Ventilator Waveforms
Graphical Presentation
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Introduction

This pocket guide will help you identify different ventilatory waveform patterns and show you how to use them when making ventilator adjustments. Graphically displayed waveforms can help you better understand the patient-ventilator relationship and the patient’s response to the many types of ventilatory support.

Waveforms are graphical representations of data collected by the ventilator either integrated with changes in time (as in Pressure-Time, Flow-Time or Volume-Time curves) or with one another (as in Pressure-Volume or Flow-Volume loops).

Waveforms offer the user a “window” into what is happening to the patient in real time in the form of pictures. The digital values generated and displayed by the ventilator generally lag by at least one breath and in some cases four to eight breaths.

Waveforms can help the clinician evaluate the effects of pressure, flow and volume on the following four aspects of ventilatory support:

- Oxygenation and ventilation
- Lung damage secondary to mechanical ventilation (barotraumas/volutrauma)
- Patient rest and/or reconditioning
- Patient comfort

Waveform analysis can also help the clinician detect circuit and airway leaks, estimate imposed ventilatory work, and aid in assessing the efficacy of bronchodilator therapy.

In this workbook, all waveforms depicted are color-coded to represent the different types of breaths or breath phases represented by the waveforms displayed.

- GREEN represents a mandatory inspiration.
- RED represents a spontaneous inspiration.
- YELLOW represents exhalation.
Pressure-Time Curves

**FIGURE 1: Typical Pressure-Time Curve**
Pressure is defined as “force per unit area.” Commonly measured at or near the circuit wye, pressure for mechanical ventilation applications is typically expressed in cm H$_2$O and abbreviated as $P_{AW}$ (Airway Pressure).

Figure 1 shows a graphic representation of pressure changes over time. The horizontal axis represents time; the vertical axis represents pressure.

Inspiration is shown as a rise in pressure (A to B in the figure). Peak inspiratory pressure ($P_{PEAK}$) appears as the highest point of the curve. Exhalation begins at the end of inspiration and continues until the next inspiration (B to C in the figure).

Beginning pressure is referred to as the baseline, which appears above zero when PEEP/CPAP is applied. Average (mean) pressure is calculated from the area under the curve (shaded area) and may be displayed on the ventilator as $P_{MEAN}$ or MAP.

Several applications for the pressure-time curve are described below.
Applications
The pressure-time curve can provide the clinician with the following information:

- Breath type delivered to the patient
- Work required to trigger the breath
- Breath timing (inspiration versus exhalation)
- Pressure waveform shape
- Adequacy of inspiration
- Adequacy of inspiratory plateau
- Adequacy of inspiratory flow
- Results and adequacy of a static mechanics maneuver
- Adequacy of the Rise Time setting

Identifying Breath Types
The eight different breath types listed below can be identified by viewing the pressure-time curve, as shown on the following pages.

1. Ventilator-initiated mandatory breaths
2. Patient-initiated mandatory breaths
3. Spontaneous breaths
4. Pressure support ventilation
5. Pressure control ventilation
6. Pressure control with active exhalation valve
7. Bi-Level ventilation
8. Airway pressure release ventilation (APRV)
Ventilator-Initiated Mandatory Breaths

**FIGURE 2: Ventilator-Initiated Mandatory (VIM) Breath**
With no flow-triggering applied, a pressure rise without a pressure deflection below baseline (A) indicates a ventilator-initiated breath (Figure 2).

Patient-Initiated Mandatory Breaths

**FIGURE 3: Patient-Initiated Mandatory (PIM) Breath**
A pressure deflection below baseline (A) just before a rise in pressure indicates a patient’s inspiratory effort resulting in a delivered breath (Figure 3).

**NOTE:**
*Flow-triggering almost completely eliminates the work imposed on the patient to trigger a breath from the ventilator.*
Spontaneous Breaths

FIGURE 4: Spontaneous Breath
Spontaneous breaths (without Pressure Support) are represented by comparatively smaller changes in pressure as the patient breathes above and below the baseline (Figure 4). Pressure below the baseline represents inspiration (A) and pressure above the baseline represents exhalation (B).

Pressure Support Ventilation

FIGURE 5: Pressure Support Ventilation
Breaths that rise to a plateau and display varying inspiratory times indicate pressure supported breaths (Figure 5).

