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Ventilator waveform interpretation in mechanically ventilated small animals

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Abstract

Objective – To review the topic of ventilator waveforms analysis with emphasis on interpretation of ventilator waveforms and their use in the management and monitoring of mechanically ventilated small animal patients.
Data sources – Human clinical studies, scientific reviews, and textbooks, as well as veterinary textbooks and clinical examples of ventilator waveforms in mechanically ventilated dogs.
Summary – Ventilator waveforms are graphic representations of data collected from the ventilator and reflect patient-ventilator interactions. The 4 parameters pressure, volume, flow, and time are most descriptive of mechanical ventilation. Typically, 3 different graphs, also referred to as scalars, consisting of pressure versus time, volume versus time, and flow versus time, with time always plotted on the x-axis, are used. Changes in the ventilator settings as well as in the characteristics of the lungs such as airway resistance (R_{aw}) and respiratory system compliance (C_{rs}) can be recognized from specific variations in the waveforms. Flow-volume and pressure-volume loops provide additional information about changes in lung function. Patient-ventilator dyssynchrony is a common problem during mechanical ventilation and can lead to patient discomfort and an increased work of breathing. Ventilator waveforms are helpful to identify dyssynchrony, which can be divided into trigger, flow, cycle, and expiratory dyssynchrony. Ventilator waveforms allow the clinician to assess changes in respiratory mechanics, and can be useful in monitoring the progression of disease pathology and response to therapy. Adjustments in ventilator settings based on proper analysis and interpretation of these waveforms can help the clinician to optimize ventilation therapy.
Conclusions – Ventilator waveforms are graphic representations of patient-ventilator interactions. Proper interpretation of ventilator waveforms affords the critical care clinician a better understanding of the patient's respiratory function, response to therapy, and causes for patient-ventilator dyssynchrony. Ventilator waveform interpretation is an important tool in the assessment and management of mechanically ventilated small animal patients.

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Keywords: monitoring, patient-ventilator dyssynchrony, respiratory dysfunction

Introduction

Ventilator waveforms are graphic representations of data collected from the ventilator that reflect patient-ventilator interactions. Ventilator waveforms allow the clinician to assess changes in respiratory mechanics, and can be useful in monitoring the progression of disease pathology and response to therapy. Adjustments in ventilator settings based on proper analysis and interpretation of these waveforms can help the clinician to optimize ventilation therapy.

When analyzing ventilator waveforms it is important to understand how they are created and which variables affect them. This review intends to provide the critical care clinician with the basic knowledge to analyze and interpret ventilator waveforms.

Generation of Signals and Ventilator Data

Present-day mechanical ventilators have the capability to collect a wealth of patient- and ventilator-related data. Microprocessor electronics, through software control, enable mechanical ventilators to orchestrate a wide array of automatically managed functions, one of which being waveform displays of respiratory mechanics.[1] Signals, which represent the behavior of variables of interest, for example, pressure, flow, are the basis for the management of these functions. The variable-to-signal

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transformation consists of signal sensing and signal transduction.

Through analog-to-digital conversion, the signals can be converted into digitalized electronic signals that are useful in the control of the breathing algorithm, as well as in the assessment of alarm threshold violations. The digitalized electronic signals can be converted back into an analog format and displayed on a monitor in the form of numerical values, waveforms, loops, and trends. Furthermore, these data can be stored and later retrieved.[1] It is important to realize that the data collected by the mechanical ventilator are based on estimations rather than on exact measurements and must always be interpreted within the context of the individual patient.

Physiological Terms and Concepts Related to Mechanical Ventilation

Mechanics of spontaneous ventilation

Ventilation is the movement of air into and out of the lungs.[2] The conductive airways begin at the mouth and nose and end in the terminal bronchioles. Air flows through the conductive airways along the pressure gradient from the high-pressure point to the low-pressure point. Lung volumes change as a result of air flow. Air flows into the lungs when the pressure in the alveoli is lower than the pressure at the mouth and nose. Air flows out of the lungs when the pressure in the alveoli is greater than the pressure at the mouth and nose. At the end of inspiration or expiration the pressure in the alveoli and at the mouth and nose are equal. There is no pressure gradient across the conductive airways and air flow ceases. Ventilating pressures are typically measured in centimeters of water pressure (cm H_2O) and referenced to atmospheric pressure with a baseline value of zero.

Basic definitions related to mechanical ventilation

The volume of air entering the lungs with each inspiration is called the tidal volume (V_T) and is expressed in mL or L.[3] The respiratory frequency (f) is the number of respiratory cycles (breaths) per minute.[3] The volume measured in mL or L of air inspired per minute represents the minute ventilation (Vmin). The time required to complete inspiration, that is, inspiratory time (T_I) is determined by the V_T and the flow rate and can be described by the equation $T_I = V_T/\text{Flow Rate}$.[3] Based on this equation an inspiratory flow rate of, for example, 5 L/min (ie, 83 mL/s) with an inspiratory time of 1 s will result in a V_T of about 83 mL. The inspiratory flow rate determines how quickly the breath is delivered and can be expressed in volume per minute or volume per second. The cycle time (T_C), which is the sum of the inspiratory time (T_I) and expiratory time (T_E), depends on the respiratory rate. The expiratory time can be calculated by subtracting T_I from T_C.[3]

Airway pressure (P_{aw}), also called airway opening pressure (P_{awo}), is the pressure measured at the mouth or nose.[4] It is zero (atmospheric) if no pressure is applied. Pleural pressure (P_{pl}) is the pressure within the potential space between the parietal and visceral pleura. An approximation of P_{pl} can be obtained by measuring esophageal pressure.[4–6] During spontaneous breathing the P_{pl} becomes more negative, for example, P_{pl} is about –5 cm H_2O at the end of expiration and about –10 cm H_2O at the end of inspiration.[4,7] Alveolar pressure (P_A) is the pressure inside the alveoli. The negative P_{pl} is transmitted to the alveolar space; therefore, changes in P_{pl} will result in changes in P_A.[4] During spontaneous breathing, the pressure gradient between the mouth and alveolus is about −3 to −5 cm H_2O causing air to flow from the mouth into the alveoli during inspiration.[4] Alveolar pressure during expiration is positive, about +5 cm H_2O, causing air to flow out of the lungs during expiration.[4,7] The P_A is zero (atmospheric) at the end of inspiration or expiration.[7]

During positive pressure ventilation the pressure measured by the manometer rises progressively until it reaches the highest pressure at the end of inspiration. This pressure is called the peak inspiratory pressure (PIP), which is the sum of the pressure required to overcome airway resistance (ie, transairway pressure, P_{TA}) and the pressure necessary to distend the alveoli (P_A).[4]

The plateau pressure (P_{Plat}) is the proximal airway pressure, that is, pressure at the mouth measured during an end inspiratory hold. During an end inspiratory hold, shown in Figure 1, gas flow stops and the pressure at the mouth is equal to the average pressure inside the alveoli.[4] The P_{Plat} is a reflection of the effect of the elastic recoil on the gas volume inside the alveoli and the pressure generated by the recoil of the plastic tubing of the ventilator.[4] It is an approximation of the P_A that cannot be measured directly. The P_{Plat} has been used in place of the P_A to assess the resistance of the airways (R_{aw}) and the static respiratory system compliance (C_{rs}).[4]

The pressure from which a ventilator breath is initiated is called the baseline pressure.[4] The baseline pressure can be zero (ie, atmospheric) or positive. A positive baseline pressure is referred to as positive end-expiratory pressure (PEEP) in the mechanically ventilated patient or continuous positive airway pressure (CPAP) in the spontaneously breathing patient. CPAP refers to maintaining a certain level of positive airway pressure during both inspiration and expiration.[4] Extrinsic and intrinsic PEEP must be differentiated. Extrinsic PEEP (PEEP_E) refers to PEEP intentionally set by the operator through manipulation of the ventilator settings. Intrinsic PEEP (PEEP_I), commonly referred to as

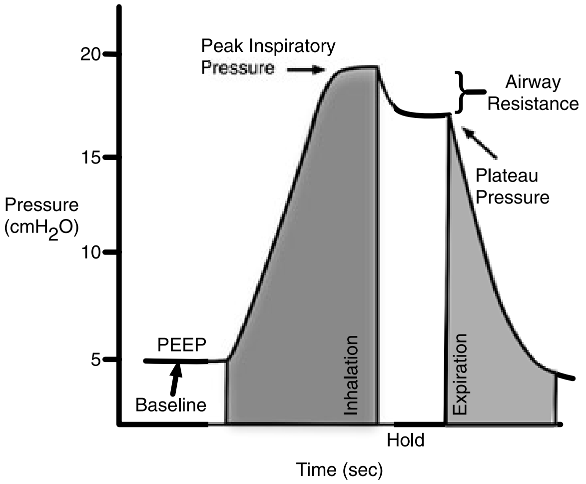

Figure 1: During the inspiratory phase of a positive pressure breath, pressure rises from baseline to a peak inspiratory pressure (PIP). The PIP is the sum of the pressure needed to overcome the resistance of the airways and the pressure needed to distend the alveoli. Airflow through the airways ceases during an inspiratory hold maneuver and transairway pressure becomes zero (in the absence of airflow there is no airway resistance to overcome). PIP during an inspiratory hold maneuver is equal to the plateau pressure, which is an approximation of alveolar pressure. During expiration, airway pressure falls progressively until it returns to baseline pressure at the end of expiration. A positive baseline pressure in the mechanically ventilated patient is called positive end-expiratory pressure (PEEP). Modified from SP Pilbeam, Cairo JM. Mechanical Ventilation Physiological and Clinical Applications. Fourth ed, Mosby Inc; 2006 with permissions.

auto-PEEP, is not set by the operator and occurs when air is inadvertently trapped in the airways.[4] Auto-PEEP typically occurs with short expiratory times, high minute ventilation, and in patients with increased airway resistance resulting in collapse of the small airways before exhalation is complete.[4,8] Clinical conditions that may lead to auto-PEEP secondary to increased airway resistance include small endotracheal tube (ET) size, bronchospasm, increased secretions, and mucosal edema.[4]

Lung characteristics

The 2 main characteristics of the lungs are compliance and resistance.[4] Elastic forces and frictional forces oppose inflation of the lungs.[4] Elastic forces arise from the elastic properties of the lungs and thorax. Frictional forces are the result of resistance of the tissues and organs against movement and displacement during breathing, that is, tissue viscous resistance, and the resistance to gas flow through the airways, that is, airway resistance R_{aw}.[4]

Compliance is the relative ease with which a structure distends. Elastance is the opposite of compliance and describes the tendency of a structure to return to its original form after being stretched.[4] With regard to the respiratory system, elastance refers to the tendency of the lungs and chest wall to recoil after distension. In pulmonary physiology, the term compliance is most commonly used to describe the elastic forces that oppose lung inflation. It is defined as the change in volume for a given change in pressure; $C = \Delta V/\Delta P$. The compliance of the respiratory system is the sum of the compliances of the lung and the surrounding thoracic structures. Compliance is usually measured under no flow conditions and is therefore referred to as static compliance.[4] Changes in the condition of the lungs, pleural space, chest wall, and intra-abdominal structures influence total respiratory system compliance and therefore the pressure required to inflate the lungs. Conditions that decrease the compliance of the respiratory system lead to an increase in the pressure required to inflate the lungs, for example, acute respiratory distress syndrome (ARDS), pleural or peritoneal effusion. The opposite is true for conditions that increase the compliance of the respiratory system, for example, emphysema.

