Short guide
Flow-i Waveforms and Loops

GETINGE

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INTRODUCTION

Scope

This document is intended to function as a guide when working with the FLOW-i anesthesia system. The main focus lies on understanding and analyzing waveforms and loops presented on the control panel. Other pocket guides describe other aspects of the FLOW-i system.

This pocket guide only covers selected topics and cannot replace the user’s manual. For detailed information, please always refer to the latest corresponding version of the user's manual.

Waveforms and loops

Waveforms and loops are used to visually display the current lung status of the patient. Their appearances are based on real-time values and are continuously updated.

Specifically, this pocket guide will provide the user with the following:

- A background on the real-time values used primarily to illustrate the breathing cycle; pressure, flow, volume and CO_2-level.
- A review of the ventilation modes and the associated waveforms and loops.
- A review of external factors affecting the appearance of waveforms and loops.

INTRODUCTION

Breathing

Breathing is a complex process, neurally controlled by a specialized centre in the brain stem, located just under the brain. The brain stem comprises, together with the brain and spinal cord, the central nervous system (CNS).

The breathing center automatically regulates the rate and depth of breathing; specific organs regularly provide feedback pertaining to the metabolic requirements of the body.

When the breathing process is compromized, e.g. during general anesthesia, breathing function is maintained by delivering air into the lungs using an increase in the external pressure.

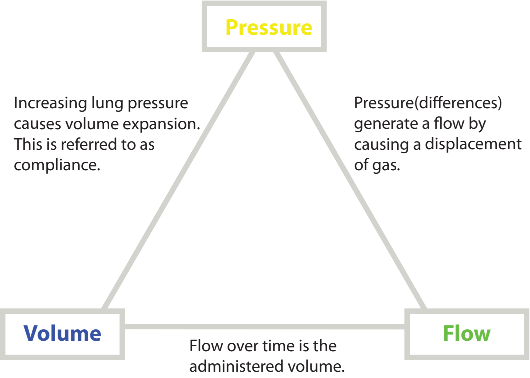
Operators of the FLOW-i system control ventilation by having the system deliver gas using pressure. This pressure can either be set directly to create a flow into the lungs (pressure control), or indirectly so by defining a target volume to be administered with every breath (volume control). Other automatic breathing modes are variants or combinations of pressure control and volume control. FLOW-i, when fully equipped, supports the following ventilation modes:

- Pressure Control
- Volume Control
- PRVC
- Pressure Support
- SIMV (PC) + PS
- SIMV (VC) + PS
- AFGO
- Manual ventilation

Estimated values and set parameters

This chapter describes three important estimated values that are used to generate waveforms and loops on the control panel:

- Pressure
- Flow
- Volume



Note: The CO_2 waveform, the capnogram, is treated in a seperate section later in this guide.

Linear and exponential change

Linear change

A linear type increase, or decrease, is characterized by a straight line in a graphical diagram (A). The change is constant irrespective of the current value.

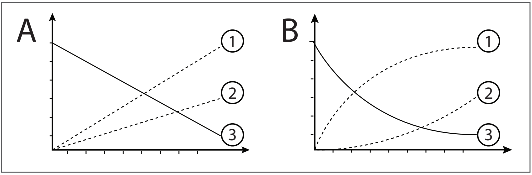
This is the case with the volume waveform in volume control. The increase in volume is constant when comparing any section of the inspiratory phase.

Exponential change

An exponential type increase, or decrease, is characterized by a parabolic (arched) line in a graphical diagram (B). The rate of change is dependant on the current value.

The gas flow during expiration can be used to illustrate this. At the start of expiration the lungs are filled with gas. When the expiratory valve opens, the large pressure difference causes gas to rapidly flow from the lungs.

At the end of expiration, the pressure difference causing the flow is small, and flow is consequently lower. Flow is thus dependant on the current value of pressure.



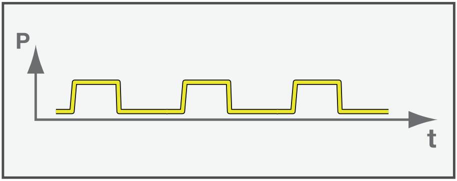
Pressure

Pressure, in the context of ventilation, refers to the compression of gas. A mechanical ventilation system uses pressure to create a pressure gradient resulting in the displacement, movement, of gas into the lungs. This movement of gas is referred to as 'flow'.

The pressure waveform on the control panel describes the external pressure used to deliver gas to the patient. It is measured inside the FLOW-i.

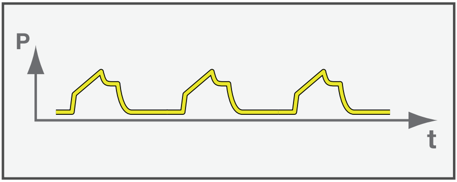
Pressure control - pressure waveform

In pressure control, pressure is constant during the entire inspiration.



Volume control - pressure waveform

In volume control, pressure increases during inspiration, thus always maintaining a pressure gradient between delivery pressure and lung pressure.

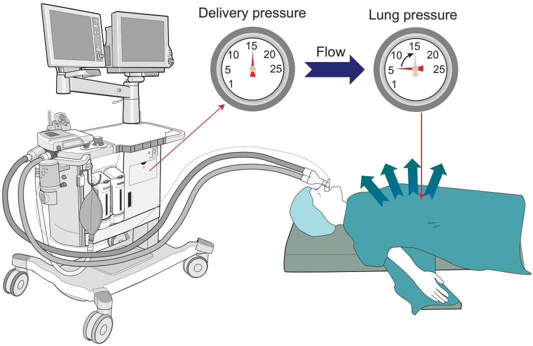


Flow

Flow, or movement of gas, is the result of a pressure gradient. The value of flow is proportional to the pressure difference. As the difference, i.e. pressure gradient, approaches zero, flow decreases.