Pressure Control Ventilation

FIGURE 6: Pressure Control Ventilation
Figure 6 shows breaths that rise to a plateau and display constant inspiratory times, indicating pressure controlled breaths.
Pressure Control With Active Exhalation Valve

Figure 7 shows pressure control ventilation with spontaneous breathing occurring at peak pressure during the plateau period (A). This pattern is commonly seen in ventilators that employ an active expiratory valve.

Bi-Level Ventilation

Figure 8 shows Bi-Level ventilation with spontaneous breathing occurring at both PEEP<sub>H</sub> (A) and PEEP<sub>L</sub> (B). Note, also, that the Bi-Level mode synchronizes the transition from PEEP<sub>H</sub> to PEEP<sub>L</sub> with the patient’s own spontaneous exhalation (C).
Airway Pressure Release Ventilation (APRV)

**FIGURE 9: Airway Pressure Release Ventilation (APRV) Using Bi-Level Mode**

Figure 9 depicts Airway Pressure Release Ventilation (APRV) showing the characteristic long inspiratory time (TIME$_{\text{H}}$) (A) and short “release” time (TIME$_{\text{L}}$) (B). Note that all spontaneous breathing occurs at PEEP$_{\text{H}}$.

Assessing Plateau Pressure

**FIGURE 10: Plateau Pressure**

Figure 10 shows that during pressure control or pressure support ventilation, failure to attain a plateau pressure (A) could indicate a leak or inability to meet the patient’s flow demand.

**NOTE:**

*In some cases the ventilator may not be able to accelerate the flow delivery quickly enough to sustain the patient’s flow requirement.*
Assessing the Work to Trigger a Breath

FIGURE 11: Work to Trigger
In Figure 11, the depth of the pressure deflection below the baseline ($P_T$) and the time the pressure remains below the baseline ($D_{TOT}$) indicates the patient’s effort to trigger a breath. Larger trigger pressures ($P_T$) and/or longer trigger delay times ($D_{TOT}$) may also indicate an inadequate trigger sensitivity setting on the ventilator or a slow response time by the ventilator itself.

Evaluating Respiratory Events

FIGURE 12: Respiratory Time Calculations
Figure 12 shows several respiratory events. A to B indicates the inspiratory time; B to C indicates the expiratory time.

If the pressure during exhalation does not return to baseline before the next inspiration is delivered, the expiratory time may not be adequate.
Adjusting Peak Flow Rate

Figure 13: Peak Flow Adjustment

Figure 13 shows that during volume ventilation, the rate of rise in pressure is related to the peak flow setting. A lag or delay (A) in achieving the peak pressure could indicate an inadequate flow setting.

A very fast rise to pressure (B), often accompanied by an increased peak pressure, could indicate an inappropriately high flow setting.

During pressure ventilation, this variation in rise to pressure may indicate a need to adjust the ventilator’s rise time setting.

Measuring Static Mechanics

Figure 14: Static Measurements

Figure 14 illustrates a stable static pressure plateau measurement that differentiates the pressure caused by flow through the breathing circuit and the pressures required to inflate the lungs. The pressure-time curve can be used to verify the stability of the plateau when calculating static compliance and resistance.

(A) Represents the peak pressure.
(B) Represents the static pressure, or pressure in the lungs for the delivered volume.
(C) Represents an unstable pressure plateau, possibly due to a leak or the patient’s inspiratory effort. Using this plateau pressure to calculate compliance or resistance may result in inaccurate respiratory mechanics values.

Assessing Rise Time

![Pressure-Time Curve](image)

**FIGURE 15: Using the Pressure-Time Curve to Assess Rise to Pressure**

The rise to target pressure in pressure ventilation often varies among patients due to differences in lung impedance and/or patient demand. These variables may result in a suboptimal pressure waveform during breath delivery.

Many clinicians believe the ideal waveform for patients receiving pressure ventilation is roughly square in shape (Figure 15, B) with a rapid rise to target pressure so that the target pressure is reached early in the inspiratory phase and remains at the target pressure for the duration of the inspiratory time. This delivery pattern may help satisfy the patient’s flow demand while contributing to a higher mean airway pressure.

If compliance or flow demand is uncharacteristically high, the rise to pressure may be too slow. The result is target pressure is achieved late in the inspiratory phase, causing a decreased mean airway pressure (A). Patient comfort and synchrony can also be influenced if the rise time is too slow.