Resistance associated with ventilation is the result of the anatomical structure of the conductive airways and the tissue viscous resistance of the lungs and the surrounding tissues and organs.[4] Tissue viscous resistance typically remains constant during mechanical ventilation.[4] Resistance to airflow through the conductive airways depends on the viscosity and density of the gas, the flow rate of the gas, and the length and diameter of the conductive airways. In the clinical setting, the diameter of the ET and patient's airways, as well as the flow rate of the gas are the most important factors influencing airway resistance.[4] Bronchospasm, increased airway secretions and kinks or secretions in the ET, can decrease the diameter of the airway lumen and ET and increase resistance to airflow. The rate at which gas flows into the lungs is controlled by the mechanical ventilator.

Equation of motion

During mechanical ventilation, the pressure applied to the respiratory system is equal to the sum of the pressure generated by the ventilator and the pressure generated by the respiratory muscles.[9] These pressures produce motion, that is, flow, to deliver a volume of gas into the lungs. The compliance and resistance of the respiratory system make up the load against which the ventilator and the respiratory muscles must work to deliver a breath. When a patient is on full ventilatory support, the pressure developed by the respiratory muscles is negligible.[9] The equation of motion describes the relationship between pressure, flow, and volume delivery and is given below.[4,9]

Ventilator pressure (Pvent) + muscle pressure (Pmus) = elastic recoil pressure + flow resistance

The pressure necessary to deliver a breath must overcome the elastic recoil forces of the lungs and chest wall, and the resistance to air flow through the airways. Elastic recoil pressure can be expressed as the product of elastance and volume, and the resistive pressure as the product of resistance and flow.[4]

Pvent + Pmus = (elastance × volume) + (resistance × flow)

Because elastance is the inverse of compliance, elastic recoil pressure is equal to the volume divided by compliance.[9]

Pvent + Pmus = (volume/compliance) + (resistance × flow)

The pressure and flow generated by the ventilator are measured by the pressure and flow transducers built into the ventilator. Volume and flow are closely related, that is, volume is derived mathematically from the integration of the flow waveform.[9] In summary, the equation of motion is used to describe the dynamic relationship between pressure, volume, and flow, which are the three interdependent variables that may be manipulated by the ventilator.[9,10] The ventilator can control either the left-hand side of the equation by controlling the airway pressure or the right-hand side by controlling volume and flow. Patient characteristics determine respiratory system compliance and resistance. The equation of motion is built into the ventilator software and is the basis for machine operation.

Basic concepts underlying ventilator waveform analysis and interpretation

The 4 parameters pressure, volume, flow, and time are most descriptive of mechanical ventilation. Six basic waveforms can be derived from these 4 parameters including rectangular, descending ramp, ascending ramp, sinusoidal, and exponential rising and decaying as shown in Figure 2.[4] Pressure waveforms are usually rectangular or rising exponential, whereas volume waveforms are usually ascending ramp or sinusoidal. Flow waveforms can take various forms. The waveform of a spontaneous breath is characteristically sinusoidal in shape.

Typically, 3 different graphs consisting of pressure versus time, volume versus time, and flow versus time are used. These graphs are also referred to as scalars as shown in Figure 3. Time is always plotted on the x-axis, and pressure, flow, and volume are plotted on the y-axis. The ventilator draws the waveforms based on preset as well as calculated parameters. Changes in the ventilator settings result in predictable changes in the graphs. Changes in the characteristics of the lungs such as airway resistance (R_{aw}) and respiratory system compliance (C_{rs}) can be recognized from specific variations in the waveforms. Other graphs such as flow-volume (FV) and pressure-volume (PV) loops provide additional information about changes in lung function.[3]

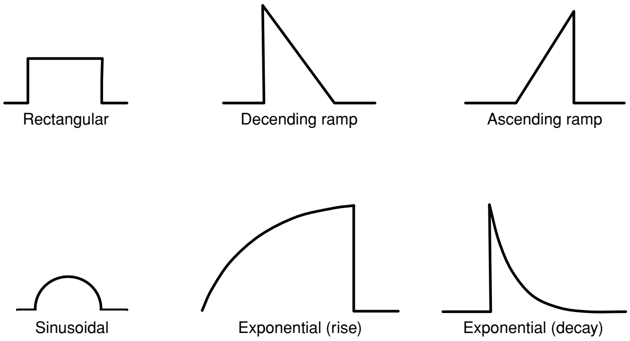

Figure 2: The 6 basic waveforms derived from the 4 parameters pressure, volume, flow, and time. Modified from SP Pilbeam, Cairo JM. Mechanical Ventilation Physiological and Clinical Applications. Fourth ed, Mosby Inc; 2006 with permissions.

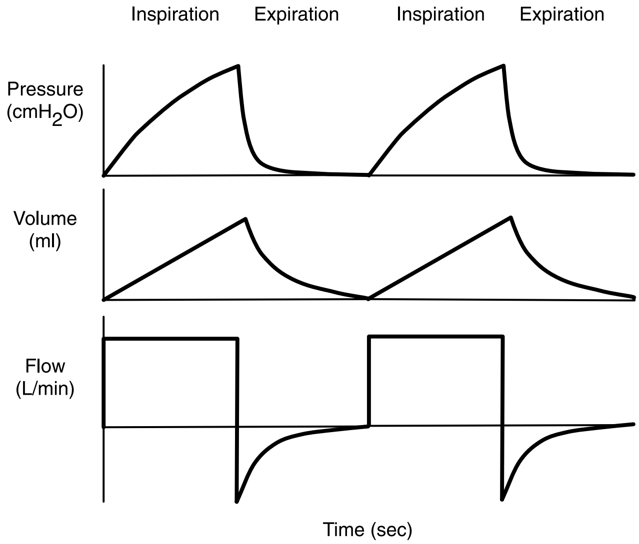

Figure 3: Pressure-time, volume-time, and flow-time scalars. Scalars represent changes in pressure, flow, and volume during inspiration and expiration. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Ventilator waveforms and the phases of the mechanical breath

Pressure, volume, and flow scalars can be used to divide the mechanical breath into six phases, including beginning of inspiration, inspiration, end of inspiration, beginning of expiration, expiration, and end of expiration as shown in Figure 4.

The beginning of inspiration (A) depends on the triggering mechanism, which is the mechanism by which a breath is initiated. A breath can be ventilator-triggered or patient-triggered. A ventilator-triggered breath is initiated after a predetermined time and is therefore also called time-triggered. The pressure versus time scalar shows that a ventilator-triggered breath starts at baseline in contrast to a patient-triggered breath, which has a negative deflection at the onset of the breath.[3] The mechanical breath is delivered during inspiration (B). Flow, volume, and pressure characteristics of the breath depend on different factors such as airway resistance, lung compliance, type and magnitude of flow, and the delivered tidal volume. The cycling mechanism that is determined by the clinician is responsible for the termination of inspiration (C) and the switch from inspiration to expiration. A breath can be volume, pressure, time, or flow cycled. The beginning of expiration (D) is marked by the opening of the exhalation valve that usually coincides with the end of inspiration. In special situations such as activation of end inspiratory pause, the expiration valve does not open even though the inspiratory gas flow has stopped. An end inspiratory pause holds the delivered volume in the lungs to obtain the plateau pressure. On the volume versus time and pressure versus time scalars C and D are at the same point. On the flow versus time scalar, however, C and D are separated. The expiratory phase begins with a negative deflection indicating flow away from the patient. Exhalation (E) occurs passively. Several factors including airway resistance, resistance of the artificial airway, and the elastic recoil force of the lung affect the exhalation characteristics of the graph. Termination of expiration (F) and the beginning of the next breath (A).[3]

Modes of Mechanical Ventilation and Corresponding Flow, Volume, and Pressure Scalars

Three main modes of ventilation, including continuous mandatory ventilation (CMV), intermittent mandatory ventilation (IMV), and continuous spontaneous

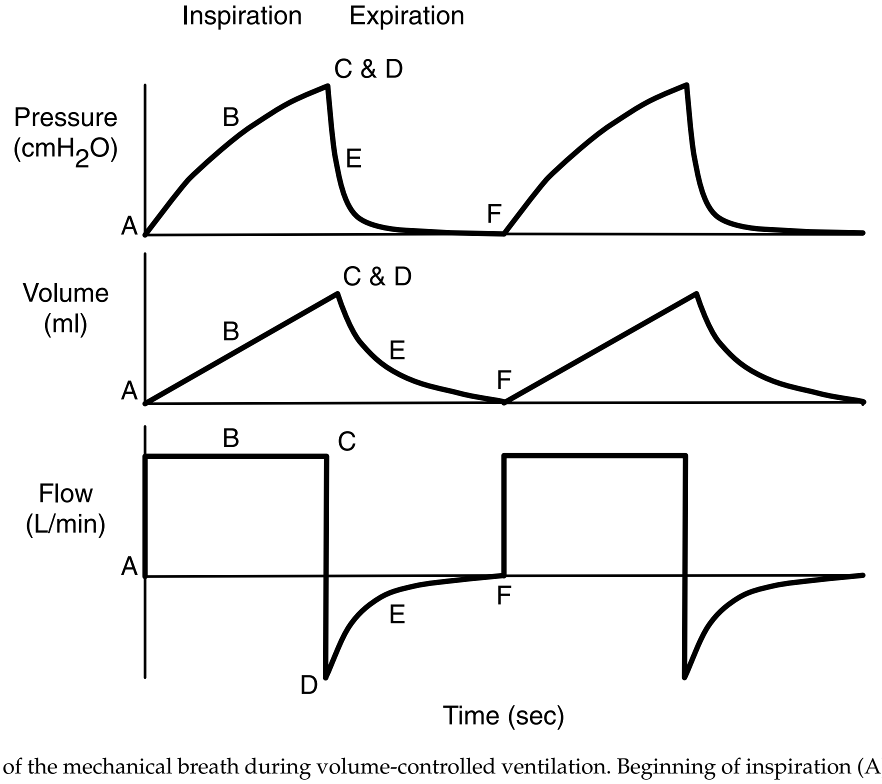

Figure 4: Six phases of the mechanical breath during volume-controlled ventilation. Beginning of inspiration (A), inspiration (B), end of inspiration (C), beginning of expiration (D), expiration (E), and end of expiration (F). Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

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ventilation (CSV) can be differentiated.[10] CMV and IMV commonly use either pressure or volume as the control variable, which are the main variables manipulated through the ventilator.[10] Examples of the different modes of ventilation and their corresponding ventilator waveforms will be discussed individually. A brief description of the modes of ventilation is provided; however, further details and clinical applications are beyond the scope of this article.

