gradually. The patient can trigger breath and if apnea alarm is detected, the ventilator switches to PRVC. (Figure 17)
Figure 17: Volume Support Ventilation: (1), VS test breath (5 cm H2O); (2), pressure is increased slowly until target volume is achieved; (3), maximum available pressure is 5 cm H2O below upper pressure limit; (4), VT higher than set VT delivered results in lower pressure; (5), patient can trigger breath; (6) if apnea alarm is detected, ventilator switches to PRVC.

The feedback loop starts once the patient trigger a breath; the ventilator deliver a pressure based on the VT/C and maintain this pressure limit as long as the flow is not reached the cycling threshold (5% of the peak flow for example). Once the flow reaches the predetermined value; the ventilator will cycle off and terminate the breath. The respiratory system compliance will be calculated based on the required pressure and the delivered tidal volume of the previous breath. If the delivered volume is equal to the set tidal volume; the machine will do no changes and deliver the next breath with same parameters. In case the delivered volume was higher (improved compliance) or lower (worsened compliance); the machine will calculate a new lower or higher pressure limit respectively. (Figure 18)
Respiratory Mechanics & Equation of Motion

Understanding equation of motion is crucial in understanding pulmonary mechanics and the effect of their changes on pressure, flow and volume. The pressure at the airway opening minus the pressure at the body surface is called the transrespiratory system pressure which is the pressure needed to drive the gas into the lung. This pressure has two components, transairway pressure (airway opening pressure minus lung pressure) and transthoracic pressure (lung pressure minus body surface pressure). The difference between the opening pressure and the pleural pressure is called transpulmonary pressure. (Figure 19)
The equation of motion dictates that the change of pressure required to deliver gas into the airways and inflate the lung ($\Delta P$) is equal to the resistance of the airways ($R$), the air flow ($F$), the change of volume ($\Delta V$) and the respiratory system Elastance ($E$):

$$\Delta P = R \times F + \Delta V \times E$$

The change in pressure represents the sum of muscle pressure and the ventilator pressure. If the patient is paralyzed, the only pressure change would be the ventilator pressure. This equation can be is expressed in terms of compliance ($Cst$) instead of elastance:

$$\Delta P = R \times F + \Delta V / Cst$$

Any change on one side of this equation mandates a change on the other side so the equation is kept in balance. In the next few sections, we will present different scenarios that you may
face in regard to changing pulmonary dynamics in volume control and pressure control ventilation.

**Changing Resistance**

In volume controlled ventilation, the tidal volume is fixed and any change in the resistance, flow or compliance on one side of the equation of motion will lead to a change in the pressure on the other side. The increased resistance (red) will result in an increased pressure (green) while the volume is not changing (blue).

\[ \uparrow \Delta P = \uparrow R \times F + \Delta V/Cst \]

Bronchospasm, secretions in the airways, kinked ETT, or biting on the ETT will lead to increased airway resistance. The pressure scalar will show an increased airway pressure (Paw) and peak inspiratory pressure (PIP) without a change in the plateau pressure (Pplat). The difference between PIP and Pplat will be equivalent to the increased Paw. (Figure 20)
The volume will be targeted to the same control level and no change will occur on the inspiratory flow wave. The expiratory phase will show the flow limitation due to increased resistance and increased time constant; and the flow may not return to the zero point before the next breath if the expiratory time is not long enough.

On the other hand, in pressure controlled ventilation, the pressure (ΔP) is fixed on the left side of the equation and the increased resistance (red) will result in a decrease in the delivered volume (green) without a change in the pressure (blue) to keep the equation in balance.

\[ \Delta P = \uparrow R \times F + \downarrow \Delta V/Cst \]

![Figure 121: Changing resistance in pressure control ventilation](image)

The rise in resistance in pressure control ventilation will show no change in the pressure on the pressure scalar, but the volume will be decreased and the flow will be limited during both inspiration and expiration. (Figure 21)
Changing Compliance
In volume controlled ventilation, the tidal volume is fixed and any change in the resistance, flow or compliance on one side of the equation of motion will lead to a change in the pressure on the other side. The decreased compliance (red) will result in an increased pressure (green) while the volume is not changing (blue).