A rise time that is too fast could result in delivered pressure exceeding the set target pressure and potentially exposing the patient to higher-than-acceptable pressures (C). “Overshoot” in pressure ventilation is commonly seen with low compliance and/or high resistance.
**Setting Rise Time**

**FIGURE 16:** Using the Pressure-Time Curve to Set Rise Time %

An adjustable Rise Time setting allows the clinician to tailor breath delivery in pressure ventilation to more closely meet the patient’s demand and clinical conditions.

If the patient’s demand is excessive or compliance is very high, resulting in a slow rise to pressure (Figure 16, A), increasing the flow output with the Rise Time setting may result in a more ideal “square” pressure waveform (B).

If the patient’s compliance is very low or the resistance is high, the rapid rise to pressure may produce an undesirable pressure overshoot (C). A slower rise time may reduce or eliminate the overshoot (B).

**Assessing Auto-PEEP Maneuver**

**FIGURE 17:** Assessing the Auto-PEEP Maneuver

Figure 17 depicts a successful expiratory pause maneuver for a determination of Auto-PEEP, or Intrinsic PEEP ($\text{PEEP}_1$). An expiratory pause allows pressure in the lungs to equilibrate with pressure in the circuit, which is measured as Total PEEP ($\text{PEEP}_\text{TOT}$). An algorithm then subtracts the set PEEP, and the difference is considered Auto-PEEP.
A successful expiratory pause maneuver requires sufficient pause time for full equilibration between the lungs and circuit. (A) in the figure represents the point of equilibration and also represents the minimum adequate time for the expiratory pause. A shorter pause time would not allow complete pressure equilibration, resulting in a potential underreporting of the \( P_{\text{EEP}} \) and therefore an underestimation of the patient’s Auto-PEEP.

Observing the pressure-time curve during the Auto-PEEP maneuver allows the clinician to assess the quality of the maneuver and the accuracy of the reported \( P_{\text{EEP}} \) value.

**FLOW-TIME CURVES**

![Flow-Time Curve Diagram](image)

**FIGURE 18: Typical Flow-Time Curve**

Flow is defined as a volume of gas moved or displaced in a specific time period; it is usually measured in liters per minute (L/min). Figure 18 shows flow (vertical axis) versus time (horizontal axis).

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**NOTE:**

*Flow shown above the zero flow line is inspiratory flow and flow shown below the zero flow line is expiratory flow.*

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Inspiratory time is measured from the beginning of inspiration to the beginning of exhalation (A to B). Expiratory time is measured from the beginning of exhalation to the beginning of the next inspiration (B to C).

The peak inspiratory flow is the highest flow rate achieved during inspiration (D). The expiratory peak flow rate is the highest flow rate achieved during exhalation (E).

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**NOTE:**

*Some ventilators do not measure flow at the wye. Instead, inspiratory flow is measured at the gas supply flow sensor; expiratory flow is measured at the exhalation flow sensor.*
Applications
The flow-time curve can be used to detect:

- Waveform shape
- Type of breathing
- Presence of Auto-PEEP (Intrinsic PEEP)
- Patient’s response to bronchodilators
- Adequacy of inspiratory time in pressure control ventilation
- Presence and rate of continuous air leaks

Verifying Flow Waveform Shapes

*FIGURE 19: Flow Patterns*

Inspiratory flow patterns can vary based on the flow waveform setting or the set breath type as illustrated in Figure 19. In volume control ventilation, the ventilator can be set to deliver flow in:

- A square wave pattern, where the peak flow rate is set and the flow is constant through the inspiratory phase. Square flow waveforms can result in higher peak pressures.

- A descending ramp flow wave, where the set peak flow is delivered at the beginning of the breath and decreases in a linear fashion until the volume is delivered. Descending flow waveforms can produce lower peak pressures but can increase the inspiratory time significantly.

- A sine waveform, where the inspiratory flow gradually increases and then decreases back to zero. This method of delivering flow may cause patient discomfort.
A decelerating flow waveform, where the flow is highest at the beginning of inspiration but decelerates exponentially over the course of inspiration due to the effects of lung impedance. Decelerating flow is generated in pressure ventilation modalities, such as pressure control or pressure support.

**Detecting the Type of Breathing**

Figure 20 shows five typical flow-time curves for different types of breaths.

**Mandatory Breaths**

The square and descending ramp flow patterns are characteristic of volume control mandatory breaths with the volume, flow rate and flow waveform set by the clinician.

