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The Basics of Ventilator Waveforms

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Abstract

Purpose of Review Knowledge of ventilator waveforms is important for clinicians working with children requiring mechanical ventilation. This review covers the basics of how to interpret and use data from ventilator waveforms in the pediatric intensive care unit.

Recent Findings Patient-ventilator asynchrony (PVA) is a common finding in pediatric patients and observed in approximately one-third of ventilator breaths. PVA is associated with worse outcomes including increased length of mechanical ventilation, increased length of stay, and increased mortality. Identification of PVA is possible with a thorough knowledge of ventilator waveforms.

Summary Ventilator waveforms are graphical descriptions of how a breath is delivered to a patient. These include three scalars (flow versus time, volume versus time, and pressure versus time) and two loops (pressure-volume and flow-volume). Thorough understanding of both scalars and loops, and their characteristic appearances, is essential to being able to evaluate a patient's respiratory mechanics and interaction with the ventilator.

Keywords Ventilation · Waveforms · Graphics · Scalars · Loops · Pediatric

Introduction

Mechanical ventilation is a widely used therapeutic modality in the pediatric intensive care unit (PICU). Clinicians who take care of PICU patients must not only have a thorough understanding of the different ventilators and their function but also knowledge of how those ventilators can interact with the patient. Conventional ventilators used today provide for evaluation of respiratory mechanics with graphics. These graphics, or waveforms, can tell the bedside clinician important information about airway resistance, lung compliance, and patient-ventilator synchrony. Therefore, it is important that clinicians using mechanical ventilation have a thorough understanding of ventilator waveforms and their interpretation.

Ventilator Mode Basics

Before reviewing the graphics associated with mechanical ventilation, it is important to understand the concepts of how ventilators can deliver breaths. A mechanical breath is classified based on three main variables—how the breath starts, how the breath is delivered by the machine, and how the breath is stopped [1]. A breath can be started by either the patient (referred to as a supported or assisted breath) or by the machine (referred to as a controlled breath). This variable is also referred to as the trigger. After the breath is started, the gas is delivered to the patient in a set pattern that is sustained throughout the course of inspiration. This is also referred to as the target variable. The two main target variables are either a specific inspiratory flow rate or a pressure goal. The delivery of the breath is stopped when a certain amount of time has elapsed, a goal amount of volume has been inspired, or the ventilator senses a decrease in the flow taken in by the patient. This is the cycle variable [1, 2]. Any combination of the above variables can define the type of breath delivered by the machine.

Scalars

Now that we have reviewed the basic ways breaths are delivered from a ventilator, it is important to understand how those

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breaths are represented in graphical form. The first of these graphics are termed scalars. Scalars on conventional mechanical ventilators are representations of specific respiratory parameters over time. The three scalars commonly utilized are volume, pressure, or flow plotted on the vertical *y*-axis against time plotted on the horizontal *x*-axis. Pressure and flow are measured values, while the volume of each breath is a calculated value. Each scalar represents the entire breath from the beginning of inspiration to the end of expiration. Most ventilators have these three scalars displayed on the main screen [3]. Ability of the bedside clinician to interpret these scalars remains essential to understanding a patient's ventilation.

Volume Versus Time Scalar

The volume versus time scalar is the graphical representation of the amount of gas delivered into the lungs by the ventilator over time. It is calculated from the measurement of flow. The upslope is the inspiratory volume and the downslope is the expiratory volume (Fig. 1) [4]. Inspiratory and expiratory volumes should be similar, and differences can indicate air leaks in the system or intrinsic positive end-expiratory pressure (i.e. auto-PEEP or air trapping) [5•]. This is shown when the part of the curve representing expiration decreases as expected but plateaus and never reaches the baseline of zero volume before the next breath [6, 7]. In addition to showing potential air leaks or trapping, the volume versus time scalar can be used to evaluate the volume of a patient's spontaneous breath and the effect adjustment of the ventilator settings may have on tidal volume [3].

Flow Versus Time Scalar

Gas flow in between the patient and the ventilator is represented by the flow versus time scalar. Inspiratory flow is a positive value on the graph, whereas expiratory flow is a negative value. The area under the curve represents the volume moved during the phases of breathing [5•]. The shape of the inspiratory limb of the curve depends on the mode of ventilation. In pressure-targeted modes, the peak inspiratory pressure (PIP) and inspiratory time are set and flow is variable. At the beginning of the breath, flow is delivered at a high rate but then tapers off over the course of inspiration, resulting in a decelerating shape of the curve (Fig. 2a) [8••]. Pressure-supported modes may also have a flow pattern that is decelerating or sinusoidal in shape. In volume control or flow-targeted modes, the tidal volume, inspiratory time, and inspiratory flow are set resulting in a constant flow or square shape to the flow scalar (Fig. 2a). The use of one type of flow pattern versus another is usually clinician preference. In volume control modes, flow is constant until the goal tidal volume is achieved, resulting in a constant rise in the pressure and a higher PIP, but a lower mean airway pressure. A clinician wanting to minimize mean airway pressure may choose this mode of ventilation for this reason. In pressure control modes, since a specific PIP is delivered for a period of time, the overall PIP is lower but the mean airway pressure is higher. This may be beneficial in situations with increased airway resistance [5•, 8••].