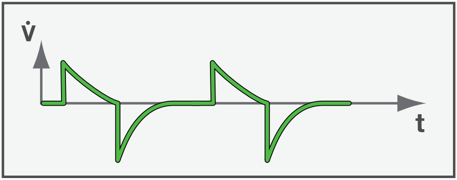
The flow waveform on the control panel describes the amount of gas per unit of time that moves into, or out of, the patient. Common units are l/min and ml/sec.

By convention, inspiratory flow is positive and expiratory flow is negative.



Pressure control - flow waveform

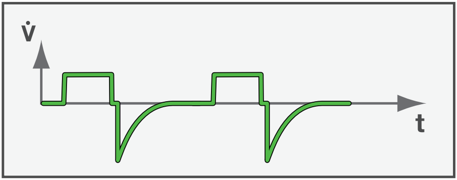
In pressure control, the numeric value for flow is highest at the beginning of inspiration and at the beginning of expiration. This is when the pressure gradient is largest. Inspiration and expiration can both be described by an exponential function.



Volume control - flow waveform

In volume control, flow is made constant during inspiration by continuously increasing the pressure used when delivering gas. This section is described by a linear function.

Expiratory flow in volume control can be described by an exponential function.

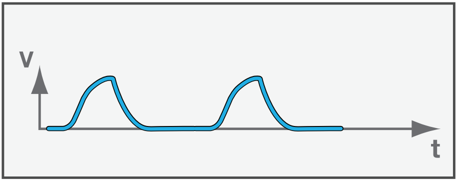


Volume

The delivered volume is either specified by setting the tidal volume/minute volume in volume control mode, or is a subsequent effect of setting the pressure level above PEEP in pressure control mode. In pressure control, lung and thorax characteristics such as resistance and compliance effect the final delivered volume.

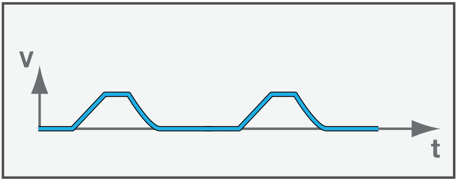
Pressure control - volume waveform

Delivered volume increases exponentially in pressure control, slowing down as the pressure gradient becomes smaller. There is no inspiratory pause, expiration follows immediately after inspiration.

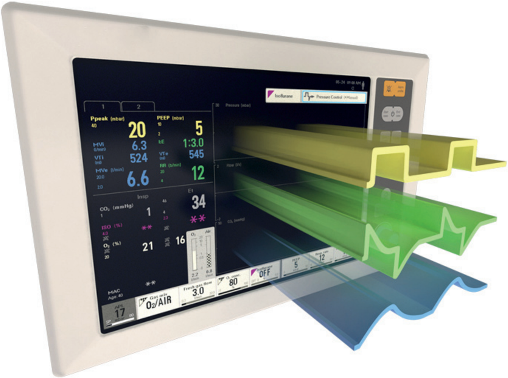


Volume control - volume waveform

Delivered volume increases linearly in volume control. The inspiratory pause is evident from the plateau between inspiration and expiration.



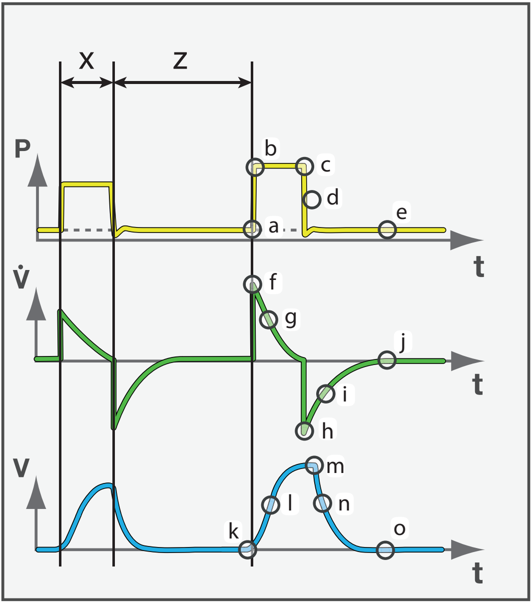
Waveforms



Waveforms allow for a quick assessment of how ventilation parameters interact and how patient dependant factors contribute to their appearance.

Changes in resistance and compliance are immediately reflected in the waveform (and loop) appearance.