The decelerating flow waveform characteristic of pressure ventilation may actually display a flow of zero at the end of inspiration, in Pressure Control, if the inspiratory time is set long enough.

**Spontaneous Breaths**

A spontaneous breath without pressure support will result in a sine-like inspiratory flow pattern often displaying a lower peak flow rate.

A pressure support breath will be represented by a decelerating flow waveform which does not return to zero at the end of inspiration.
Determining the Presence of Auto-PEEP

Auto-PEEP, or Intrinsic PEEP (PEEP\textsubscript{i}), refers to the presence of positive pressure in the lungs at the end of exhalation (air trapping). Auto-PEEP is most often the result of insufficient expiratory time.

Auto-PEEP (Figure 21) is indicated by an expiratory flow that does not return to zero before the next inspiration begins (A).

A higher end-expiratory flow generally corresponds to a higher level of Auto-PEEP (B).

A lower end-expiratory flow generally corresponds to a lower level of Auto-PEEP (C).

**NOTE:**
The flow-time waveform can indicate the presence and relative levels of Auto-PEEP but should not be used to predict an actual Auto-PEEP value.

Missed Inspiratory Efforts Due to Auto-PEEP

FIGURE 22: Missed Inspiratory Efforts
Patients who require longer expiratory times are often unable to trigger a breath if the inspiratory times are too long resulting in Auto-PEEP.

Figure 22 illustrates the presence of patient inspiratory efforts that did not trigger a breath. This occurs when the patient has not been able to finish exhaling when an inspiratory effort is made (A).

To trigger a breath, the patient must inspire through the Auto-PEEP and meet the set trigger threshold to trigger the ventilator. Patients with weak inspiratory efforts are often unable to trigger breaths when significant Auto-PEEP is present.

**Evaluating Bronchodilator Response**

![Figure 23: Bronchodilator Response](image)

Figure 23 shows flow-time curves before and after the use of a bronchodilator. Compare the peak expiratory flow rates (A) and the time to reach zero flow (B). The post-bronchodilator curve shows an increased peak expiratory flow rate and a reduced time to reach zero flow, potentially indicating improvement following bronchodilator therapy.

This improvement in expiratory air flow may also be seen after the patient is suctioned.
Evaluating Inspiratory Time Setting in Pressure Control

**FIGURE 24: Inspiratory Time Adjustment**

Figure 24 shows the effect of inspiratory time in pressure control on flow delivery to the patient.

Shorter inspiratory times may terminate inspiration before the inspiratory flow reaches zero (A). Increasing the inspiratory time so the inspiratory flow reaches zero before transitioning into exhalation (B) can result in the delivery of larger tidal volumes without increasing the pressure.

Further increasing the inspiratory time beyond the zero flow point will generally not deliver any additional tidal volume but results in a pressure plateau (C), which may be desirable in some cases.

Evaluating Leak Rates With Flow Triggering

**FIGURE 25: Leak Rate**

Figure 25 shows a flow-time curve for a patient with flow triggering and a continuous air leak (e.g., uncuffed ET tube, bronchopleural fistula). When the flow trigger sensitivity is set higher than the leak rate, the flow-time curve can display the leak.
The leak allows some of the ventilator’s base flow to escape the circuit during the expiratory phase, as shown on the flow-time curve (B).

The distance between the zero flow baseline (A) and the flow curve (B) represents the actual leak rate in L/min.

**Assessing Air Leaks and Adjusting Expiratory Sensitivity in Pressure Support**

![Figure 26: Setting Expiratory Sensitivity (E\text{SENS})](image)

Figure 26 displays how leaks can affect the inspiratory time of pressure support breaths. Typically, pressure support breaths cycle into exhalation when the inspiratory flow decelerates to a termination threshold. With some ventilators this breath termination criteria (or expiratory sensitivity) is fixed at a value typically expressed as a percent of the peak flow delivered for that breath (10%, 25%). Other ventilators allow the clinician to vary the breath termination criteria to compensate for the effects of leaks or variations in lung impedance on inspiratory time.