In addition to helping identify the mode of ventilation, the flow versus time scalar can provide useful information about a patient's exhalation. The shape of the expiratory limb of the curve is affected by the resistance to air flow and the compliance of the lung. In instances of higher airway resistance from some obstructive process, the flow scalar will show a decreased peak expiratory flow and a prolonged time for the expiratory curve to return to a baseline of zero flow (Fig. 2b) [5•]. All of this represents that the resistance to airflow is limiting how fast and how much volume the lung empties. Conversely, when compliance is decreased, the peak expiratory flow rate increases [9••].

Air trapping or auto-PEEP (also referred to as intrinsic PEEP) can also be identified on the flow scalar. Under normal

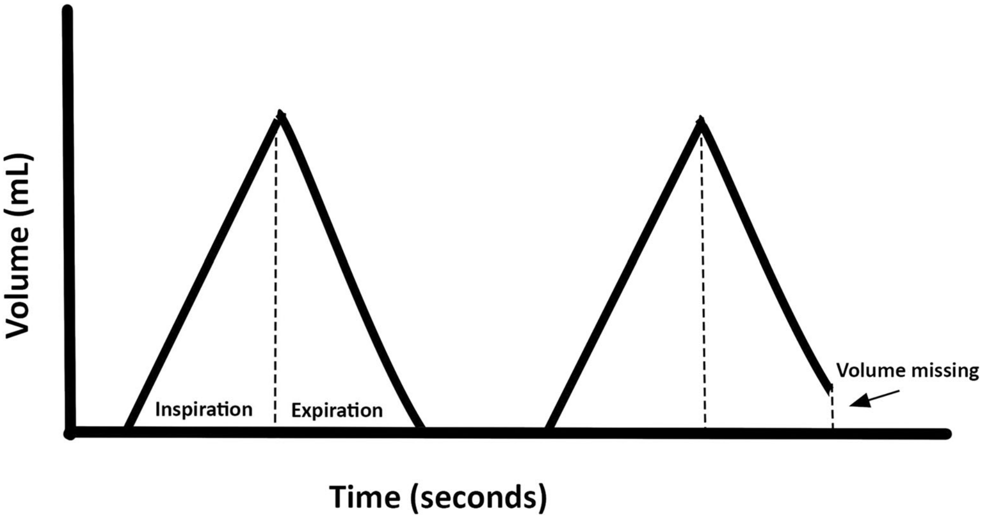


Fig. 1 Volume versus time scalar. The volume versus time scalar showing the volume of air upon inspiration and expiration. The second scalar shows a sudden drop off in volume, representing a potential air leak

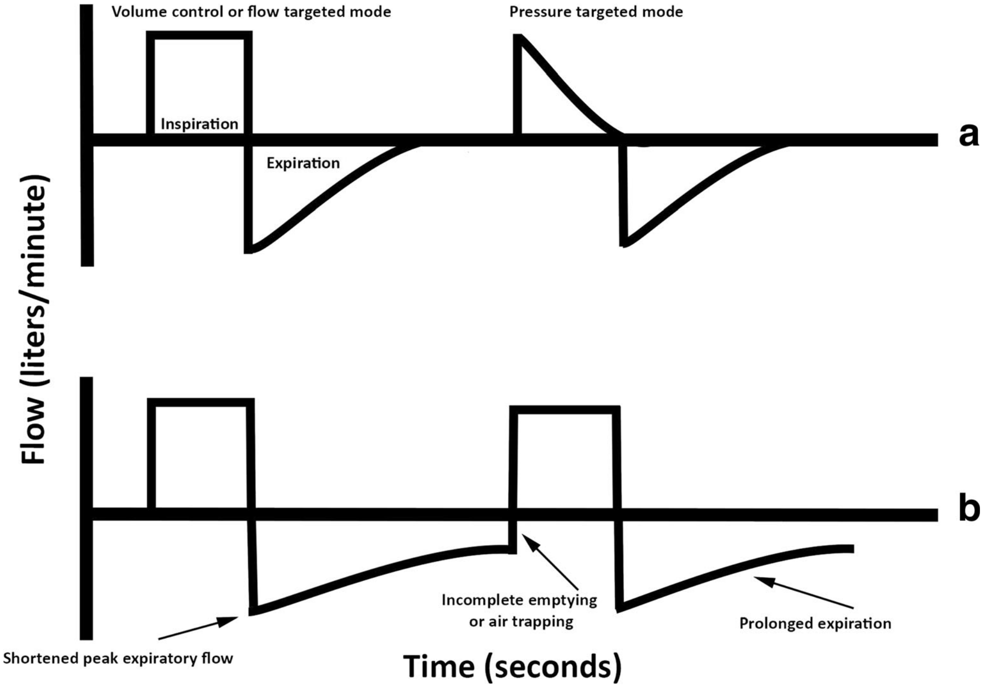


Fig. 2 Flow versus time scalar. **a** The first scalar represents the square waveform pattern in volume control. The second scalar shows a decelerating pattern in pressure control. **b** Examples of scalars with flow waveform abnormalities representing changes to airflow resistance or obstruction