In CMV, the clinician sets a minimum respiratory rate. CMV includes control mode and assist-control mode.[10] The control mode is time-triggered, whereas the assist-control mode is either patient- or time-triggered.[4] If the patient makes no respiratory effort then ventilator-driven breaths are delivered at a preset rate (ie, most anesthesia ventilators are time-triggered). In the assist-control mode, the operator sets a minimum respiratory rate, and the patient can trigger additional breaths each of which is assisted by the ventilator. Ventilator-assisted breaths can be pressure- or flow-triggered. The inspiratory effort of the patient leads to either a drop in pressure (eg, –2 cm H_2O) or in flow (eg, 2 L/min) in the patient circuits, which is sensed by the ventilator and a breath is delivered.[11]

In IMV, the ventilator delivers a set number of mandatory breaths (pressure- or volume-controlled), however the patient can take spontaneous breaths in between the mandatory breaths. In synchronized intermittent mandatory ventilation (SIMV) the ventilator attempts to synchronize the mandatory breaths with the patient's inspiratory efforts, which helps avoid patient discomfort due to breath stacking.

In CSV, all breaths are spontaneous. There are no mandatory ventilator-driven breaths. This mode is reserved for patients with strong inspiratory efforts, as the inspiratory time and the V_T are determined by the patient.[10] CPAP and pressure support ventilation (PSV) may be used to enhance CSV. In CPAP, a constant level of positive pressure is applied during both inspiration and expiration, without augmenting airflow during inspiration.[10] Pressure-support ventilation provides a preset amount of airway pressure during inspiration to augment a patient's spontaneous breath. The pressure rises rapidly to the set level of pressure support and is maintained at that level throughout inspiration. Pressure-support ventilation is typically used in conjunction with other modes of ventilation such as SIMV or CPAP.[10]

Controlled mandatory ventilation using volume-controlled vs. pressure-controlled ventilation

Pressure-time scalar During volume-controlled ventilation shown in Figure 5, airway pressure rises abruptly at the beginning of inspiration when gas flow encounters the frictional resistance of the airways. After airway resistance is overcome, gas flows into the alveoli where it meets elastic resistance. The more gradual increase in pressure seen is due to elastic resistance and is dependent on the volume and flow delivered, as well as the compliance of the lungs. Volume delivery ends when the set V_T is reached. The down slope represents the expiratory limb of the graph. The exhalation valve of the ventilator opens and pressure decreases to baseline.[3]

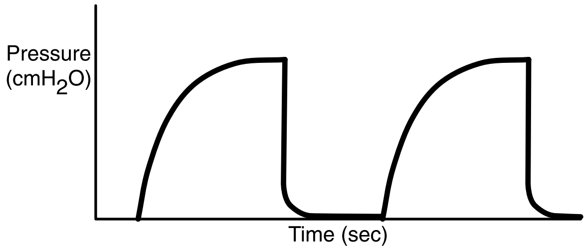


Figure 5: Pressure-time scalars during volume-controlled ventilation. Pressure will rise during inspiration until the set volume is reached. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

During pressure-controlled ventilation, shown in Figure 6, the airway pressure rises rapidly to the set pressure and remains constant throughout the inspiratory phase. The shape of the pressure-time scalar changes according to the rise time and the inspiratory time.[8] The curve on the left shows a faster rise time and a shorter inspiratory time than the curve on the right. The rise time does not affect the inspiratory time, however it determines how quickly the ventilator achieves the set target pressure. The pressure-time scalar is typically used to help differentiate between controlled and assisted breaths.[8] Figure 7A represents pressure-time scalars during volume-controlled ventilation on the left and pressure-controlled ventilation on the right. Notice in Figure 7a, the breaths are patient-triggered

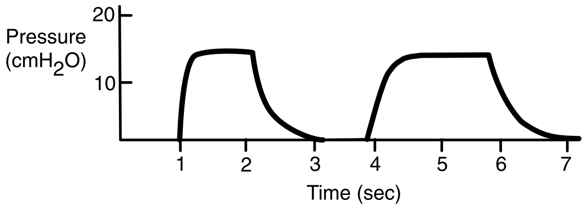


Figure 6: Pressure-time scalars during pressure-controlled ventilation. Notice the scalar on the left shows a slightly faster rise time and a shorter inspiratory time than the scalar on the right. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

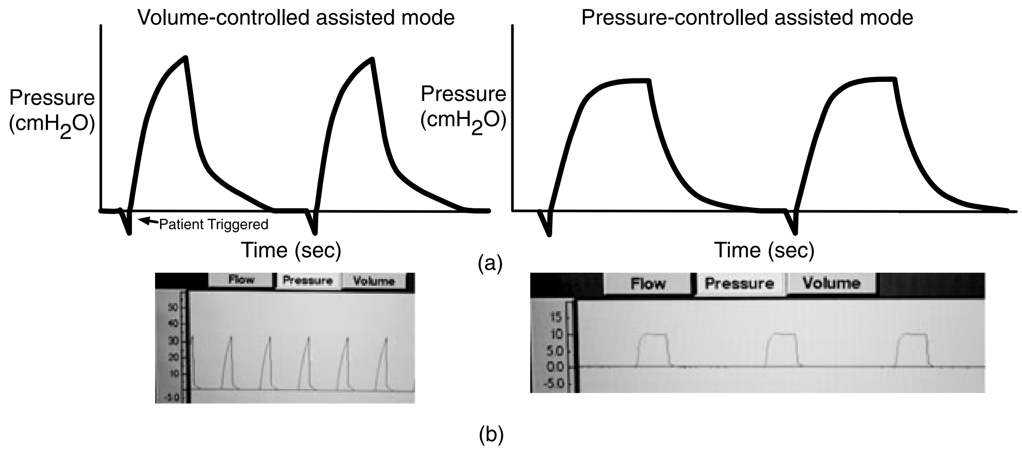


Figure 7: (A) Pressure-time scalars during volume-controlled ventilation versus pressure-controlled ventilation. Notice the difference in appearance of the scalars in volume-controlled ventilation versus pressure-controlled ventilation. In volume-controlled ventilation the scalars have a curvilinear shape and the peak inspiratory pressure (PIP) will vary with the resistance of the airways, the compliance of the lungs, and the flow rate. In pressure-controlled ventilation the scalar shows a rise in pressure during inspiration to the preset PIP. The negative deflection at the onset of the breath helps to differentiate between controlled and assisted breaths. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Examples of pressure-time scalars during volume-controlled and pressure-controlled assist/control mode in a mechanically ventilated dog. Notice there is no patient triggering at the beginning of inspiration identifying the breaths as ventilator-triggered breaths.

ventilator-assisted breaths characterized by a negative deflection at the onset of the breaths.[3]

Volume-time scalar In Figure 8, the left side of the graph illustrates a volume-time scalar during volume-controlled ventilation. Due to the rectangular flow pattern in volume-controlled ventilation, volume is delivered in fixed increments per unit of time resulting in a straight-line upslope that terminates when the set V_T is reached. The right side of the graph in Figure 8, illustrates a volume-time scalar during pressure-controlled ventilation. Due to the decelerating flow pattern in pressure-controlled ventilation the volume-time scalar

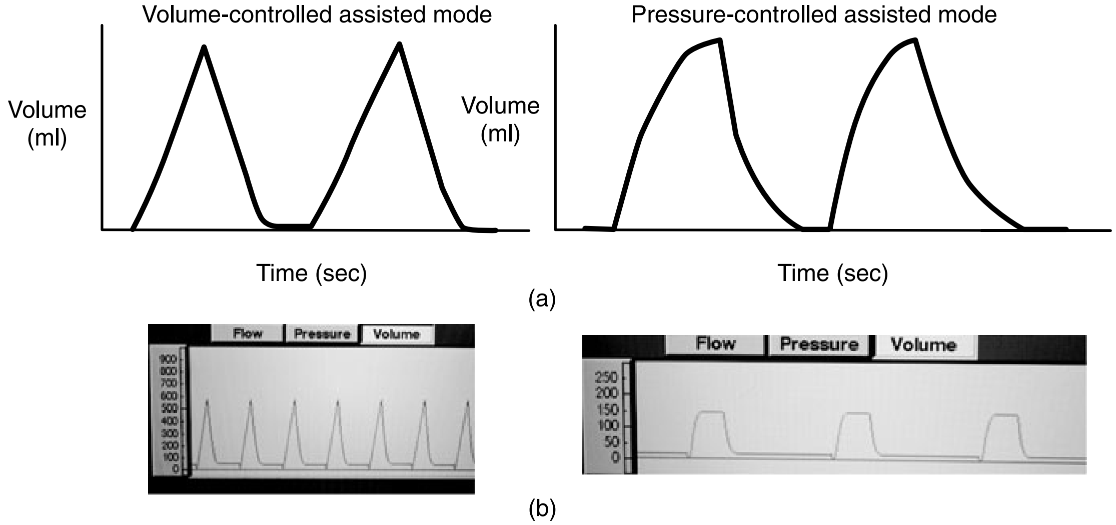


Figure 8: (A) Volume-time scalars during volume-controlled ventilation versus pressure-controlled ventilation. In volume-controlled ventilation, the delivered volume will remain constant, while it may vary depending on changes in airway resistance and lung compliance during pressure-controlled ventilation. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Examples of volume-time scalars during volume-controlled and pressure-controlled assist/control mode in a mechanically ventilated dog.

is curvilinear. Delivered volume will remain relatively constant during volume-controlled ventilation, but will vary in pressure-controlled ventilation as the patient's lung characteristics change.

The down slope of the 3 scalars shown in Figure 9 represent the expiratory limbs. During expiration, the exhalation valve of the ventilator opens and volume decreases to baseline as shown in the volume-time scalar labeled A.[3] Typically an air leak in the expiratory circuit of the ventilator, a bronchopleural fistula, or gas trapping in the lung (ie, auto-PEEP) is responsible when the expiratory limb of the tracing does not return to baseline as shown in the volume-time scalar labeled B.[4,12] A drop of the expiratory limb of the curve below the baseline, represented by the volume-time scalar labeled C indicates active patient exhalation or flow transducer malfunction.[4,8,12]