Pressure control, waveform example

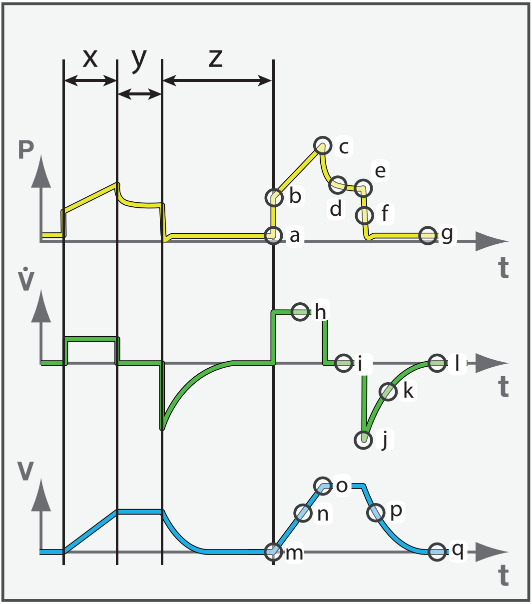


Pressure-Time waveform. Points and regions of interest	
x. Inspiration z. Expiration	a. Start of Inspiration b. Early inspiratory pressure c. End inspiratory pressure d. Early expiratory pressure e. End expiratory pressure

Flow-Time waveform. Points and regions of interest	
x. Inspiration z. Expiration	f. Peak inspiratory flow g. Decelerating flow h. Peak expiratory flow i. The slope represents the decreasing flow from the patient during expiration j. End expiratory flow

Volume-Time waveform. Points and regions of interest	
x. Inspiration z. Expiration	k. Start of inspiration l. The slope represents current delivery of inspiratory tidal volume m. End inspiration n. The slope represents current patient delivery of expiratory tidal volume o. End expiration

Volume control, waveform example

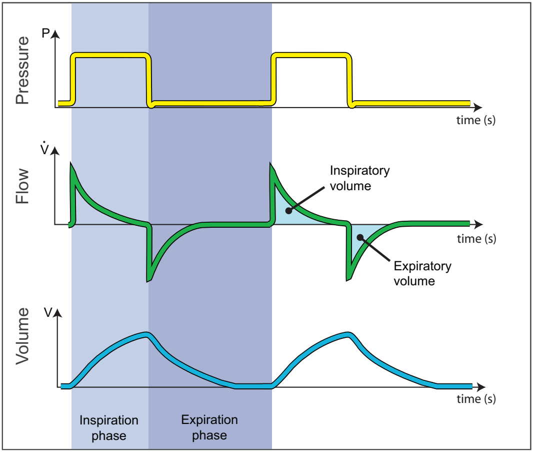


Pressure-Time waveform. Points and regions of interest	
x. Inspiration y. Pause time z. Expiration	a. Start of Inspiration b. Inspiratory rise time c. Peak inspiratory pressure d. Early inspiratory pause pressure e. End inspiratory pause pressure f. Early expiratory pressure g. End expiratory pressure

Flow-Time waveform. Points and regions of interest	
x. Inspiration y. Pause time z. Expiration	h. Peak inspiratory flow i. Zero flow phase j. Peak expiratory flow k. The slope represents the decreasing flow from the patient during expiration l. End expiratory flow

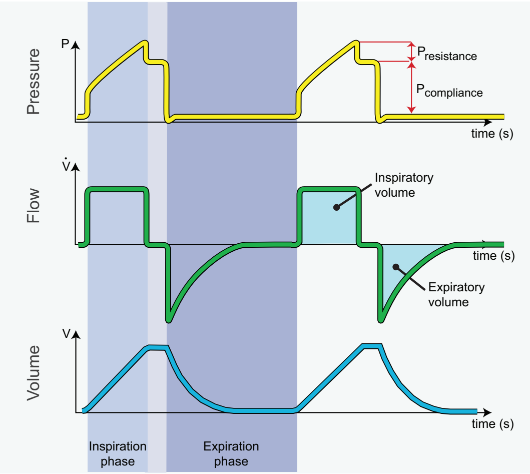
Volume-Time waveform. Points and regions of interest	
x. Inspiration y. Pause time z. Expiration	m. Start of inspiration n. The slope represents current delivery of inspiratory tidal volume o. End inspiration p. The slope represents current patient delivery of expiratory tidal volume q. End expiration

Pressure control - summary



- Pressure remains constant during the inspiratory phase. Expiration starts when the valves open, removing the delivery pressure.
- Flow decreases exponentially during inspiration and expiration. The rate is dependant on the pressure difference between the system and lungs.
- The delivered volume is an estimated parameter, it depends on the inspiratory pressure and the bio-mechanical properties of the lung (compliance, resistance etc.).

Volume control - summary



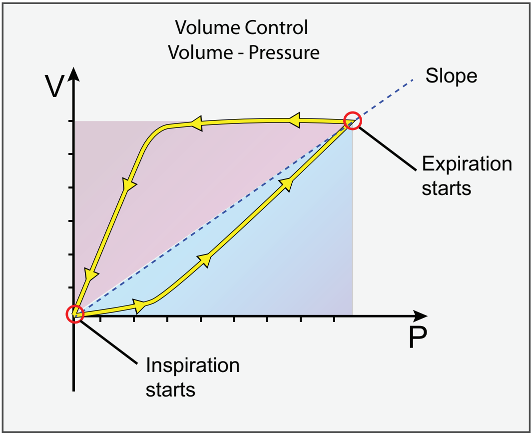
- Pressure increases linearly during the inspiratory phase to maintain a constant flow as lung pressure builds up. During the inspiratory pause, the pressure distributes evenly across the upper and lower airways, causing the measured pressure in the breathing circuit to decrease and stabilize at a level below the peak pressure, i.e. the $P_{plateau}$. The decrease is a measure of the internal resistance (penetration of gas into the alveoli) in the lungs.
- Flow is constant during inspiration. This ensures that a specific volume can be delivered by defining the inspiration time. Expiration starts when the expiratory valve opens, removing the delivery pressure.
- Volume increases linearly during inspiration. Delivered volume depends solely on flow and time.