\[ \uparrow \Delta P = R \times F + \Delta V / \downarrow Cst \]

A pneumothorax or hemothorax leads to decreased chest wall compliance. The pressure scalar will show a normal airway pressure (Paw) but an increased peak inspiratory pressure (PIP) and plateau pressure (Pplat). The difference between PIP and Pplat will remain normal and represent the airway pressure. (Figure 22)

On the other hand, in pressure controlled ventilation, the pressure (\( \Delta P \)) is fixed on the left side of the equation and the decreased compliance (red) will result in a decrease in the delivered
volume (green) without a change in the pressure (blue) to keep the equation in balance. (Figure 23)

$$\Delta P = R \times F + \downarrow V / \downarrow Cst$$

![Figure 23: Decreased compliance in pressure control ventilation](image)

**Changing Pea Flow**

According to the equation of motion, any change in the flow will directly affect the pressure. If the flow is increased, the pressure will be increased and the needed time to deliver the tidal volume with the higher flow will be shorter leading to increase plateau time in volume control mode with time cycling mechanism. (Figure 24 and Figure 25)
Figure 24: Changing flow in volume control ventilation
Figure 25: Changing flow in volume control ventilation

**Changing Inspiratory Pressure Rise Time**

The inspiratory pressure rise time or the slope is determined by measure the time require for the pressure to rise from the end expiratory pressure to the peak inspiratory pressure. In pressure control ventilation, the shorter the rise time (higher slope), the higher and the steeper the peak flow is. At the same time the volume wave will reflect the higher flow with the increase concavity of the curve as a result of a higher volume delivered earlier in inspiration. (Figure 26)
Figure 26: Effect of the decreased rise time on flow and volume curves.

On the other hand, an increase in the rise time (decreased slope) will result in a decrease in the peak flow with a decrease in its slope associated with decreased concavity of the volume curve. (Figure 27)
Ventilator loops

Pressure-Volume Loop
The pressure-volume loop is the most important loop that needs to be understood as it gives an idea about the lung compliance. The loop is plotted against two axes, with the pressure being plotted on the X axis and the volume on the Y axis.
In volume control ventilation, inspiration start at the point of end expiratory pressure where there is an initial increase from point 1 to point 2 (Figure 28). This increase in pressure represent the airway pressure ($P_{AW}$) and is associated on the Y axis with a slight increase in the delivered volume. As you notice, the curve takes a turn at point 2 that is called the lower inflection point where a little increase in the pressure after that point is associated with remarkable increased in the inspired volume till the pressure reaches the peak inspiratory pressure at point 3 and the volume reaches the targeted tidal volume that the ventilator is
intended to deliver as a control variable. After point 3, the pressure decreases slightly to point 4 without any change in the volume which correlated with the plateau pressure on the pressure-time scalar. The loop will hold at point 4 for an interval equal to the plateau time before the pressure is released and the ventilator cycles from inspiration to expiration. The pressure decreased to the end expiratory pressure and the volume is exhaled before another breath is started and the loop repeats itself.

**Flow-Volume Loop**
The flow-volume loop plots the changes flow on axis Y against the changes of volume on axis X and represent the breath with its inspiratory part above the X axis and the expiratory part below it.

![Flow-volume loop in volume control ventilation.](image-url)
In volume control ventilation, the loop at the zero point of both flow and volume (point 1) with a sharp increase in the flow to the peak inspiratory flow (point 2) associated with an increase in the delivered volume on axis X. The flow then becomes fixed at the value of the peak inspiratory flow as the mode is a volume control mode and the volume continues to increase to the tidal volume level at which point the flow is decreased to zero (point 3). You will notice that the flow and the volume will hold at point 3 for an interval equal to the plateau time (when present) before the flow converts to negative and reaches the peak expiratory flow at point 4 and then gradually back to the zero point before next inspiration. The tidal volume is gradually exhaled as the expiratory flow continue.