Air leaks can often prevent the flow rate from decelerating to the set termination threshold (A), resulting in a long inspiratory time (B). Adjusting the expiratory sensitivity level to a higher percentage of peak flow (C) permits the breath to terminate earlier, decreasing the patient’s inspiratory time and helping to restore patient-ventilator synchrony.
**Bi-Level Ventilation**

**Figure 27**: Bi-Level Ventilation With Spontaneous Breathing

Figure 27 shows inspiratory and expiratory flow during Bi-Level ventilation. The high inspiratory flows indicate the beginning of the mandatory breath (A) with the lower inspiratory flows indicating spontaneous inspirations during both $TIME_H$ (B) and $TIME_L$ (C). The high peak expiratory flow represents the mandatory breath exhalation (D).

**APRV in Bi-Level Mode**

**Figure 28**: APRV in Bi-Level Mode With Spontaneous Breathing

Figure 28 shows inspiratory and expiratory flow during APRV with its characteristically long $TIME_H$ (A) and short “release time” (B). The high inspiratory flows represent the beginning of the mandatory breaths, and the lower inspiratory flows represent the spontaneous breathing during the $TIME_L$. Also note the presence of Auto-PEEP (C), which is also characteristic of APRV.
Volume-Time Curves

Volume is defined as a quantity of gas in liters. Figure 29 shows a typical volume-time curve. The upslope (A) indicates inspiratory volume while the downslope (B) indicates expiratory volume. Inspiratory time (I Time) is measured from the beginning of inspiration to the beginning of exhalation. Expiratory time (E Time) is measured from the beginning of exhalation to the beginning of inspiration.

**Figure 29**: Typical Volume-Time Curve

In Figure 29, the patient has exhaled fully after 1.7 seconds and again after 3.3 seconds. Because of the significant time between the end of exhalation and the beginning of the next inspiration, increasing the respiratory rate in this example would probably not cause air trapping.

**Applications**

The volume-time curves may be used to detect:

- Air trapping
-Leaks in the patient circuit
Detecting Air Trapping or Leaks

**Figure 30:** Air Trapping or Leaks

Figure 30 shows exhalations that do not return to zero (A). Volume in and volume out are not always equal. Air leaks or air trapping often result in an expiratory volume that is lower than the inspired volume. The plateau displayed during exhalation (A) is the expired volume until the start of the next inspiration.

Bi-Level Ventilation

**Figure 31:** Bi-Level Ventilation

Figure 31 shows flow delivery during the mandatory breaths (A) and spontaneous breathing at PEEP<sub>H</sub> (B) as well as at PEEP<sub>L</sub> (C).
FIGURE 32: APRV Using Bi-Level Ventilation

Figure 32 shows APRV using Bi-Level ventilation with spontaneous breathing at PEEP_H.

**COMBINED CURVES**

Many conditions can be identified by viewing two curves simultaneously. The curve examples that follow show combined pressure, flow and volume-time curves in these five ventilatory modalities:

- Assist Control (A/C or CMV)
- Synchronized Intermittent Mandatory Ventilation (SIMV)
- Spontaneous (SPONT or CPAP)
- Pressure Support
- Pressure Control
- Bi-Level
- APRV
Pressure and Volume-Time Curves

Figures 33-39 compare pressure and volume over time.

**Assist Control**

![Assist Control Diagram]

**Figure 33: Assist Control**

Figure 33 shows volume and pressure during A/C ventilation. Note that volume and pressure rise simultaneously. A patient-initiated breath is indicated by a slight negative deflection in pressure (A).

**SIMV**

![SIMV Diagram]

**Figure 34: SIMV**
Figure 34 shows volume and pressure changes during SIMV. The small pressure fluctuations and concurrent volume changes indicate spontaneous breathing (A). Negative pressure deflections just before a pressure rise indicate a patient-initiated breath (B).

**SPONT (CPAP)**

![Diagram showing pressure and volume changes during SIMV]

**FIGURE 35: SPONT**

Figure 35 shows volume and pressure changes during SPONT breathing. The small fluctuations in pressure and volumes (A and B) indicate spontaneous breathing. The variability in volume from breath to breath is characteristic of spontaneous breathing.

**NOTE:**

*If flow triggering is active on the ventilator, there may be little negative pressure deflection during inspiration.*
FIGURE 36: Pressure Support
Figure 36 shows volume and pressure during pressure support. Note the changes in volume (A) that correspond to changes in the patient’s inspiratory time and inspiratory effort.

FIGURE 37: Pressure Control
Figure 37 shows volume and pressure during pressure control ventilation. The characteristic plateau on the volume curve (A) appears as the target pressure is maintained for the set inspiratory time. This is because inspiratory flow has reached zero at this point in the inspiratory time.