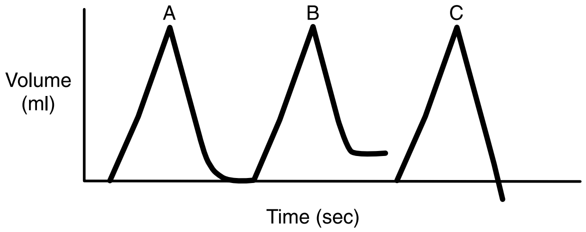
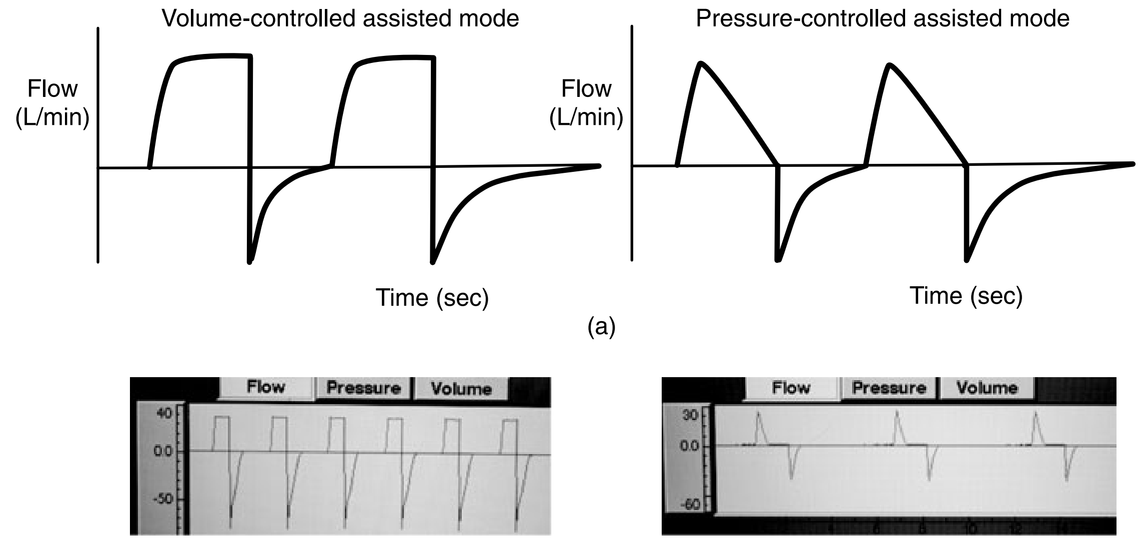


Figure 9: Volume-time scalars during volume-controlled ventilation with differing expiratory limbs. Normal expiratory limb (A). Expiratory limb not returning to baseline indicative of an air leak (B). Expiratory limb dropping below baseline indicative of active patient exhalation (C). Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

Flow-time scalar In Figure 10, the left side of the graph illustrates a flow-time scalar during volume-controlled ventilation. The ventilator delivers a constant flow throughout inspiration depicted by the rectangular inspiratory flow pattern. The flow instantly reaches the set flow rate, remains constant for the determined inspiratory time, and then decreases to zero during expiration. Some ventilators allow for a change in flow pattern from rectangular to decelerating, however a rectangular inspiratory flow pattern is characteristic for volume-controlled ventilation. The right side of the graph illustrates a flow-time scalar during pressure-controlled ventilation. The inspiratory flow reaches a maximum at the beginning of inspiration and then tapers off throughout the inspiratory phase and may or may not reach zero before the end of inspiration. A decelerating flow pattern during the inspiratory phase is characteristic for pressure-controlled ventilation.[3]



(a)

(b)

Figure 10: (A) Flow-time scalar during volume-controlled ventilation versus pressure-controlled ventilation. Notice the rectangular inspiratory flow pattern in volume-controlled ventilation due to delivery of a preset tidal volume at a constant inspiratory flow rate. During pressure-controlled ventilation, inspiratory flow reaches a maximum at the beginning of inspiration and then tapers off throughout the inspiratory phase resulting in a decelerating flow pattern. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Examples of flow-time scalars during volume-controlled and pressure-controlled assist/control mode in a mechanically ventilated dog. Notice the distinct difference in appearance of the inspiratory limbs between the two modes.

Expiratory flow is passive and depends on the airway resistance, resistance of the artificial airways, as well as the elastic recoil forces of the lung and chest wall. Regardless of the control variable, only the flow-time scalar has a negative tracing during expiration. Typically, expiratory flow reaches a maximum during the beginning of expiration and then rapidly tapers off toward zero until the next mechanical breath is delivered.

Synchronized intermittent mandatory ventilation (SIMV)

SIMV can be distinguished from CMV by the presence of spontaneous, ventilator-unassisted breaths. Ventilator waveforms of spontaneous breaths appear distinctly different from the mandatory or assisted breaths, as well as from each other depending on the scalar being evaluated.

Pressure-time scalar

Figure 11 shows a pressure-time scalar with a spontaneous breath following each of the ventilator-assisted breaths. Spontaneous breaths are sinusoidal with a negative deflection, that is, negative pressure during inspiration and a positive deflection, that is, positive pressure during expiration. The ventilator-assisted breaths on the other hand show positive pressure during inspiration. Breaths 1 and 3 are patient-triggered ventilator-assisted breaths as seen by the negative deflection at the onset of inspiration.[3]

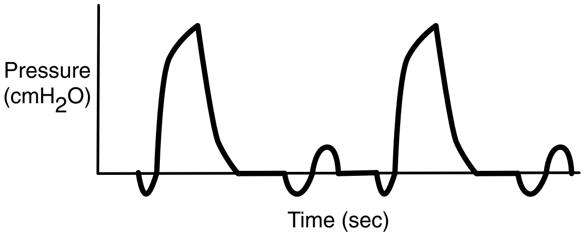


Figure 11: Pressure-time scalar during volume-controlled SIMV with alternating ventilator-assisted breaths and spontaneous breaths. Notice the ventilator-assisted breaths as previously described for positive pressure ventilation (PPV) in contrast to the sinusoidal shape of spontaneous (ventilator-unassisted) breaths. During normal spontaneous breathing a negative pressure is generated during inspiration and a positive pressure during expiration. The amplitude of the pressures generated during spontaneous breaths are smaller than the amplitude generated during ventilator-assisted breaths. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Volume-time scalar

Figure 12 shows a volume-time scalar with a spontaneous breath following each of the ventilator-assisted breaths. The V_T for the mechanical breaths reaches the volume set by the operator (eg, 400 mL) whereas the V_T for the spontaneous breaths may only reach a fraction of that volume (eg, 100 mL).[3]

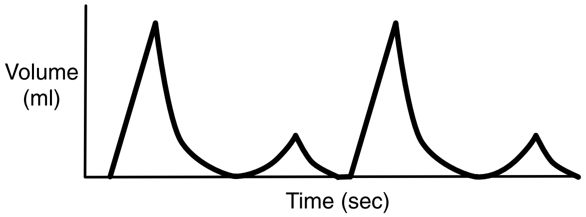


Figure 12: Volume-time scalar during volume-controlled SIMV with alternating ventilator-assisted breaths and spontaneous breaths. Notice the tidal volumes generated during the spontaneous breaths are less than the preset tidal volumes generated during the ventilator-assisted breaths. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Flow-time scalar

Figure 13 shows a flow-time scalar with a spontaneous breath following each of the ventilator-assisted breaths. Breath 1 and 3 are ventilator-assisted breaths characterized by the typical rectangular inspiratory flow pattern. The breaths following the ventilator-assisted breaths are spontaneous breaths that can be identified by the sinusoidal shape of their waveform with the inspiratory portion above the baseline and expiratory portion below the baseline.[3]

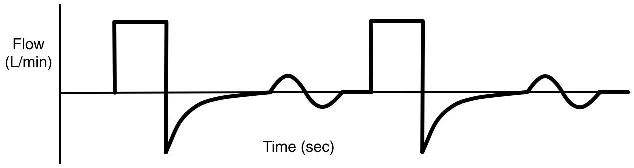
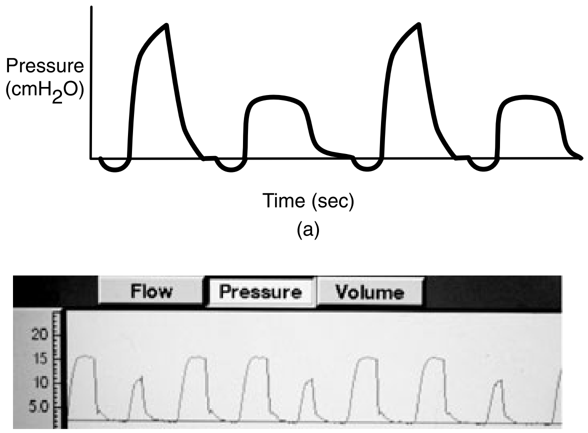


Figure 13: Flow-time scalar during volume-controlled SIMV with alternating ventilator-assisted breaths and spontaneous breaths. Notice that although the shape of the flow-time scalar during the spontaneous breaths and ventilator-assisted breaths is different, flow rises during inspiration and drops below baseline during expiration in both spontaneous and ventilator-assisted breaths. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Synchronized intermittent mandatory ventilation (SIMV) with pressure support ventilation (PSV)

As stated previously, the V_T during a spontaneous breath is typically smaller than the V_T during a ventilator-assisted breath and may not be sufficient to maintain adequate oxygenation and ventilation. In addition, spontaneous breathing through the ventilator circuit may increase the work of breathing. Adding pressure support to a spontaneous breath may increase the V_T and decrease the work of breathing.[8]

Pressure-time scalar PSV is meant to support a patient's spontaneous breath by helping to decrease the work of breathing. The pressure is typically set to reach a lower peak airway pressure than during a pressure-controlled ventilator-assisted breath. Figure 14 shows alternating pressure-supported spontaneous breaths and ventilator-assisted breaths. All of the breaths are patient-triggered as seen by the negative deflection at the onset of inspiration. The pressure-supported breath maintains the set pressure throughout the inspiratory phase. The pressure decreases to baseline during the expiratory phase.[3]

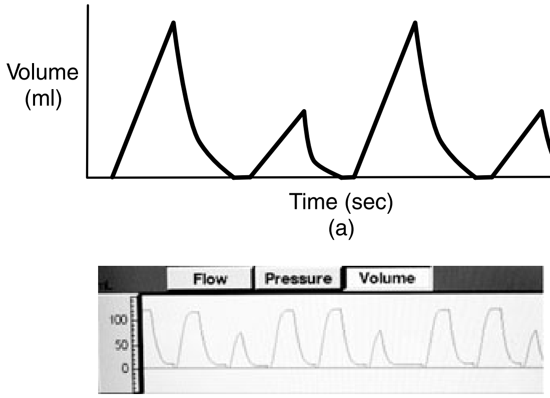


(a)

(b)

Figure 14: (A) Pressure-time scalar during volume-controlled SIMV with pressure support. Notice the ventilator-assisted breaths reach higher peak pressures than those of the pressure-supported spontaneous breaths. Both breath types display a negative deflection before each breath reflecting the patient's inspiratory efforts. The pressure-supported breaths will maintain the set pressure throughout the inspiratory phase. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Example of a pressure-time scalar during pressure-controlled SIMV with pressure support in a mechanically ventilated dog. Notice again the ventilator-assisted breaths reach higher peak pressures than those of the pressure-supported spontaneous breaths (eg, breaths 2, 5, 8).

Volume-time scalar Figure 15 shows a pressure-supported spontaneous breath following each of the ventilator-assisted breaths. The V_T of a pressure-supported breath tends to be greater than the V_T of a spontaneous breath without pressure support (see Figure 12).



(a)

(b)

Figure 15: (A) Volume-time scalar during volume-controlled SIMV with pressure support. Compare the scalars in this figure to the scalars in Figure 12. Notice the V_T of a pressure-supported breath is greater than the V_T generated by a spontaneous breath without pressure support. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Example of a volume-time scalar during pressure-controlled SIMV with pressure support in a mechanically ventilated dog. Notice the V_T of a ventilator-assisted breath is greater than the V_T generated by a pressure-supported spontaneous breath (eg, breaths 3, 6, 9).