Loops

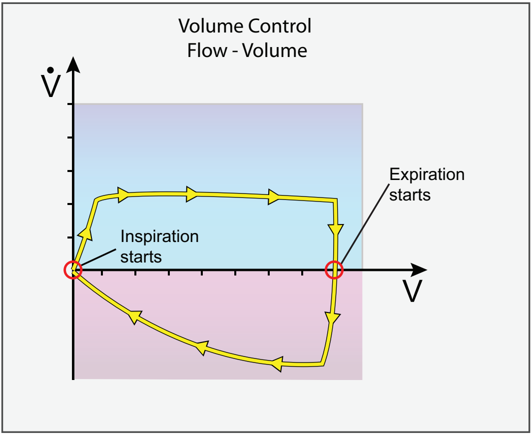
Loops provide another means of illustrating the relationships between pressure, flow and volume.

Loops are updated with every breath. With the possibility of storing a reference loop, the development of compliance and resistance can be monitored.

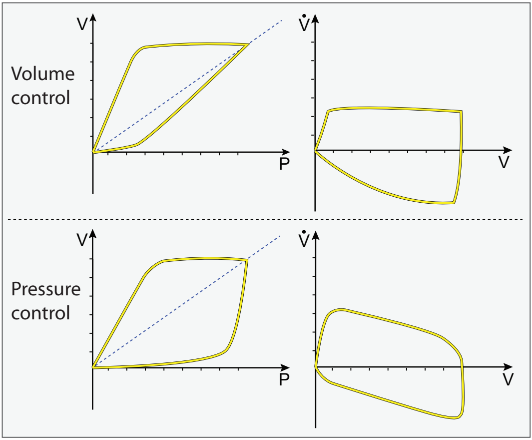
Additionally, when selecting the 'overlay loops' option, the last two displayed loops are kept on the control panel. These are continuously replaced as new loops are drawn.



- A completed loop represents one breathing cycle, divided into inspiration (blue area) and expiration (pink area).
- The volume vs pressure loop is a combination of the volume and pressure waveforms. Tracing along the path, each pressure value at any particular point has a corresponding volume value.
- The slope (not shown on the control panel) is an indication of current patient compliance (compliance defined as change in volume due to increase in pressure).
- The loops are updated in real time just like waveforms.
- The shape of the loop is determined by each patient's resistance and compliance. The chapter on abnormal loops shows examples of changes associated with varying resistance/compliance.



- A completed loop represents one breathing cycle, divided into inspiration (blue area) and expiration (pink area).
- The flow vs volume loop is a combination of the flow and volume waveforms. Tracing along the path, each volume value at any particular point has a corresponding flow value.
- The loops are updated in real time just like waveforms.
- The shape of the loop is determined by each patient's resistance and compliance. The chapter on abnormal loops shows examples of changes associated with varying resistance/compliance.

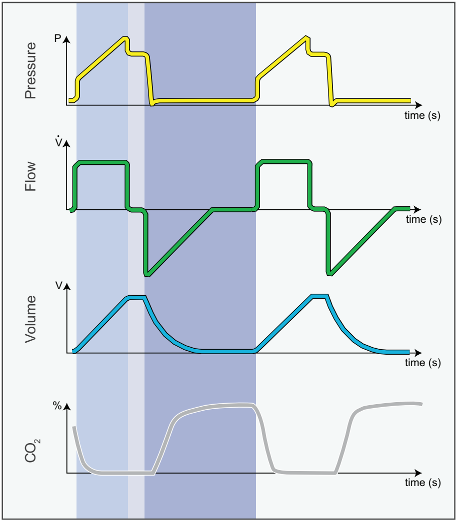


When comparing volume control and pressure control, differences in loop appearance are most prominent during inspiration. Expiration follows the same exponential pattern in both types of modes, and the loops look similar.

Volume-pressure loop	Flow-volume loop
In volume control, pressure and volume both increase throughout the inspiration phase, creating an elongated loop.	In volume control, the constant flow during inspiration is recognisable from the horizontal section of the loop during inspiration. During the inspiration pause, there is no flow or change in volume, hence the 90 degree break-off and immediate shift to maximum expiratory flow.
In pressure control, pressure rapidly reaches the set value and remains constant during inspiration. The majority of volume increase takes place after the peak pressure has been reached. This amounts to a predominantly square shaped loop.	In pressure control, both flow and volume follow exponential patterns, hence the smooth transition from inspiration to expiration. There is no inspirational pause.

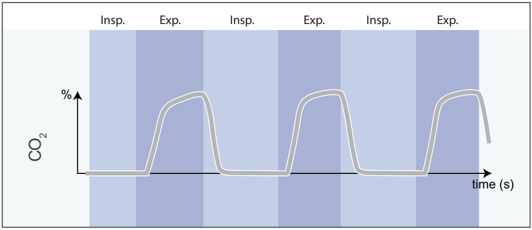
The capnogram

The FLOW-i continuously monitors the level of CO_2 in the breathing circuit. Enabling the CO_2 waveform allows for quick assessment of the status of the patient.