**Bi-Level Ventilation**

![Bi-Level Ventilation Graph](image)

**Figure 38: Bi-Level Ventilation With Spontaneous Breathing**

Figure 38 shows pressure and volume during Bi-Level ventilation, with spontaneous breathing at both $\text{PEEP}_H$ (A) and $\text{PEEP}_L$ (B).
**FIGURE 39: APRV**

Figure 39 depicts volume and pressure with APRV, with spontaneous breaths occurring at PEEP_H.

**Volume and Flow-Time Curves**

Figures 40-46 compare volume and flow over time.

**Assist Control**

**FIGURE 40: Assist Control**
Figure 40 shows volume and flow during A/C ventilation with a square wave. Inspired volume corresponds to inspiratory flow (A); exhaled volume corresponds to expiratory flow (B).

**SIMV**

![SIMV Diagram]

**FIGURE 41: SIMV**

Figure 41 shows volume and flow during SIMV with a square wave. The figure also shows the differences in volume and flow waveform between mandatory and spontaneous breaths.
FIGURE 42: SPONT
Figure 42 shows volume and flow during SPONT. The sine-like flow waveform and reduced volume are characteristic of spontaneous breathing. Inspiration (A) and exhalation (B) are plotted simultaneously for both volume and flow.

Pressure Support Ventilation

FIGURE 43: Pressure Support Ventilation
Figure 43 shows volume and flow during pressure support ventilation. The slope of the volume curve may be very steep during the early part of inspiration (A). As flow decreases in a decelerating pattern (C) the slope of the inspiratory volume curve decreases (B).

**Pressure Control Ventilation**

![Pressure Control Ventilation Diagram]

**FIGURE 44: Pressure Control Ventilation**

Figure 44 shows volume and flow during pressure control ventilation. Delivered volume (A) increases as inspiratory time (B) increases.
Bi-Level

FIGURE 45: Bi-Level Ventilation
Figure 45 shows volume and flow in Bi-Level ventilation.

APRV

FIGURE 46: Airway Pressure Release Ventilation
Figure 46 shows volume and flow in APRV.
Pressure and Flow-Time Curves

Figures 47-53 compare pressure and flow over time.

Assist Control

FIGURE 47: Assist Control
Figure 47 shows pressure and flow with a square flow pattern (A) and a descending ramp flow pattern (B). Note the characteristic lower peak pressure and longer inspiration of a descending ramp flow pattern.
**FIGURE 48: SIMV**
Figure 48 shows pressure and flow in a square flow wave mandatory breath (A) and a non-pressure supported, spontaneous breath (B).

**FIGURE 49: SPONT**
The graph above represents purely spontaneous breaths.
Figure 50: Pressure Support Ventilation

Figure 50 shows pressure and flow during pressure support ventilation. The negative deflection in the pressure tracing at the beginning of inspiration (A) indicates patient-initiated breaths. Pressure increases to the target pressure support level above PEEP (B). The decelerating flow waveform represents the high initial flow rate (C) that decreases as the target pressure is reached. The pressure support breath terminates when the inspiratory flow decreases to a set level or percentage of the peak flow for that breath (D).
FIGURE 51: Pressure Control Ventilation

Figure 51 shows pressure and flow during pressure control ventilation. The two waveforms can be used together to adjust inspiratory pressure and inspiratory time. As inspiratory time is increased and plateau pressure is sustained (A), note the reduction in inspiratory flow rate (B). A short inspiratory time may result in an inspiratory flow that does not reach zero (C). Increasing the inspiratory time can allow flow to reach zero (D), resulting in a larger delivered tidal volume.
**Bi-Level**

**Figure 52: Bi-Level Ventilation**

Figure 52 shows pressure and flow during Bi-Level ventilation.

**APRV**

**Figure 53: Airway Pressure Release Ventilation**

Figure 53 shows pressure and flow over time with APRV.
PRESSURE-VOLUME LOOP

Introduction

Graphical “loops” are the result of two of the three ventilator variables (pressure, flow and volume) plotted against one another as opposed to the scalar curves that plot one variable against time. In this booklet, pressure-volume loops, or P-V loops, are plotted with pressure on the horizontal axis and volume on the vertical axis. The P-V loop is composed of two segments representing the inspiratory and expiratory phases of ventilation.