conditions, the expiratory limb of the curve returns to a baseline of zero flow prior to the next breath being initiated. However, if expiration of air is still ongoing when inspiration starts, then the lungs are not emptying completely and air trapping occurs. This is shown in the scalar when the expiratory limb does not return to baseline before the new breath starts (Fig. 2b) [3, 5•, 6, 9••].

Pressure Versus Time Scalar

The pressure scalar provides a good information about airway compliance to the clinician. It represents the pressure in the airway as a function of time. This can be a fixed or variable amount depending on the mode of ventilation [5•]. During pressure control ventilation, the pressure delivered is constant and the pressure scalar is square-shaped. In volume control ventilation, the pressure scalar is ascending due to the rise in pressure with a constant flow pattern [6, 7, 9••]. In the typical graphic displayed on the ventilator, the baseline pressure indicates the PEEP and the maximum pressure at the end of the curve indicates the PIP (Fig. 3a).

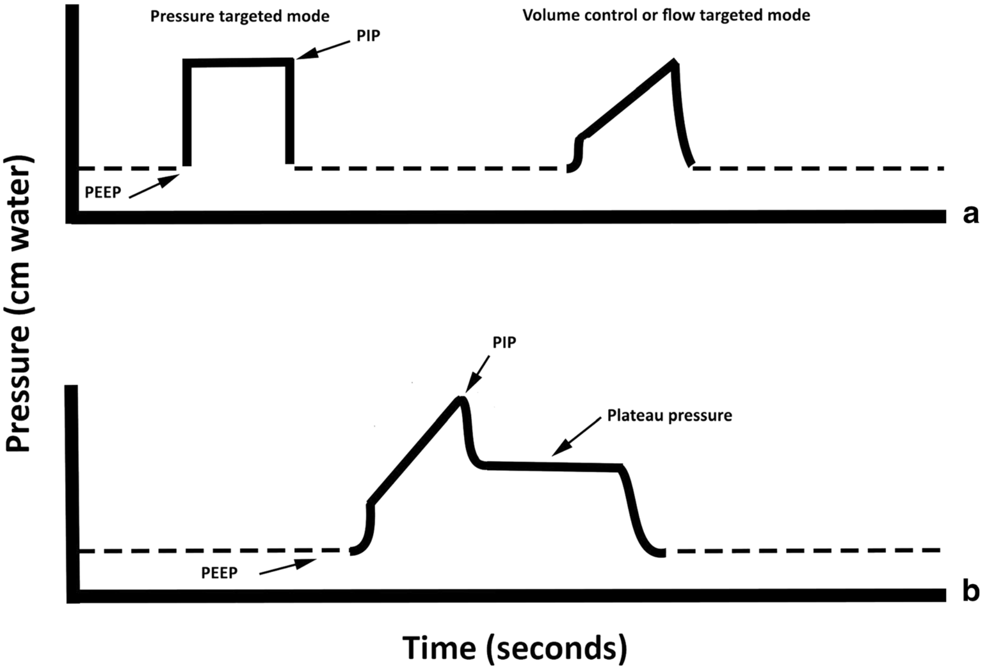
In addition to the PIP and the PEEP, the pressure versus time scalar can show a few other pressure measurements when specific ventilator maneuvers are done. The first is the plateau pressure (P_{plat}) (Fig. 3b). This is the pressure in the airway under static conditions, or when there is no air flow. PIP is mathematically calculated by adding the pressure created by airway resistance, the pressure related to the lung's compliance, and the total PEEP. When there is no flow in the system, the pressure due to airway resistance drops to zero, and the resultant value is the P_{plat}. This value is thought to represent the pressures at the alveolar level, and is obtained by doing an inspiratory hold on the ventilator [5•, 8••]. It is best measured in a volume control mode as compared to a pressure control mode, although can be measured in both. Volume-targeted modes use constant flow and therefore have a larger pressure differential between PIP and P_{plat} when an inspiratory hold maneuver is completed and flow abates. In contrast, during pressure-targeted ventilation, the descending flow pattern means flow is nearing zero during inspiration, allowing for less of a pressure drop when inspiration is held. Regardless of mode the P_{plat} is measured in, a large difference between the PIP and the P_{plat} indicates high resistance in the airway as can exemplified in severe bronchospasm [5•]. Use of a P_{plat} target in adults with acute respiratory distress syndrome (ARDS), along with a low tidal volume strategy, has been shown to be beneficial for improved outcomes [10–12]. However, studies in pediatric acute respiratory distress patients have not shown the same benefits of protective lung ventilation [13, 14].