Flow-time scalar Figure 16 shows alternating pressure-supported spontaneous breaths and ventilator-assisted breaths. The inspiratory flow pattern during the ventilator-assisted breaths is rectangular as is characteristic for volume-controlled ventilation. The inspiratory flow pattern during the pressure-supported spontaneous breath tapers toward baseline as the inspiratory phase progresses. Pressure-supported breaths are flow-cycled breaths, which means that the inspiratory flow terminates when the rate of flow decreases below a certain level of peak flow, typically 25%.[3,8]

Continuous positive airway pressure (CPAP)

CPAP may be used in spontaneously breathing patients that do not require full ventilatory support but

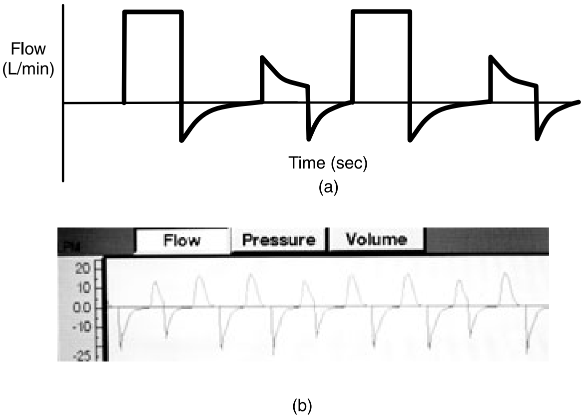


Figure 16: (A) Flow-time scalar during volume-controlled SIMV with pressure support. Notice the ventilator-assisted volume-controlled breaths have the characteristic rectangular inspiratory flow pattern, but during the pressure-supported spontaneous breaths, the inspiratory flow pattern tapers toward baseline during the inspiratory phase. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Example of a flow-time scalar during pressure-controlled SIMV with pressure support in a mechanically ventilated dog. Notice the breaths of smaller magnitude are the pressure-supported breaths (eg, breaths 2, 5, 8).

demonstrate refractory hypoxemia, for example, due to atelectasis secondary to sedation or anesthesia. In addition, CPAP may be helpful in lung recruitment maneuvers and spontaneous breathing trials.[13] CPAP improves oxygenation by increasing functional residual capacity (FRC).[4] The pressure-time scalar, as shown in Figure 17, is the scalar that identifies the presence of CPAP. There is an elevation of the baseline from zero (ie, atmospheric).[3] Inspiratory and expiratory airway pressures remain positive and do not return to zero baseline. The volume-time scalar shows variable spontaneous V_T. The flow pattern on the flow-time scalar indicates inspiratory and expiratory spontaneous flow.

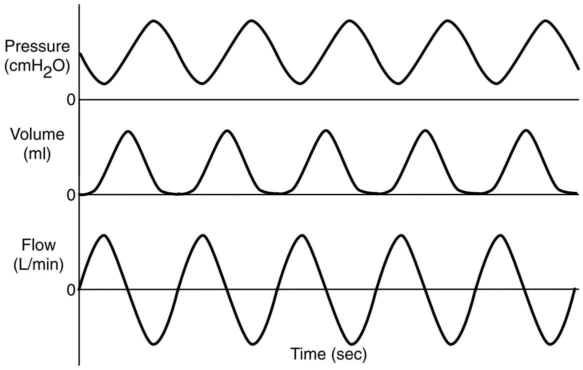


Figure 17: Continuous positive airway pressure (CPAP). Notice the elevation of the baseline pressure from zero in the pressure-time scalar. Inspiratory and expiratory airway pressures remain positive and do not return to zero baseline. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Loops

Loops are continuous graphs of the inspiratory and expiratory portions of the breath.[3] Loops, unlike scalars, do not depict time. They typically plot volume against pressure or volume against flow. Similar to scalars, information can be derived from numerical values as well as the shape of the waveforms.[3]

Pressure-volume loops

PV loops display the interaction between pressure and volume and can therefore be used to assess the patient's respiratory system compliance.[4] They also provide information on airway resistance R_{aw} and help to differentiate between a spontaneous breath and an assisted or controlled positive pressure breath. During a spontaneous breath as shown in Figure 18, the PV loop moves in a clockwise direction, starting at zero, that is, intersection of x- and y-axis.[12,14] The inspiratory portion of

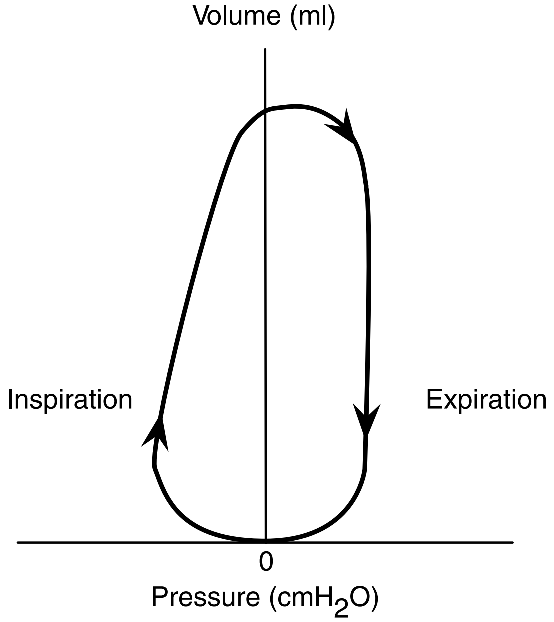
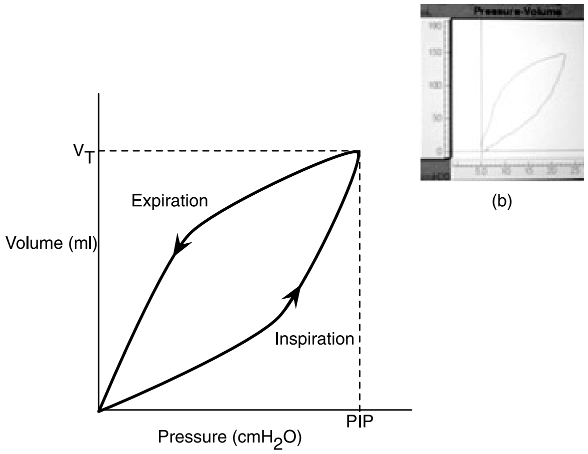


Figure 18: PV loop of a spontaneous breath. Notice the PV loop moves in a clockwise direction, starting at zero. The inspiratory portion of the loop occurs on the left side of the y-axis, and the expiratory portion of the loop on the right side of the y-axis. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

the loop occurs on the left side of the *y*-axis as airway pressure drops, that is, becomes more negative during inspiration. The expiratory portion of the loop occurs on the right side of the *y*-axis as airway pressure increases, that is, becomes more positive during expiration.[4,12,14]

During a positive pressure breath, the PV loop moves in a counter-clockwise direction as shown in Figure 19. The starting point of the loop depends on the amount of PEEP applied. Both the inspiratory and expiratory portion of the loop are on the right side of the *y*-axis.[12] The maximum pressure reached on the *x*-axis is the PIP and the maximum volume reached on the *y*-axis is the V_T.[4]



(a)

(b)

Figure 19: (A) PV loop of a mandatory ventilator-driven breath. Notice during a positive pressure breath, the PV loop moves in a counter-clockwise direction with both the inspiratory and expiratory portions of the loop occurring on the right side of the *y*-axis. The starting point of the loop is zero indicating the absence of PEEP in this example. PIP is the maximum pressure reached on the *x*-axis and V_T is the maximum volume reached on the *y*-axis. Modified from SP Pilbeam, Cairo JM. Mechanical Ventilation Physiological and Clinical Applications. 4th ed. Mosby Inc; 2006 with permissions. (B) Example of a PV loop of a mandatory ventilator driven-breath in a mechanically ventilated dog.

A patient-triggered breath creates a "trigger tail" at the beginning of inspiration as illustrated in the PV loops shown in Figure 20. Similar to a spontaneous breath, the initiation of the breath is associated with a drop in airway pressure below baseline, and the tracing moves to the left (clockwise) reflecting the patient's effort. Subsequently, the tracing moves to the right (counter-clockwise) as the ventilator delivers the breath.[4] The size of the "trigger tail" is a reflection of the patient's effort to trigger the ventilator as demonstrated in Figure 21. The bigger the "trigger tail," the bigger the effort. An increased effort to trigger the ventilator will increase the work of breathing. The trigger level is influenced by the sensitivity settings of the ventilator.[4,12,14]

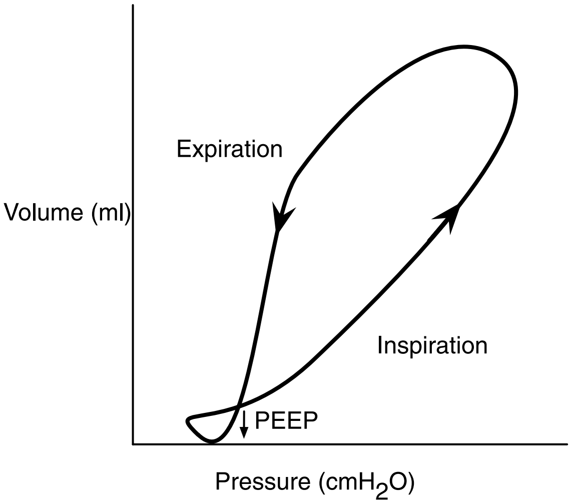


Figure 20: PV loop of a patient-triggered ventilator-assisted breath in a patient receiving PEEP. Notice the "trigger tail" at the beginning of inspiration caused from the brief drop in airway pressure when the patient initiates the breath. The tracing moves to the left (clockwise) reflecting the patient's effort. Positive flow from the ventilator is triggered, and the tracing moves to the right (counter-clockwise) as the ventilator completes the breath. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

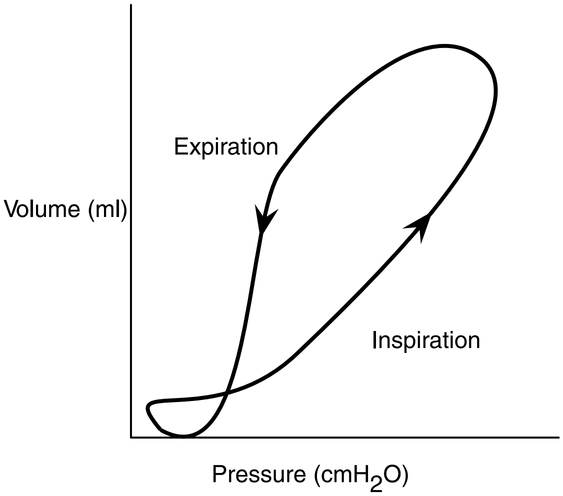
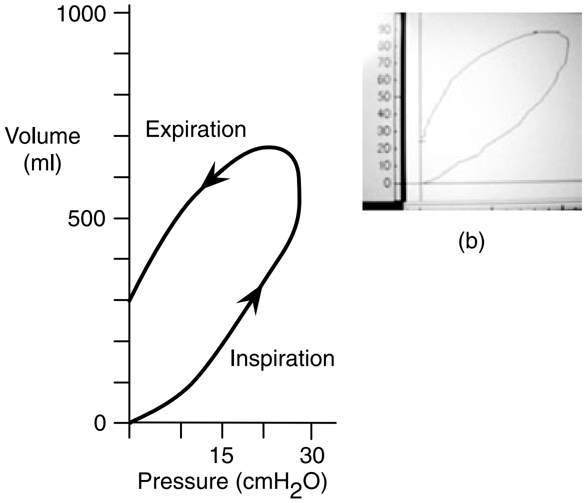