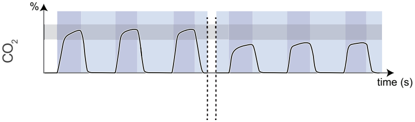
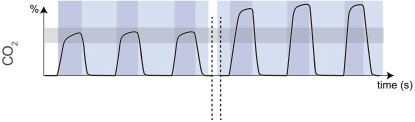
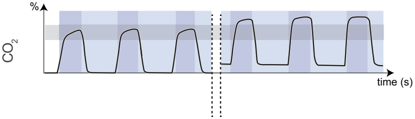
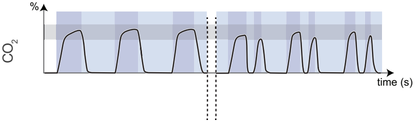
The capnogram will not appear to be in synchrony with the other displayed waveforms with respect to start of inspiration and start of expiration. This is a consequence of two factors:

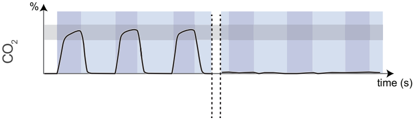
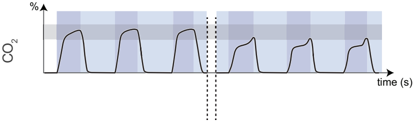
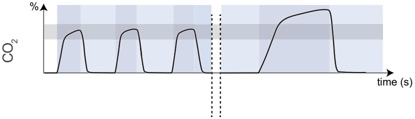
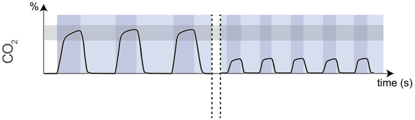
- At the end of inspiration, the upper respiratory tract is filled with the administered gas containing no CO_2 (ideally). This volume is known as the dead space, and is roughly equivalent to 150 ml for adults. Samples taken during the start of expiration will thus not contain any CO_2.
- The side stream monitoring of gas includes transporting the sampled gas from the Y-piece to the gas analyzer inside the system. This also introduces a small time delay.



CAPNOGRAM, END-TIDAL CO_2 MONITORING

The capnogram makes it possible to monitor the ventilation of the lungs and acquire information on circulation, pulmonary blood flow and metabolism. The following table lists a few examples of capnogram anomalies. The gray area symbolizes the range 3.5% - 4.5% CO_2 (~24-35 mmHg) concentration.

Condition	Effect on capnogram
Severe pulmonary embolism Decrease in end tidal CO_2 at constant tidal and minute ventilation.	
Malignant hyperthermia End tidal CO_2 increase	
Exhaustion of CO_2 absorber, rebreathing. The capnogram does not reach zero during inspiration	
Spontaneous breathing during automatic ventilation Inspiration is prematurely terminated and interrupted by a new breath.	

Condition	Effect on capnogram
Esophageal intubation, disconnection, obstruction of the endotracheal tube, extubation etc. No apparent sampling of CO_2, levels drop to zero.	
Leakage Lower total measured CO_2 levels. Abnormal shape of waveform depending on the severity of leakage.	
Hypoventilation Decreased breathing frequency combined with increased levels of CO_2.	
Hyperventilation Increased breathing frequency combined with decreased levels of CO_2.	

Laprascopic procedures include insufflating the abdomen with CO_2. The CO_2 will diffuse into the abdominal muscle and enter the blood stream, causing the CO_2 output to increase. The extent of this effect is individual but should be kept in mind during these types of procedures.

Other factors

The appearance of waveforms and loops are not only affected by system settings. Other, less predictable, factors also contribute to their appearance.

Relevant to interpretation and analysis of waveforms and loops are:

- **Resistance**
- **Compliance**
- **Leakage**

The following overview shows which waveforms are affected by these factors depending on the chosen ventilation mode.

	Volume Control and SIMV (VC)	Pressure Control/Support, PRVC and SIMV (PC)
Pressure-time waveform	Affected by changes in resistance and compliance	Unaffected
Flow-time waveform	Affected by changes in resistance and compliance	Affected by changes in resistance and compliance, and by leakage
Volume-time waveform	Affected by changes in resistance, compliance and by leakage	Affected by changes in resistance, compliance and by leakage

Resistance

Resistance, as measured in mechanical ventilation, is a measure of the friction gas encounters when flowing through the breathing circuit (ET tube and patient tubings) and patient airways.

In other words, it is a measure of the difficulty gas has when moving through the tubings and patient airways.

Examples of factors increasing resistance:

- Breathing circuit tubing length
- Diameter of tubes, smaller diameter increases resistance
- Coiled tubings increase resistance as opposed to straight tubings
- Ventilatory settings, high flow is coupled to increased resistance
- Medical issues
- Occlusion of the airways or patient tubings
- Filters
- Heat and moisture exchanger (HME)
- Angled adapters

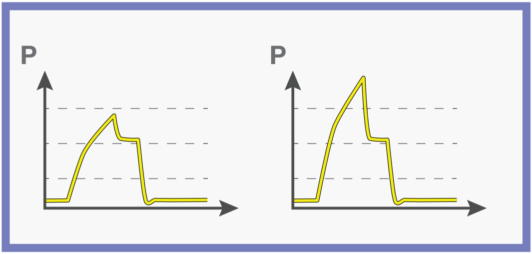
Examples 1 to 5 show the effect of increased resistance on waveform appearance.

Waveforms associated with volume control are indicated by a blue border.

Waveforms associated with pressure control are indicated by a yellow border.

OTHER FACTORS

Example 1



Volume control, pressure - time

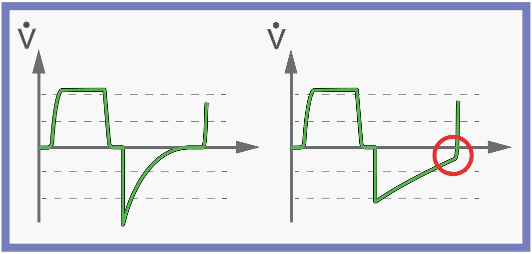
Observations:

- Ppeak has increased
- Ppause remains unchanged
- The difference in pressure between Ppeak and Ppause has increased

Conclusion:

These symptoms are indicative of an increase in inspiratory resistance. Possible causes include partial occlusion in the endotracheal tube, or increased intrathoraic pressure due to CO_2 insufflation.