An additional pressure measurement that can be obtained from the pressure versus time scalar is the intrinsic PEEP. This is obtained by completing an expiratory hold maneuver on the ventilator.

Stress Index

Another useful measurement that can be calculated from the pressure versus time scalar is the stress index. This is a coefficient derived from the pressure scalar during volume-controlled ventilation. It is usually calculated by the ventilator software; however, methods of stress index assessment through visual analysis of the pressure scalar have been

Fig. 3 Pressure versus time scalar. **a** The first scalar represents a control breath. The second scalar represents a volume control breath. Peak inspiratory pressure (PIP) and positive end-expiratory pressure (PEEP) are shown. **b** A graphical depiction of plateau pressure



described [9••, 15•]. This measure is based on the theory that in normally compliant lungs, pressure rises at a constant rate with a constant rise in volume. This equates to a stress index of one and a scalar with a straight slope. A decrease in the slope of the scalar is consistent with a stress index less than one, giving it a downward curved shape. This suggests improvement in compliance and recruitment of the lung with increasing volume. An increase in the scalar's slope resulting in an upward curved shape, or a stress index greater than one, is seen when the lung compliance is worse with a rise in volume. This may indicate overdistension of the lung [1]. Studies titrating both PEEP and tidal volume toward an optimal stress index have shown this to be an effective method of lung recruitment [9••].

Loops

The next ventilator graphics that are important to understand are the loops. These graphics are one of the two variables, either pressure or flow, plotted against the volume during a breath. Each loop consists of an inspiratory and expiratory curve and allows for evaluation of respiratory mechanics [5•, 9••, 16]. There are two loops—the pressure-volume curve and the flow-volume curve.

Pressure-Volume Curve

The pressure-volume loop shows pressure (in cm water) plotted along the *x*-axis and volume (in mL) along the *y*-axis (Fig. 4a). The curve starts in the lower left corner near the origin of the graph, with this point representing functional residual capacity. If PEEP is present, then the curve begins at that level of pressure along the *x*-axis. As inspiration progresses, the curve rises in a counterclockwise direction until it ends in the upper right hand corner when either the goal volume or pressure is reached. The inspiratory limb of the curve takes on a sigmoidal shape, with an initial flat part indicating movement of air into collapsed airways with low compliance, the middle steep part indicating lung recruitment, and the flattening of the curve again representing the end of inspiration [17]. Rapid changes to the slope of the limb, called inflection points, signify instances where compliance changes suddenly. A lower inflection point (LIP) correlates to the opening of collapsed alveolar units and a sharp rise in volume. The steep part of the curve after the LIP occurs when compliance is high and increased volume into the airways leads to a minimal increase in pressure. An upper inflection point (UIP) occurs at the end of inspiration when accumulation of more pressure leads to minimal increase in volume, compliance is low again, and the curve may take on a beaking appearance representing overdistension (Fig. 4b) [5•, 16, 17]. Inflection points are more easily appreciated in volume control modes than in pressure-targeted modes [8••]. Once exhalation begins, the curve continues in a counterclockwise direction, but starts its descent back to the origin. The shape of the graph in a ventilated patient under ideal conditions resembles a football and the slope of the whole loop correlates to lung compliance [5•, 6, 16]. When the slope of the curve is flatter, this represents decreased compliance. Conversely, a steeper slope to the curve indicates increased compliance [5•].