Figure 21: PV loop of a patient-triggered ventilator-assisted breath in a patient receiving PEEP. Notice the larger size of the trigger tail compared to Figure 20 indicating an increased patient effort when triggering the ventilator. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

An incomplete PV loop is an indication of an air leak either in the ventilator circuit or the patient, for example, bronchopleural fistula.[4] In Figure 22, the expiratory limb of the PV loop does not return to baseline indicating



(a)

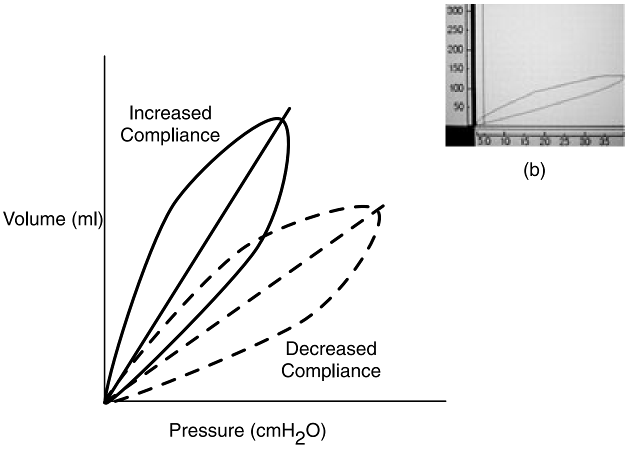
(b)

Figure 22: Incomplete PV loop. (A) Notice the expiratory limb of the PV loop does not return to baseline indicating that more volume is delivered during inspiration than returned during expiration. The loss of volume in this example is approximately 300 mL. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions. (B) Example of an incomplete PV loop in a mechanically ventilated dog.

that more volume is delivered during inspiration than returned during expiration. This loss of volume can be quantified by identifying the end point of the expiratory limb of the PV loop (ie, 300 mL).[4,12]

Evaluation of the slope of the PV loop can help to assess for changes in respiratory system compliance as demonstrated in Figure 23.[14] A decrease in compliance, that is, the tidal volume decreases for the same distending pressure, results in a shift of the PV loop to the right and downward (ie, decreased slope).[4,12,14] An increase in compliance, that is, the tidal volume increases for the same distending pressure, results in a shift of the PV loop to the left and upward (ie, increased slope).[14]

PV loops are also useful in the assessment of R_{aw}. When compliance remains constant and R_{aw} increases the amount of pressure needed to overcome R_{aw} increases. In Figure 24, the widening or bowing of the PV loop is suggestive of increased R_{aw} (solid line).[3,4,12,14] The size and shape of the bowing depend on different variables including ventilation mode, for example, pressure- or volume-controlled ventilation, an increase in predominantly inspiratory or expiratory resistance, as well as respiratory system compliance.[3,4]



(a)

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Figure 23: (A) PV loop illustrating changes in respiratory system compliance. Notice a decrease in compliance results in a shift of the PV loop to the right and downward. An increase in compliance results in a shift of the PV loop to the left and upward. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions. (B) Example of decreased respiratory system compliance in a mechanically ventilated dog.

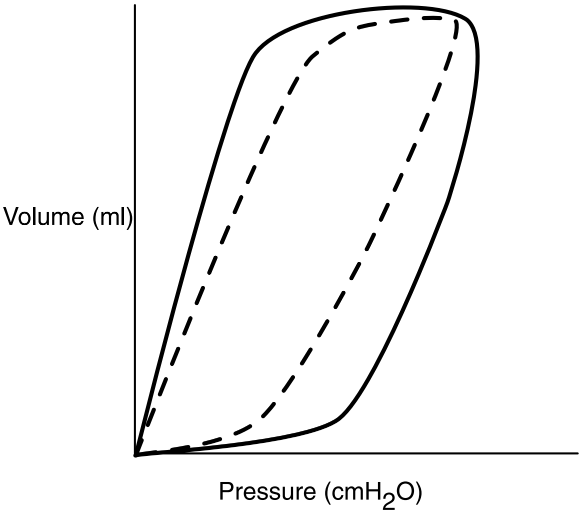

Figure 24: PV loop illustrating changes in airway resistance. Notice the widening or bowing of the PV loop shown by the solid line indicating increased R_{aw} as compared to the normal conformation of the PV loop shown by the dashed line. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

The PV loop may exhibit a lower inflection point (LIP) and an upper inflection point (UIP) during the inspiratory phase as shown in Figure 25.[4,12,15] An inflection point is the point where the slope of a line changes.[3] The LIP indicates the pressure at which large numbers of alveoli are recruited.[4,12] The UIP indicates the pressure at which the alveoli become overdistended.[4,12] When the volume capacity of the lungs has been exceeded, application of additional pressure causes very little increase in volume.[3] The volume limit is identified on the PV loop as

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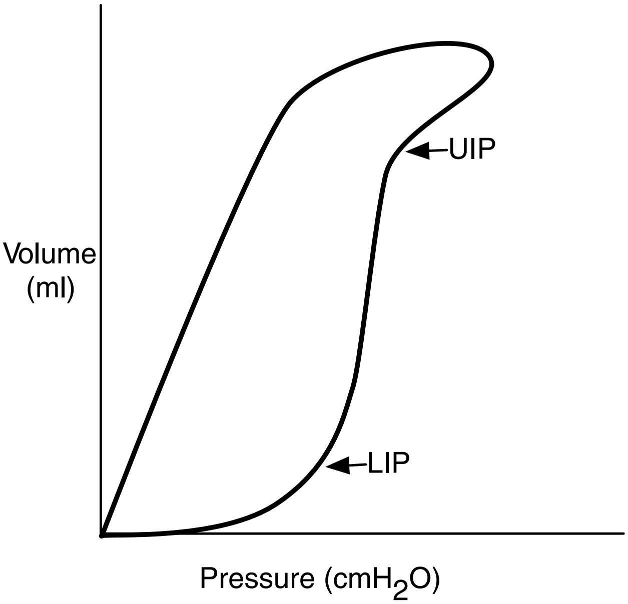
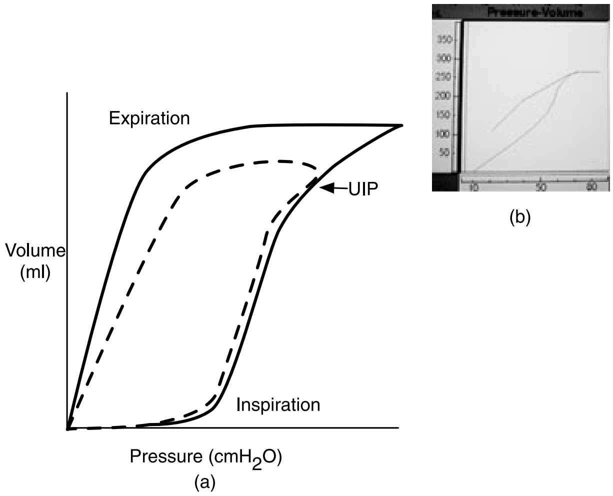


Figure 25: PV loop illustrating the LIP and UIP. The LIP indicates the pressure at which large numbers of alveoli are recruited where as the UIP indicates the pressure at which the alveoli become over distended. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.



(a)

(b)

Figure 26: PV loop illustrating "beaking" (solid line). (A) Notice the abnormal shape of the PV loop at the terminal phase of inspiration as the limit of alveolar distension is reached. The UIP signifies an abrupt change in compliance as the alveoli become over distended. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Critical Care* 2009; 4(1): 43–55 with permissions. (B) Example of "beaking" in a mechanically ventilated dog. Notice that at the moment the PV loop of the breath was recorded, the expiratory portion was not fully complete.

the UIP and signifies an abrupt change in compliance in the terminal phase of inspiration.[3] Figure 26 shows this abnormal loop shape (solid line) that is typically referred to as "beaking."[3,8,12] Ways to decrease "beaking" involve decreasing the pressure in pressure-controlled ventilation or decreasing the volume in volume-controlled ventilation.[3] It is recommended to try and ventilate patients within the LIP and the UIP.[4] This can be achieved by setting the PEEP above the LIP and the V_T below the UIP. This ventilation strategy may be helpful to keep the alveoli from collapsing and to avoid "baro-" and "volutrauma" associated with high distending pressures.[4]

Flow-volume loops

FV loops are most commonly used to evaluate changes in R_{aw}. In a recently published article noninvasive tidal breathing FV loops were used to aid in the diagnosis and staging of dogs with tracheal collapse.[16] FV loops obtained from patients receiving positive pressure ventilation can assist in the detection of changes in airway resistance such as from mucous plugs and air leaks, and can be helpful to detect auto-PEEP.[12] Typically the inspiratory flow is depicted above the x-axis and the expiratory flow below the x-axis. This arrangement may be reversed depending on the ventilator.[3]

Figure 27 illustrates important points on the FV loop during ventilation. The transition from expiration to inspiration (A) and back again (C) occurs where the loop crosses the x-axis. At this point the flow rate is

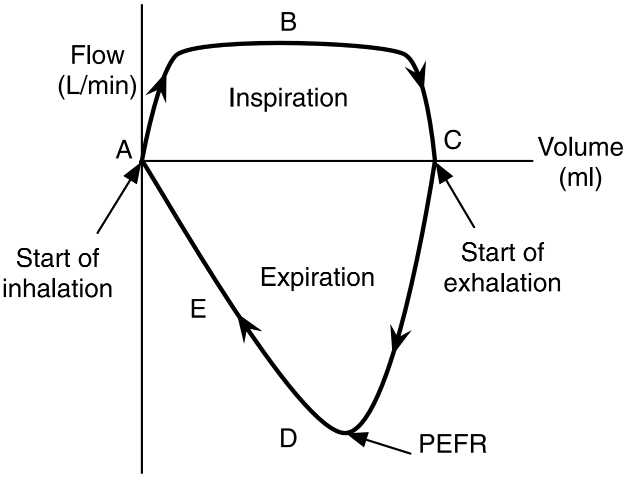


Figure 27: Different phases of the FV loop. Start of inspiration (A), inspiratory portion (B), start of expiration (C), peak expiratory flow rate (D), and passive expiratory curve (E). Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

momentarily zero.[3] The shape of the inspiratory portion (B) of the loop reflects the flow pattern set on the ventilator. The peak point of the expiratory portion (D) of the loop represents the peak expiratory flow rate (PEFR). The typical shape of the descending portion of the expiratory curve is represented by E. The shape of the passive expiratory portion of the loop is influenced by changes in R_{aw}.[3] The FV loop of a spontaneous breath is similar in appearance to a mechanical breath, except for the inspiratory portion of the loop, which takes on a more circular shape because of the generally lower peak inspiratory flow rates generated during quiet spontaneous breathing.[3]