FIGURE 54: Pressure-Volume Loop Axes

In a P-V loop, inspiration is drawn first, starting at the point where the two axes intersect (A). Properly positioned, the volume axis should intersect the pressure axis at a point representing the patient’s baseline, or PEEP, pressure. Figure 54 represents the axes of a P-V plot with the volume axis positioned at a PEEP of 3 cm H₂O (B). The baseline setting for the plot is displayed to the left of the plot grid.

Inspiratory Area

The box to the right of the plot grid displays a numerical value that represents the calculation of the area of the loop to the left of the volume axis. With the baseline set correctly, the inspiratory area gives an approximation of the work imposed by the ventilator. The higher the number, the greater the work imposed by the ventilator. This calculated value may change from breath to breath.
Breath Types
Pressure-Volume loops are plotted differently for mandatory and spontaneous breaths.

Mandatory Breaths

FIGURE 55: Mandatory Breath
The loop in Figure 55 represents a mandatory breath. It is plotted in a counterclockwise direction, starting at PEEP, with inspiration (A) being drawn first, then exhalation (B). Since mandatory breaths normally result in the delivery of pressures greater than PEEP, the loop is drawn to the right of the volume axis, in the positive pressure area of the grid. The end of inspiration (C) reflects both the peak inspiratory pressure and the delivered volume for that breath. After inspiration is finished, the expiratory portion of the loop (B) reflects pressure and volume changes as the patient exhales, with the volume returning to zero and the pressure returning back to PEEP.
Spontaneous Breaths

The loop in Figure 56 represents a spontaneous breath. It is also plotted in a counterclockwise direction. The letter A represents inspiration and B represents exhalation.

![Figure 56: Spontaneous Breath](image)

Assisted Breaths

Assisted breaths, as shown in Figure 57, begin plotting clockwise due to the patient’s initial inspiratory effort (A). When the ventilator begins to deliver flow to the patient, the pressure becomes positive and the plot direction shifts to counterclockwise. Note the characteristic “trigger tail” of the assisted breath P-V loop.

![Figure 57: Assisted Breath](image)
Bi-Level Ventilation Without Spontaneous Breathing

Figure 58 shows Bi-Level ventilation without spontaneous breathing at PEEP$_H$, resulting in a typical mandatory breath P-V loop.

![Bi-Level Ventilation Graph](image)

**FIGURE 58: Bi-Level Ventilation**

Bi-Level/APRV Ventilation With Spontaneous Breathing

In most cases the P-V loop will represent one complete breath cycle (inspiration and exhalation). Since Bi-Level ventilation and APRV allow spontaneous breathing during TIME$_H$, the P-V loop for a patient breathing spontaneously with Bi-Level (or APRV) will likely show the mandatory inspiration and a short expiratory phase at PEEP$_H$ (Figure 59) that is displayed just before a spontaneous inspiratory effort is made.

![Bi-Level APRV Graph](image)

**FIGURE 59: Bi-Level/APRV With Spontaneous Breathing**
FIGURE 60: Bi-Level/APRV With Spontaneous Breathing

It is also common to see a P-V loop that represents only the spontaneous breath taken at PEEP$_H$. This appears as a small loop beginning and ending in the upper right area of the P-V axes (Figure 60), since the breath actually begins and ends at a pressure greater than the PEEP$_L$.

**Applications**

Pressure-Volume loops may be used to detect the following:

- Inspiratory area calculations
- Work to trigger a breath
- Changes in compliance and resistance
- Lung overdistention
- Adjustments to pressure support
- Inflection points
- Adequacy of peak flow rates
Assessing the Work to Trigger a Breath

**FIGURE 61: Assessing the Work to Trigger a Breath**

Figure 61 shows a P-V loop for a pressure-triggered, mandatory breath. If the ventilator is set correctly (i.e., the inspiratory flow meets the patient’s demands), then the inspiratory area calculation is an estimate of the work to trigger a breath. The larger the “trigger tail,” with its higher inspiratory area value, the more work the patient is doing to trigger the breath from the ventilator.