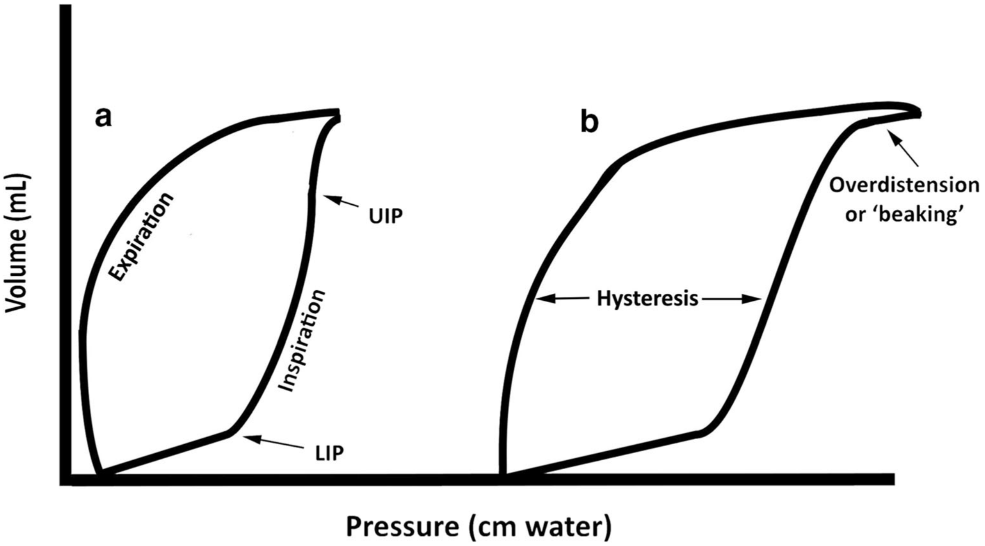


Fig. 4 Pressure-volume loop. **a** Pressure-volume loop showing a typical pattern. The lower inflection point (LIP) and upper inflection point (UIP) are shown. **b** The representations of overdistension and hysteresis in a pressure-volume curve

The use of inflection points to prescribe ventilator settings that allow for a lung protective strategy has been described [16, 18–20]. It has been suggested that setting the PEEP just above the LIP in ARDS patients may lead to less barotrauma and improved survival [18]. Another recommendation is to aim for ventilating patients between the LIP and UIP on the curve [6]. However, these recommendations remain controversial as there are limitations to using the pressure-volume curve in this way [9••, 19].

Another important feature of the pressure-volume curve is called hysteresis (Fig. 4b). In the respiratory system, hysteresis is failure of the lung tissue to act the same with inspiration and expiration. It takes more energy to inflate the lungs than to deflate them, representing that the lung volume at any given pressure is different depending on the phase of ventilation. This is shown in the pressure-volume curve as the inflation and deflation limbs taking on different shapes, with hysteresis representing the area between the two limbs. Hysteresis in the lungs is related to alveolar air-liquid surface forces and the opening and closing of alveoli [19, 21, 22]. Changes in resistance to air flow will affect the hysteresis, with the curve appearing wider with increasing resistance. It may be possible to identify changes to either inspiratory or expiratory resistance, therefore identifying potential etiologies of ventilatory changes, by comparing the shape of successive pressure-volume curves [8••].

Flow-Volume Curve

The flow-volume loop describes how air flows in and out of the lungs during a breath. In this graph, the volume (in milliliters) is on the *x*-axis and the flow rate (in liters/min) is on the *y*-axis. Conventionally, during pulmonary function testing, inspiration is below the *x*-axis and expiration is above. However, this is often reversed on ventilators with the inspiratory limb of the curve on top and the expiratory limb on the bottom (Fig. 5a). This is dependent of ventilator software, and clinicians should be familiar with the orientation of their graph to properly interpret it [3, 5•, 6]. Further discussion of this curve will assume that inspiration is above the *x*-axis and expiration is below. With the first breath, the inspiratory limb starts at the intercept of the *x*- and *y*-axes, where both flow and volume equal zero, and travels in a clockwise fashion. As the volume rises, and the curve travels along the both axes further, flow also increases. Volume continues to rise as flow starts to decrease, with the curve continuing on the *x*-axis but changing directions on the *y*-axis. Once the flow reaches zero, when the curve crosses the *x*-axis, inspiration is over and expiration begins. The curve continues moving in a clockwise fashion, this time with volume decreasing, as flow increases and then decreases similarly to before. The curve is complete when both volume and flow reach zero, signifying the end of expiration, completion of the breath, and complete emptying of volume inspired. The shape of the inspiratory portion of the curve is often dependent on the mode of ventilation. For example, in volume-controlled or flow-targeted modes, since flow remains the same throughout inspiration, this limb takes on a square shape. In pressure-controlled modes, flow is represented as descending as volume increases during inspiration [5•, 8••].

Several important pieces of information about air flow in and out of the lungs can be obtained from evaluation of the flow-volume loop, particularly the expiratory limb. First, the loop provides for measurement of a peak expiratory flow rate. A lower peak expiratory flow rate indicates potential obstruction, such as can be seen with bronchoconstriction. Also seen in this situation is an expiratory limb with more concavity or a "scooped out" appearance, representing lower flows at a given volume, as would be expected with an obstructive process (Fig. 5b). The expiratory limb may also show air trapping when it does not return to zero along the *y*-axis, or return to