Increases in R_{aw}, for example, airway obstruction from mucous plugs or decreases in R_{aw}, for example, air leak in the ventilator circuit can cause characteristic changes in the FV loop. Significant airway obstruction will reduce PEFR as demonstrated in Figure 28. A curvilinear shape or "scooping" of the descending segment of the expiratory curve is typically seen in patients with medium and small airway obstruction causing decreased expiratory volume and flow as demonstrated in Figure 28.[3] Oscillations in the expiratory or inspiratory limb of the FV-loop are known as the "saw tooth" sign and result most commonly from increased airway secretions (Figure 29).[8] A gap between the end of expiration and the beginning of inspiration as shown in the FV loop in Figure 30, is indicative of an air leak. The FV loop does not close because of the loss of volume during expiration.[3]

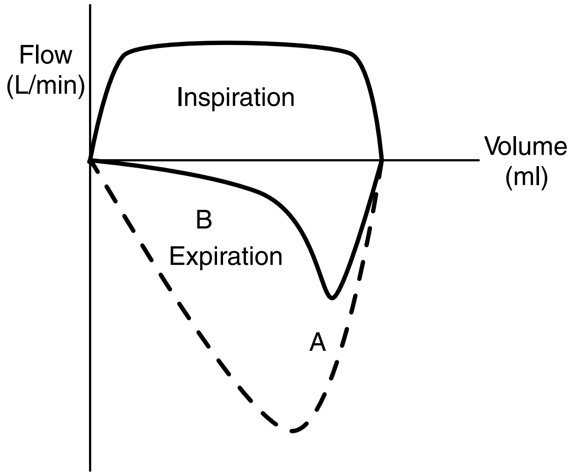


Figure 28: FV loop illustrating increased airway resistance (solid line). Notice the reduced PEFR represented by A as compared to normal PEFR (dashed line) caused by increased airway resistance. The descending segment of the expiratory curve has a scooped out appearance represented by B, which is typically seen in patients with medium and small airway obstruction. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

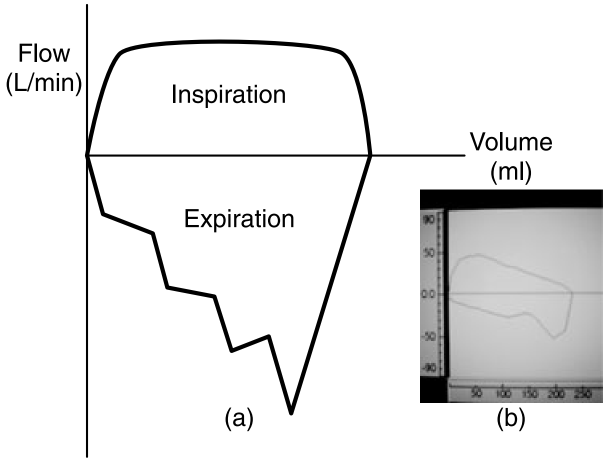


Figure 29: (A) FV loop illustrating a "saw tooth" sign. Oscillations in the expiratory limb of the FV loop are known as "saw tooth" sign and result most commonly from increased airway secretions. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid interpretation of ventilator waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Example of a FV loop illustrating increased airway secretions in a mechanically ventilated dog.

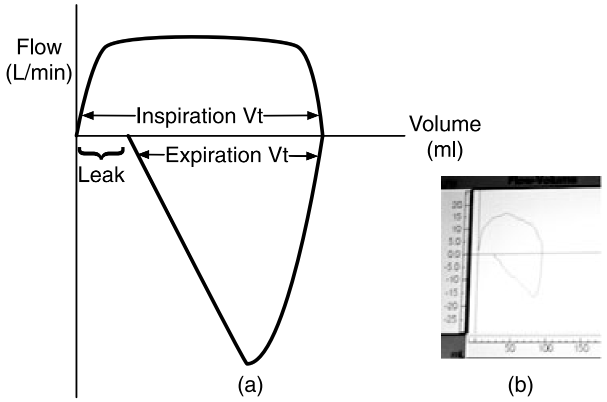


Figure 30: Incomplete FV loop. (A) Notice the gap between the end of expiration and the beginning of inspiration indicative of an air leak. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions. (B) Example of an incomplete FV loop in a mechanically ventilated dog with an air leak in the breathing circuit.

Use of Ventilator Waveforms to Identify Patient-Ventilator Dyssynchrony

Patient-ventilator interactions can be described as the interaction between 2 respiratory mechanisms, that is, the ventilator and the patient's respiratory system.[17,18] The ventilator is controlled by the settings chosen by the operator and the function of the flow valve.[17]

The patient's respiratory system is controlled by the neuromuscular system and influenced by the respiratory mechanics of the lung and thorax.[17] When these 2 mechanisms function in synchrony every phase of the breath is perfectly matched.[18] Anything that disturbs the harmony between the two mechanisms results in dyssynchrony and can lead to considerable patient discomfort and an increase in the work of breathing.[17] Ventilator waveforms are helpful to identify patient-ventilator dyssynchrony. Dyssynchrony can occur in any of the four phases of the breath cycle, that is, initiation of inspiration, inspiratory flow phase, end of inspiration, and expiratory phase.[17]

The initiation of inspiration is influenced by the trigger mechanism, which includes trigger sensitivity setting, patient effort, and valve responsiveness.[17] During the inspiratory flow phase the patient's flow demand must be met by the ventilator.[5]

At the end of inspiration the ventilator should terminate inspiratory flow in synchrony with the patient's neural timing.[17] Different modes of ventilation (eg, pressure-controlled versus volume-controlled) will allow the operator to adjust variables that affect the termination of inspiration. A prolonged expiratory phase is of little consequence, unless it is so long as to cause hypoventilation. A shortened expiratory phase, however, has major clinical implications because it can lead to auto-PEEP.[17]

To analyze patient-ventilator dyssynchrony one has to evaluate triggering (ie, trigger dyssynchrony), flow delivery (ie, flow dyssynchrony), breath termination (ie, cycle dyssynchrony), and expiratory phase (ie, expiratory dyssynchrony).[17] Dyssynchrony can be identified relative to these 4 phases by use of pressure, volume, and flow scalars and loops.

Trigger dyssynchrony

Trigger dyssynchrony occurs when a patient's inspiratory effort is not sufficient to trigger the ventilator, because the sensitivity setting of the ventilator is not appropriate for the patient.[4,12,19] Trigger dyssynchrony can occur in any ventilation mode and can be identified on the flow-time and pressure-time scalars. The pressure-time scalar shown in Figure 31 shows a patient-triggered breath (A) followed by an unsuccessful attempt to trigger the ventilator (B) indicated by a negative deflection during the expiratory phase that is not followed by a rise in pressure. Breath C is a patient-triggered breath following an increased inspiratory effort when compared to breath A. Auto-PEEP and inappropriately set sensitivity settings are the most common causes of trigger dyssynchrony.[4,12,13] Auto-PEEP makes triggering the ventilator more difficult. In the presence of auto-PEEP, a patient's inspiratory effort may not be sufficient to generate a large enough change in baseline pressure or baseline flow to trigger a mechanical breath. The trigger sensitivity settings can be either flow- or pressure dependent, with flow usually being preferred. When the sensitivity settings are too sensitive, auto-triggering, that is, false triggering of the ventilator can occur as shown in Figure 32.

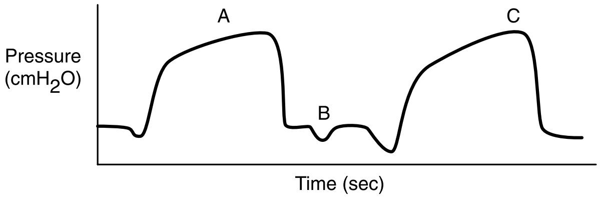


Figure 31: Pressure-time scalar illustrating trigger dyssynchrony. Compare the negative deflections in breaths A, B, and C. Notice that when the patient's effort is adequate and the sensitivity setting appropriate, the patient's breath successfully triggers the ventilator (A). If there is a weak inspiratory effort relative to the sensitivity settings, the effort may be ineffective at triggering a ventilator breath; there is no rise in pressure following the patient effort (B). When the sensitivity setting is insensitive, an increased patient effort is required to trigger a ventilator breath (C). Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

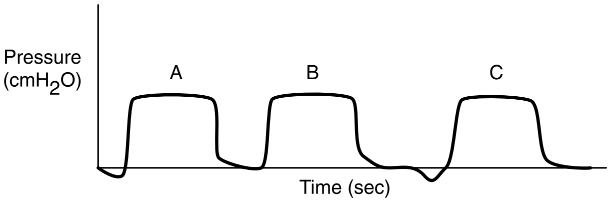


Figure 32: Pressure-time scalar during PSV illustrating auto-triggering. Breaths A and C are patient-triggered as indicated by the negative deflections before the onset of inspiration. Breath B shows a pressure supported breath without a preceding patient effort suggestive of auto-triggering. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

Flow dyssynchrony

Flow dyssynchrony occurs whenever the ventilator flow does not match the patient's flow demand.[17] Flow dyssynchrony is a common problem, and the flow setting may be the most frequently incorrectly set ventilator parameter.[17] Flow dyssynchrony is sometimes referred to as flow starvation.[12] The ventilator mode, for example, volume-controlled versus pressure-controlled ventilation and the flow pattern used determine how much flow is available. In volume-controlled ventilation with constant flow, flow may not be sufficient to satisfy the patient's flow demand. Adjusting the peak flow and/or selecting a different flow pattern, for example, descending flow pattern may be helpful to correct the problem.[4,17] In pressure-controlled ventilation, the ventilator rapidly provides a high flow to achieve and maintain the set pressure; however, this high flow rate at the beginning of inspiration may be too excessive or uncomfortable for a patient.[4] In that case, evaluating and adjusting the rise time may be helpful. As long as the set pressure is adequate, the flow will be adequate.[4] Pressure-controlled ventilation tends to be more synchronous in patients with high flow demands.[4] Pressure-time scalars or PV loops are typically used to evaluate for flow dyssynchrony.

Figure 33 depicts the pressure-time scalar of two ventilator-assisted breaths. The pressure-time scalar of breath A has a normal appearance. The pressure-time scalar of breath B shows a drop in airway pressure and a concave or scooped-out appearance of the ascending inspiratory limb of the tracing indicating inadequate flow.[12] Low peak flow rates will prolong inspiratory time and decrease expiratory time that may contribute to the development of auto-PEEP.[17] Features of flow dyssynchrony on a PV loop include a concave appearance of the inspiratory limb of the tracing as seen in Figure 34 or a figure eight appearance of the tracing as seen in Figure 35. These changes are a result of active patient inspiration in an attempt to increase airflow, which leads to a decrease in airway pressure.