Example 2



Volume control, flow - time

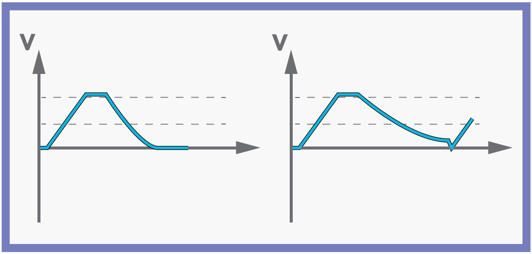
- Inspiratory peak flow is unchanged
- Expiratory peak flow has decresed
- The decrease in expiratory flow appears linear.
- End expiratory flow does not reach zero before the next inspiration starts = Auto PEEP (red circle)

Conclusion:

During volume control, inspiratory flow remains unaffected by changes in resistance and compliance. The decreased expiratory peak flow and linear decline in flow indicate expiratory flow limitation. If the expiratory flow has not reached zero at the beginning of inspiration, air-trapping and increases in auto-PEEP are likely consequences.

OTHER FACTORS

Example 3



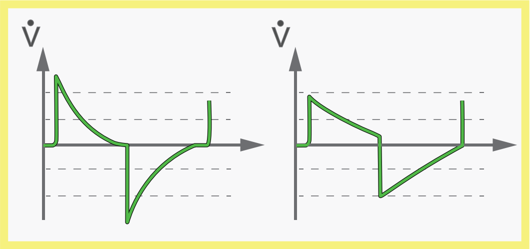
Volume control, volume - time

- Inspiratory tidal volume unchanged
- Stable plateau
- The decrease in volume is slow
- Expiratory volume curve does not reach baseline and is truncated

Conclusion:

A slower decrease in volume is indicative of flow limitation. A truncated expiratory volume curve is in itself indicative of leakage or air-trapping.

Example 4



Pressure control, flow - time

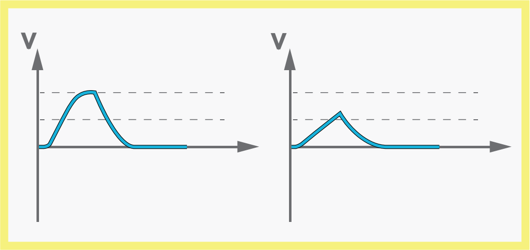
- Decreased inspiratory- and expiratory peak flow.
- Inspiratory and expiratory decrease appears linear
- Slower decrease in inspiratory and expiratory flow.
- Inspiration stops before baseline is reached

Conclusion:

Increased inspiratory and expiratory resistance resulting in smaller volumes being delivered to the patient (volume = area under curve in a flow-time waveform).

OTHER FACTORS

Example 5



Pressure control, volume - time

- Inspiratory tidal volume has decreased
- The increase in volume is slow and appears linear.
- The volume does not reach a plateau before expiration starts.
- The decrease in volume is slow

Conclusion:

A slow increase in volume during inspiration indicates increased inspiratory resistance. The slow decrease in volume during expiration indicates expiratory flow limitation.

Compliance

Compliance is an estimate of how an inflatable object, e.g. a lung, increases in size as a result of increased inner pressure. A common unit is ml/cmH_2O.

A compliance of 50 ml/cmH_2O means that for every increase in pressure by one cmH_2O, the volume increases by 50 ml.

Lung compliance decreases with age and medical conditions such as Chronic Obstructive Lung disease (COL) and atelectasis.

Thoracic elasticity also contributes to lung compliance. This has to be taken into account when performing open chest surgery. With no surrounding tissue acting against expansion, lung compliance is greatly increased.

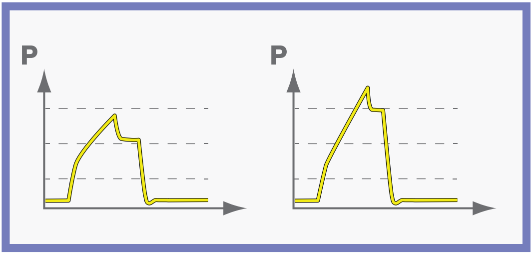
Lung compliance decreases when CO_2 insufflation is employed during surgery due to the increase in pressure surrounding the lung.

Examples 6 to 10 show the effect of decreased compliance on waveform appearance.

Waveforms associated with volume control are indicated by a blue border.

Waveforms associated with pressure control are indicated by a yellow border.

Example 6



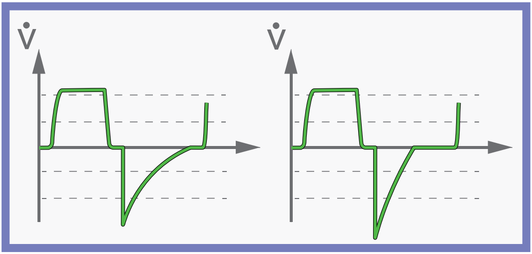
Volume control, pressure - time

- Peak inspiratory pressure has increased, but the difference between P_{peak} and $P_{plateau}$ remains unchanged.