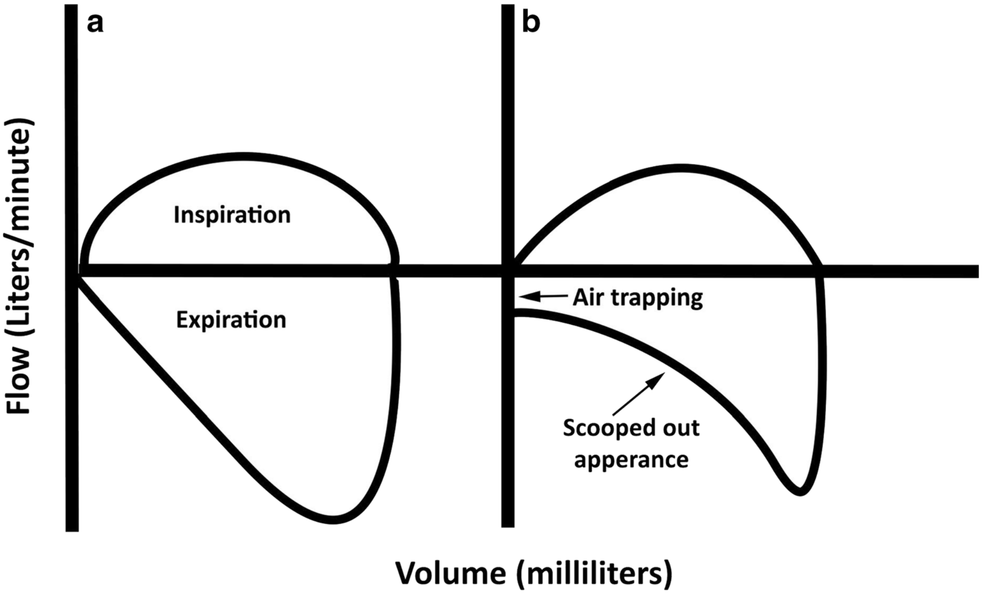


Fig. 5 Flow-volume loop. **a** A typical flow-volume loop with inspiration on the top and expiration on the bottom. **b** A flow-volume loop showing an obstructive air flow pattern with lower peak expiratory flow, a scooped out expiratory limb, and air trapping

zero flow, before another breath is started. In addition to information about airway obstruction, air leak may be identified when the volumes in the inspiratory and expiratory sides of the curve are different. This may be seen when flow drops to zero suddenly, but volume does not [5•, 6, 8••, 16].

Ventilator Waveforms and Synchrony

Now that the basics of ventilator waveform structure and meaning have been explained, it is important to understand how the application of this knowledge can be used at the bedside. When a clinician is able to properly interpret these graphics, it can show them how well, or poorly, the patient is interacting with the ventilator. When a patient is interacting poorly with the ventilator, this is called asynchrony [23•, 24, 25]. Patient-ventilator asynchrony (PVA) can be associated with negative side effects including increased sedation needs, increased work of breathing, ventilation-perfusion mismatch, increased dynamic hyperinflation, and slower weaning [26]. It can also be associated with worse outcomes including increased length of mechanical ventilation [27, 28], increased length of stay [28], and increased mortality [29•]. Pediatric patients experience PVA frequently, with recent studies showing an incidence in about one-third of mechanical breaths [23•, 24•]. Ventilator graphic interpretation has been utilized as a tool to detect PVA [27, 28], and therefore may play a role in helping the clinician optimize ventilator settings to allow for improved synchrony and outcomes.

Asynchronies Related to Breath Initiation

The first type of asynchrony is associated with the initiation, or trigger, of a breath. This occurs when the ventilator fails to respond to a patient's effort to take a breath. There are several types of trigger asynchronies including ineffective triggering leading to delayed or missed breaths, double triggering, and auto-triggering [30, 31, 32••]. When a patient initiates a breath, but the machine fails to recognize this attempt appropriately and either a breath is delayed or not given at all, this is referred to as ineffective triggering. This can be seen on the flow versus time waveform as a deflection from the baseline expiratory flow with either a minimal decrease in airway pressure or no change at all, and no breath delivered (Fig. 6a) [8••, 31, 32••, 33]. The easiest way to troubleshoot this issue is to look at how sensitive the trigger is set on the machine and adjust it to make it easier for the patient to initiate a breath. Another potential etiology of ineffective triggering is the presence of intrinsic PEEP (or auto-PEEP), a pressure that must be offset by the patient's effort before the ventilator will recognize the patient is triggering a breath. The higher the intrinsic PEEP, the more pressure that will need to be overcome. Interventions designed to decrease intrinsic PEEP (increasing time of expiration or decreasing resistance to airflow with bronchodilators) or increase external PEEP may help decrease the amount of ineffective triggering [32••, 33].

Another type of asynchrony associated with the initiation of a breath is double triggering. This is when a patient wants to take a breath with a longer inspiratory time than the ventilator settings, which may result in a second breath being triggered immediately after the first. This can be seen on all three scalars as one breath being followed immediately by a second without any time for exhalation (Fig. 6b) [8••, 30, 32••]. This can usually be improved by matching the patient's inspiratory demands better (e.g., increasing the inspiratory time, increasing the tidal volume).