**FIGURE 62: Assessing Work to Trigger**

Figure 62 shows a pressure-triggered, mandatory breath with a pressure sensitivity that is too high, and therefore imposes more work on the patient to trigger a breath. The higher inspiratory area value and the larger “trigger-tail” suggest that the pressure sensitivity is too high. Optimizing the pressure sensitivity will decrease the work to trigger, resulting in a lower inspiratory area value and a smaller “trigger-tail.”
Assessing Compliance

**FIGURE 63: Compliance Changes**

Figure 63 shows a typical pressure-volume loop for a mandatory breath. The slope (or steepness) of the loop reflects the relationship between volume and pressure, or compliance. A change in the slope of the P-V loop indicates a change in compliance. A shift in slope toward the pressure axis (A) indicates a decrease in compliance, while a shift toward the volume axis (B) indicates an increase in compliance.

Assessing Decreased Compliance

**FIGURE 64: Compliance Changes – Decreased Compliance**

Figure 64 shows a shift in slope of the P-V loop toward the pressure axis (A). This graphically illustrates an increase in the pressure required to deliver the same volume, hence a decrease in compliance.
**Assessing Resistance**

**FIGURE 65: Assessing Resistance**

Figure 65 shows a P-V loop with an increased “bow” to the inspiratory curve (A). An increase in the bowing of either limb of the P-V loop may indicate an increase in resistance to flow. An increase in bowing of the inspiratory curve may also indicate excessive inspiratory flow. An increased bowing of the expiratory curve (B) often indicates an increase in expiratory resistance.

**Detecting Lung Overdistension**

**FIGURE 66: Lung Overdistention**

Figure 66 shows a P-V loop during a mandatory breath in which a decrease in compliance occurs toward the end of inspiration. This is represented by a flattening of the inspiratory curve (A) and is the result of alveolar overdistention. As inspiration proceeds and the alveoli begin to exceed their volume capacity, their compliance begins to decrease, displaying an increase in pressure with little or no corresponding volume increase.
FIGURE 67: Effect of Flow Waveforms

Figure 67 shows a P-V loop (dotted lines) during a mandatory breath that is characteristic of a square flow waveform often used with volume control ventilation. Note the uniform nature of the bowing of the inspiratory curve as lung compliance changes with a constant flow delivery.

Using a decelerating flow waveform, or ramp, to deliver the breath will often cause a distortion of the inspiratory curve (A) as pressure increases rapidly during the early part of inspiration when flow is highest, and decreases as the flow decelerates. This increase in inspiratory bowing resulting in a flattened curve at the beginning of inspiration may be misinterpreted as a lower inflection point. Inflection point assessment of the P-V loop to estimate the critical opening pressure of the alveoli must be done using a low flow or static technique to eliminate the effect of flow on inspiratory pressure changes.

Adjusting Inspiratory Flow

FIGURE 68: Insufficient Inspiratory Flow
Figure 68 shows a P-V loop during a mandatory breath that displays the characteristic “figure eight” often seen if inspiratory flow is set too low to meet the patient’s demands, or a descending ramp flow waveform results in inadequate end-inspiratory flow. As the patient’s demand begins to outstrip the flow delivery of the ventilator, the pressure starts to decrease (A) while volume continues to increase. Exhalation becomes slightly positive at the beginning (B) and then assumes a normal configuration as the lungs empty.

Detecting Air Leaks or Air Trapping

**FIGURE 69: Air Leaks or Air Trapping**

Figure 69 shows a P-V loop for a mandatory breath in which expiratory volume fails to return to zero. This can be the result of air leaks (cuff or circuit leaks, chest tubes, bronchopleural fistula) or air trapping.
**Figure 70: Typical Flow-Volume Loop**

Figure 70 shows a typical flow-volume loop. The peak expiratory flow rate is noted at (A); peak inspiratory flow rate is noted at (B). Flow is plotted on the vertical axis and volume on the horizontal. The lower half of the loop represents inspiration; the upper half represents exhalation. The loop arrangement resembles that of a pulmonary function test, in which exhalation is plotted first followed by the next inspiration.

**Application**

The flow-volume loop may be helpful in gauging the effects of bronchodilators on patients.

**Evaluating the Effect of Bronchodilators**

**Figure 71**
Pre-Bronchodilator Flow-Volume Loop

**Figure 72**
Post-Bronchodilator Flow-Volume Loop
Figures 71 and 72 show pre- and post-bronchodilator flow-volume loops that indicate a positive response to the bronchodilator administration. The flow-volume loop before bronchodilator administration shows a low peak expiratory flow rate (A) and a scalloped shape near the end of exhalation (B) that is characteristic of poor airway conductivity. The post-bronchodilator loop shows an improved peak expiratory flow (C) as well as improved flow toward the end of exhalation (D).