Conclusion:

The increase in peak pressure combined with a similar increase in pause pressure indicate decreased compliance. The overall increase in pressure ensures that the defined target volume is delivered despite the decreased elasticity of the lung.

Example 7



Volume control, flow - time

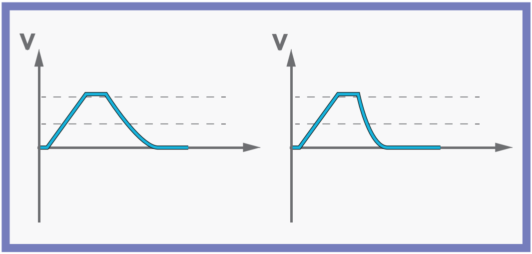
- Inspiratory peak flow is unchanged
- Expiratory peak flow has increased
- The decrease in in expiratory flow appears linear rather than exponential
- The decrease in flow is faster and the baseline is reached quicker

Conclusion:

During volume control, inspiratory flow remains unaffected by changes in resistance and compliance. The increase in peak expiratory flow and shorter time to reach baseline are consistent with a decrease in compliance.

OTHER FACTORS

Example 8



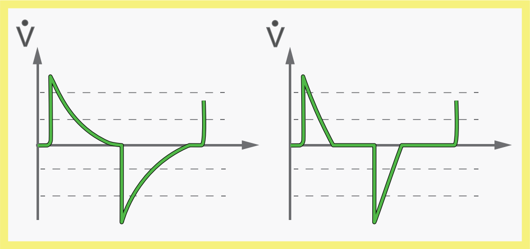
Volume control, volume - time

- Inspiration is unaffected.
- Volume decrease during expiration is rapid and the baseline is quickly reached.

Conclusion:

A rapid decrease during expiration is indicative of decreased lung compliance. The decreased elasticity of the lung creates a higher expiratory flow, resulting in a rapid volume decrease.

Example 9



Pressure control, flow - time

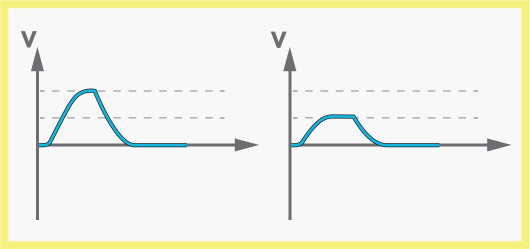
- Peak flow remains unaffected, or slightly decreased.
- Rapid linear decrease of flow during inspiration and expiration; baseline is quickly reached.
- Decrease in delivered volume.

Conclusion:

The rapid decrease in flow is an indication of decreased compliance. As a consequence, the delivered volume decreases.

OTHER FACTORS

Example 10



Pressure control, volume - time

- Delivered volume decreases.
- Rapid decrease during expiration; baseline is quickly reached.

Conclusion:

In pressure control, a decrease in delivered volume is indicative of decreased compliance or increased resistance. If the waveform reaches a plateau before expiration, decreased compliance becomes the more likely candidate.

Leakage

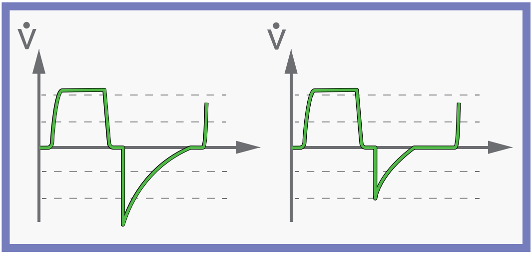
Leakage can be caused by numerous issues with the breathing circuit or airways. The FLOW-i has several systems monitoring for signs of leakage, but it is nevertheless of value to be aware of the change in waveform/loop appearance associated with leakage.

Examples 11 to 14 show the effect of leakage on waveform appearance.

Waveforms associated with volume control are indicated by a blue border.

Waveforms associated with pressure control are indicated by a yellow border.

Example 11

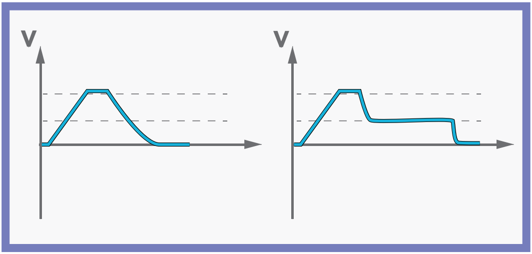


- Normal appearance during inspiration.
- Expiratory volume as depicted by the area under curve is smaller than the inspiratory volume.

Conclusion:

The difference in inspiratory and expiratory volume is suggestive of a leak in the system. In volume control, the inspiratory pressure, flow and volume waveforms are unaffected by leakage.

Example 12



Volume control, volume - time

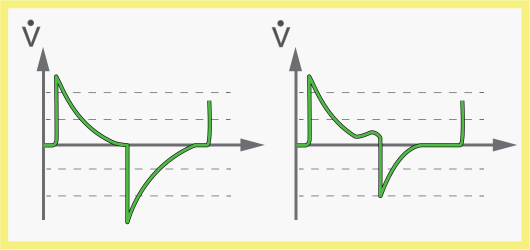
- Normal appearance during inspiration.
- Volume decrease during expiration stops before the baseline is reached.
- The waveform is truncated before the next inspiration.

Conclusion:

The premature stop of volume decrease during expiration is a consequence of delivered gas leaking out of the system. The leakage volume is obtained when comparing the delivered volume with the expired volume.