Reverse triggering may look similar to double triggering on ventilator graphics. This happens when the

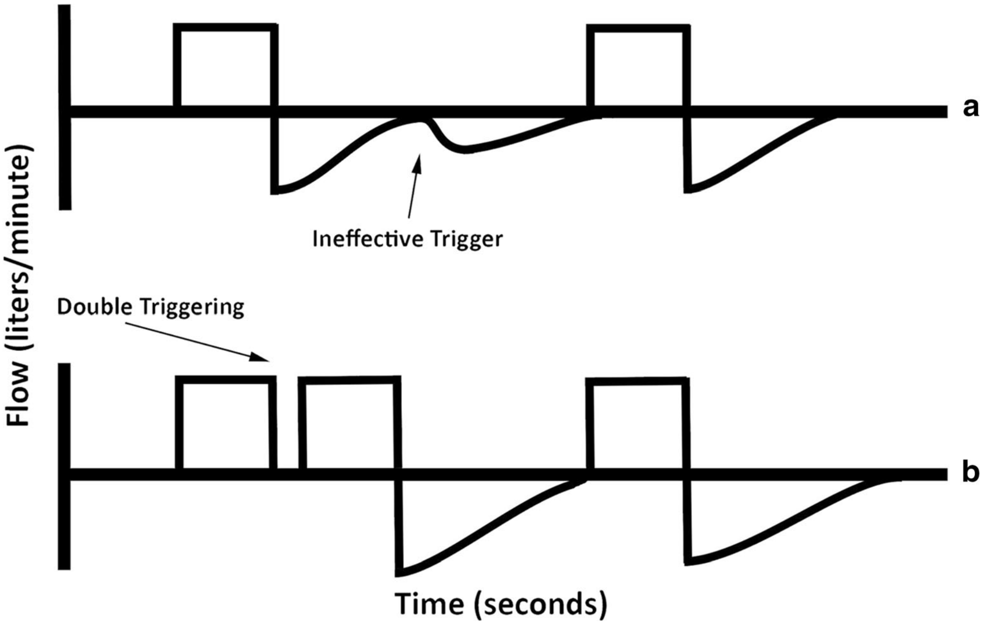


Fig. 6 Trigger asynchrony. **a** Ineffective trigger shown as a deflection from the baseline expiratory flow and no breath delivered. **b** Double triggering shown as a second breath being triggered immediately after the first

ventilator breath leads to contraction of the diaphragm that may be interpreted by the machine as the patient initiating a breath. It is often seen in patients under heavy sedation. This may be shown as more volume or flow on the scalars at the end of a ventilator delivered breath, or may look like another breath triggered before the first breath's cycle is complete [34].

The last type of triggering asynchrony is called auto-triggering (also called auto-cycling). This occurs when multiple breaths are delivered by the ventilator that were not initiated by the patient. Some etiologies of auto-triggering include air leaks in the system, inappropriately set trigger sensitivity, condensation in the ventilator tubing, or detection of cardiac movement [8••, 30, 31, 32••]. It can be seen in all three scalars as full ventilator breaths given rapidly, resembling tachypnea. When looking at the pressure versus time scalar, the lack of an initial dip in the pressure at the beginning of a breath may be a sign of auto-triggering [33].

Asynchronies Related to Flow

When a patient is not receiving as much flow as they would like from the ventilator with each breath, this is one type of asynchrony termed flow starvation. It can be identified by a