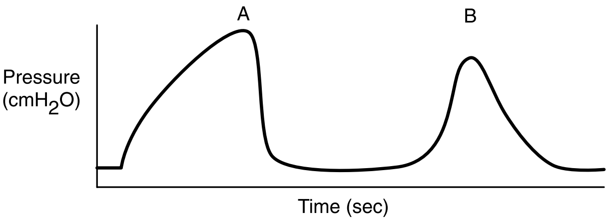


Figure 33: Pressure-time scalar illustrating inadequate flow. Notice breath A shows a normal pressure-time scalar in comparison to breath B that shows a drop in airway pressure and a concave or scooped-out appearance of the ascending inspiratory limb indicating inadequate flow. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

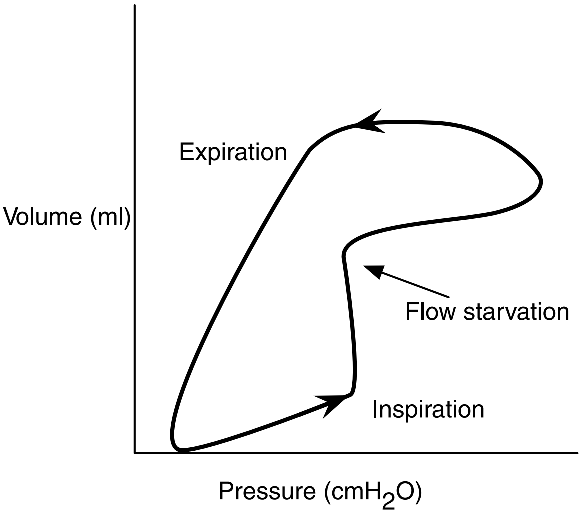


Figure 34: PV loop illustrating flow dyssynchrony. Notice the concave portion of the ascending inspiratory limb indicating inadequate flow. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

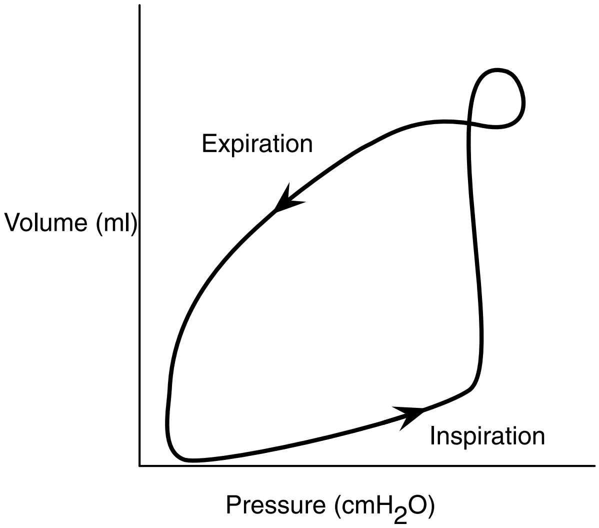


Figure 35: PV loop illustrating flow dyssynchrony. Notice the figure eight appearance of the PV loop resulting from a decrease in airway pressure secondary to active patient inspiration to increase airflow. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

Cycle dyssynchrony

Cycle dyssynchrony occurs when the patient starts to exhale before the ventilator has completed inspiration, that is, delayed breath termination, or when the ventilator's inspiratory flow stops before the patient has completed inspiration, that is, premature breath termination.[4,1217] Pressure-time and flow-time scalars are typically used to evaluate for cycle dyssynchrony. Figure 36 shows changes in the flow-time and pressure-time scalars during early breath termination. The flow-time scalar depicts an abrupt reversal in the expiratory portion of the waveform indicating the continuation of the patient's inspiratory effort (A). The expiratory portion of

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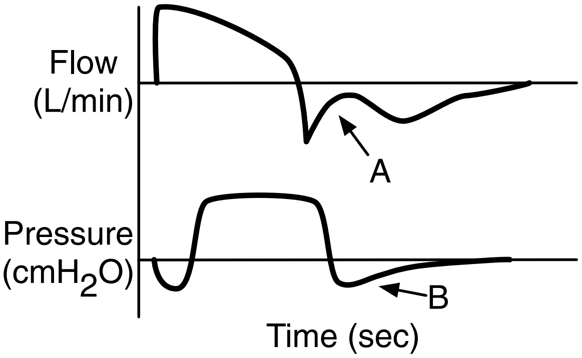

Figure 36: Cycle dyssynchrony illustrating early breath termination with flow-time and pressure-time scalars. The flow-time scalar shows an abrupt decrease in flow during the expiratory limb indicating an inspiratory effort of the patient (A). The pressure-time scalar has a concave appearance rather than a normal gradual decay to baseline indicating a continued patient inspiratory effort (B). Modified from Nilsestuen JO, Hargett KD. Using ventilator graphics to identify patient-ventilator asynchrony. *Respir Care* 2005; 50(2): 202–234; discussion 232–204 with permissions.

the pressure-time scalar returns more rapidly toward baseline giving it a concave appearance (B). In extreme cases, the continued patient inspiratory effort may result in double triggering of the ventilator.[20] Early breath termination may substantially reduce V_T and increase the work of breathing.[14,17,20]

The flow-time and pressure-time scalars in Figure 37 illustrate delayed breath termination in a patient ventilated with PSV. The patient actively exhales at the end of inspiration resulting in a rapid decline in inspiratory flow in the graph on the top (A) and a pressure spike at the end of inspiration in the graph on the bottom (B). Shortening the inspiratory time may help to match the patient's neural inspiratory time with the ventilator's inspiratory time as shown in Figure 38.[17] Increasing the flow cycle percentage during PSV that will shorten the inspiratory time may be helpful to correct cycle dyssynchrony due to delayed breath termination.[4,12]

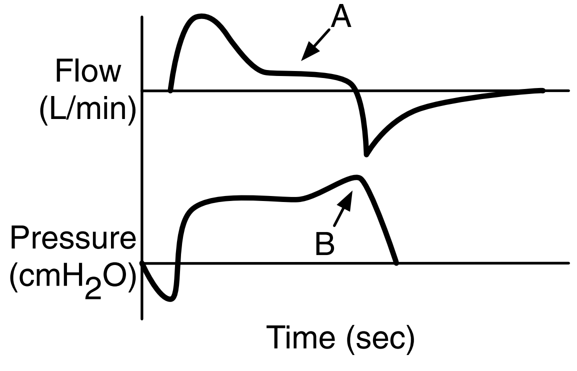

Figure 37: Cycle dyssynchrony due to delayed breath termination with flow-time and pressure-time scalars. The flow-time scalar shows a rapid decline in inspiratory flow at the end of inspiration due to active patient exhalation (A). The pressure-time scalar shows a pressure spike at the end of inspiration due to active patient exhalation (B). Modified from Nilsestuen JO, Hargett KD. Using ventilator graphics to identify patient-ventilator asynchrony. *Respir Care* 2005; 50(2): 202–234; discussion 232–204 with permissions.

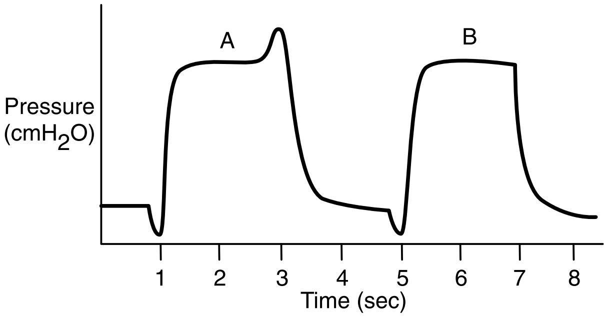

Figure 38: Effect of shortening the inspiratory time on cycle dyssynchrony. Delayed breath termination as indicated by the pressure spike due to active patient exhalation at the end of inspiration (A). Notice that shortening the inspiratory time to help match the patient's neural inspiratory time with the ventilator's inspiratory time eliminates the spike (B). Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

Expiratory dyssynchrony

Expiratory dyssynchrony may be due to a prolonged or shortened expiratory time. Prolonged expiratory times can lead to hypoventilation.[17] A shortened expiratory time is of significant clinical importance as it can lead to the development of auto-PEEP.[4,17] Auto-PEEP can lead to trigger dyssynchrony and increased work of breathing.[4,17] Flow-time scalars and FV loops are typically used to identify auto-PEEP, however pressure-time scalars and PV loops may also be helpful. In Figure 39 the expiratory portion of the flow-time scalar B, as compared to A, does not return to baseline before the next breath is delivered indicating the presence of auto-PEEP.[12,14] In the FV loop in Figure 40, the expiratory limb does not return to zero at the end of expiration, which is indicative of the presence of auto-PEEP.[3]

Management of auto-PEEP depends on the underlying cause. In general, measures to provide sufficient time for expiration should be taken. A detailed discussion about these measures is beyond the scope of this article. Trigger dyssynchrony associated with auto-PEEP may improve with the application of external PEEP approximately equal to the auto-PEEP.

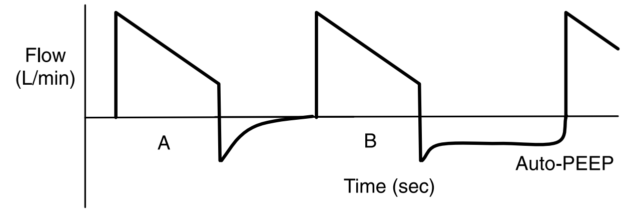

Figure 39: Flow-time scalar illustrating expiratory dyssynchrony due to auto-PEEP. Normal flow-time scalar (A). Notice the expiratory portion of graph B does not return to baseline before the next breath is delivered indicating auto-PEEP. Modified from Lian JX. Understanding ventilator waveforms and how to use them in patient care. *Nursing Crit Care* 2009; 4(1): 43–55 with permissions.

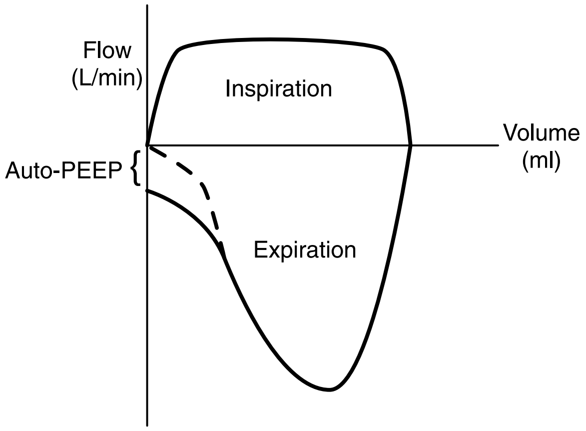

Figure 40: FV loop illustrating expiratory dyssynchrony due to auto-PEEP. Notice the expiratory portion of the curve does not return to zero at the end of expiration. Modified from Waugh JB, Deshpande VM, Brown MK, Harwood RJ. Rapid Interpretation of Ventilator Waveforms. 2nd ed. Upper Saddle River, NJ, Pearson Prentice Hall; 2007 with permissions.

Summary

An understanding of the basic concepts underlying ventilator waveform analysis and interpretation is important in the management of mechanically ventilated, critically ill, small animal patients. Ventilator waveform analysis can provide useful information about changes in respiratory pathology and causes for patient-ventilator dyssynchrony. The application of the principles outlined in this article can help the clinician to appropriately adjust ventilator settings, as well as improve patient monitoring and care.

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