OTHER FACTORS

Example 13



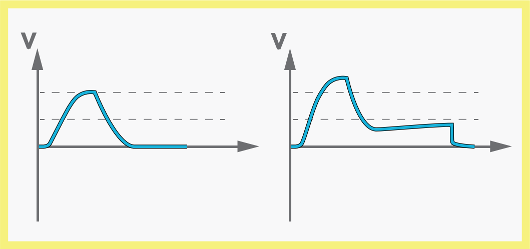
Pressure control, volume - time

- The last section of inspiratory flow does not reach baseline, or reaches baseline but produces a 'bump' immediately prior to expiration.
- The inspiratory volume is larger than the expiratory volume, as depicted by the area under waveform.

Conclusion:

The non-linear and non-exponential appearance of inspiratory flow together with a difference in delivered and expired volume, indicates leakage. In pressure control, the system ensures that a constant pressure remains in the breathing circuit, despite any leakages. This causes the flow to fluctuate during inspiration.

Example 14



Pressure control, volume - time

- Delivered volume increases.
- Volume decrease during expiration stops before the baseline is reached.
- The waveform is truncated before the next inspiration.

Conclusion:

The increase in delivered volume, combined with an expired volume that does not reach baseline suggests a leakage. The difference between delivered volume and expired volume constitutes the leak.

OTHER FACTORS

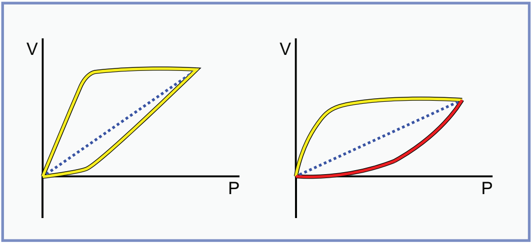
Loops

Selecting loops to be displayed on the control panel introduces another means of monitoring resistance and compliance.

The shape of the loops are ultimately defined by the ventilator settings. However, the change in appearance of loops are dependant on changes in resistance and compliance (and leakage).

It is thus helpful to store a reference loop when starting a patient case that can be used when comparing the current status with regards to compliance and resistance.

Volume control, volume - pressure



Observations:

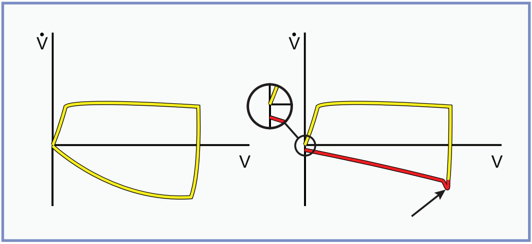
- Inspiratory section (red) is more bow shaped
- Angle of slope (blue dotted line) shifted toward the x-axis

Conclusion:

The shift in slope angle, combined with the change in appearance of the inspiratory section of the loop, is indicative of a decrease in dynamic characteristics, i.e. increase in resistance. Decreases in compliance do not effect the inspiratory section of the loop.

OTHER FACTORS

Volume control, flow - volume



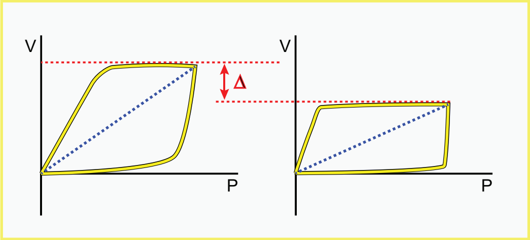
Observations:

- Inspiratory section does not change
- Peak expiratory flow has decreased and has a spike (arrow)
- Linear decrease in expiratory flow section during expiration (amber)
- The loop is not closed (magnification), flow does not reach baseline

Conclusion:

A decrease in peak expiratory flow and a linear decrease of flow indicate expiratory flow limitation. An open loop is a sign of leakage or air-trapping (loss of volume).

Pressure control, volume - pressure



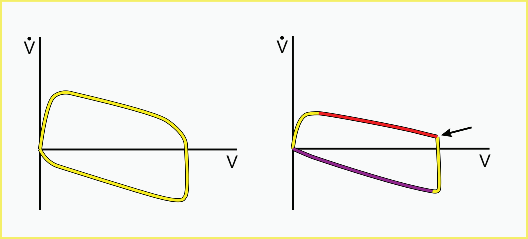
Observations:

- Angle of slope (blue dotted line) shifted toward the x-axis
- Volume at P_{peak} has decreased (red delta)

Conclusion:

The shift in slope angle indicates a decrease in dynamic characteristics. This can be caused by changes in compliance and/or changes in resistance.

Pressure control, flow - volume



Observations:

- Peak inspiratory flow has decreased
- Decrease in inspiratory flow is slower (amber)
- Inspiratory flow does not reach baseline, i.e. it is interrupted and the system switches to expiration (arrow)
- Peak expiratory flow has decresed
- Linear decrease in expiratory flow during expiration (purple)
- End expiratory flow is zero and the loop is 'closed'

Conclusion:

A decrease in peak inspiratory flow and a slower decrease in inspiratory flow indicate an increase in inspiratory resistance. Decreased compliance does not effect the peak inspiratory flow.

A decrease in peak expiratory flow and linear decrease in expiratory flow indicate expiratory air flow limitation.

References and suggested reading

1. *Tobin M.J.: Principles and Practice of Intensive Care Monitoring. McGraw-Hill of the McGraw-Hill Companies*
2. *Gravenstein J.S., Jaffe M.B., Paulus D.A.: Capnography Clinical Aspects. Cambridge University Press*

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