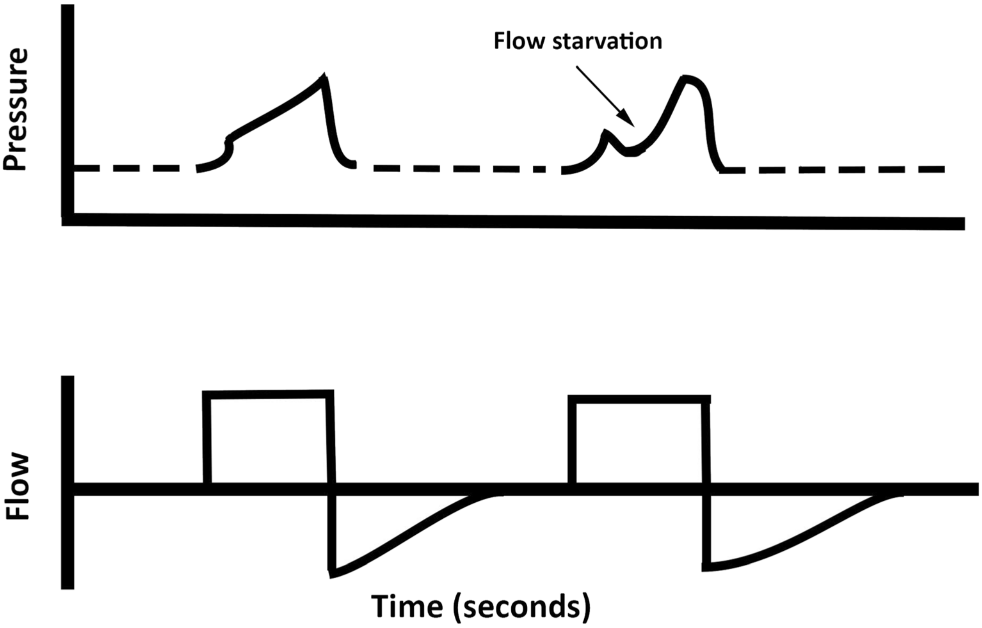


Fig. 7 Flow starvation. An example of flow starvation with a dip seen in the pressure scalar and no associated changes in the flow scalar

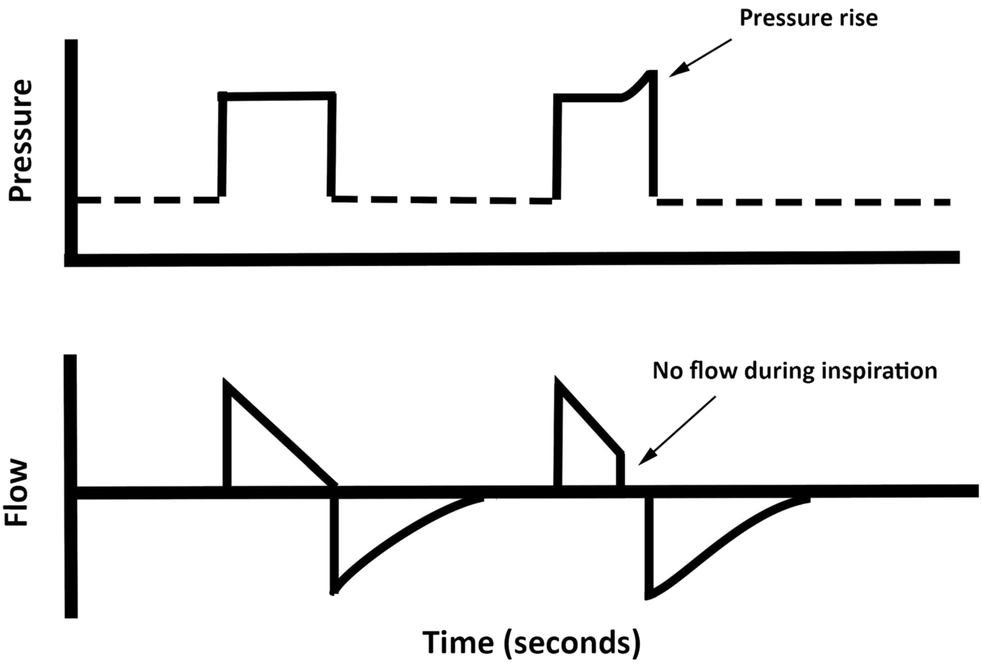


Fig. 8 Delayed cycling. Example of delayed cycling shown as a pressure rise with period of no flow at the end of a breath

dip in the pressure versus time scalar without associated changes in the flow or volume scalars (Fig. 7) [31, 32••]. This represents that the patient is generating more negative pressure to be able to pull more volume, but is not getting enough to meet their needs. It is often due to inadequately set flow on the ventilator. It is more often seen in modes where flow is constant as in volume control modes [8••, 31]. Increase of the set flow or changing to a non-constant flow pattern may fix this problem.

Asynchronies Related to Cycling

These asynchronies are related to the inspiratory time either being too short or too long compared to the patient's desired inspiratory time. When the ventilator stops a breath before the patient's inspiratory effort has finished, this is called premature cycling. It can be seen on the flow versus time scalar as an additional upward deflection after inspiration is completed by the ventilator. It may also result in double triggering and an added breath as described above [8••]. Changes to the delivered flow or inspiratory time can help fix premature cycling.

Conversely, when the ventilator's set inspiratory time is too long compared to the patient's inspiratory time, this is referred to as delayed cycling. It results in a patient trying to exhale while inspiration is still occurring, and being unable to do so, there is a rise in pressure at the end of the pressure versus time scalar and a period of zero flow during inspiration (Fig. 8). It can also be fixed by adjusting the flow rate or inspiratory time, depending on the mode of ventilation [32••].

Conclusion

Modern ventilators provide multiple graphics that help guide the clinician in evaluation and management of respiratory failure. In addition to describing the basics of how a breath is delivered to a patient, these graphics also give valuable information regarding how well a patient is interacting with the ventilator. A detailed understanding of ventilator waveforms and the ability to identify alterations in them that may indicate asynchrony is crucial to the clinician taking care of patients requiring mechanical ventilation.

Compliance with Ethical Standards

Human and Animal Rights This article does not contain any studies with human or animal subjects performed by any of the authors.

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