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Ventilator Waveforms

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Ventilator waveforms are graphic representations of changes in pressure, flow, and volume within a ventilator circuit. The changes in these parameters over time may be displayed individually (scalars) or plotted one against another (pressure-volume and flow-volume loops). There are 6 basic shapes of scalar waveforms, but only 3 are functionally distinct (square, ramp, and sine). The pressure scalar is a particularly valuable tool when constant flow (e.g., volume control) modes are employed and an inspiratory pause is added. In this setting, inspection of the pressure waveform can allow determination of static, quasistatic, and dynamic compliance, as well as relative changes in airway resistance. Inspection of the pressure waveform can also help to identify many important aspects of patient drug responses, dyssynchrony, and air trapping (auto positive end-expiratory pressure [auto-PEEP]). Depending on the ventilation mode employed, the shape of the flow waveform may be set by the ventilator operator or may be dependent on patient effort and lung mechanics. Decelerating flow patterns have several important advantages when this option is available. Inspection of flow waveforms is crucial in the recognition of dyssynchrony, setting optimal inspiratory times, evaluating responses to bronchodilators, and the recognition of auto-PEEP. The volume waveform often contains somewhat less useful information than the other 2 scalars, but plays a crucial role in the identification of leaks in the circuit. Pressure-volume loops are particularly useful in setting PEEP and peak inspiratory pressure ranges. Inspection of these loops also often helps in the evaluation of lung mechanics, in the identification of circuit leaks, and in the assessment of patient triggering effort. Flow-volume loops are extremely useful in the identification of leaks and excessive airway secretions as well as alterations in airway resistance. Lastly, serial waveform inspection is crucial to the identification and resolution of patient-ventilator dyssynchrony in many cases.

Introduction

Long-term (> 24 hours) intermittent positive pressure ventilation (IPPV) can be a life-saving therapy for patients with severe respiratory compromise.[1,2] It is also frequently employed as a short-term supportive measure for patients with transient respiratory dysfunction (e.g., depressed respiratory drive during anesthesia).[3,4] When choosing ventilator settings, the operator must first choose a mode of ventilation and then select the machine settings based on general guidelines, disease-specific guidelines, and presumed patient needs.[5] These initial settings may be adjusted based on an evolving understanding of the nature of the patient's respiratory disease and response to empiric trial. Following initiation of mechanical ventilation, the ventilator settings are altered as necessary to achieve the targeted gas exchange levels. Inspection of ventilator waveforms, in combination with arterial blood gas values and inspection of the patient, often provides the most comprehensive overview of the appropriateness of the current settings, allows monitoring of disease status and ventilator troubleshooting, and may also help to identify the source(s) of the patient-ventilator dyssynchrony (PVD).[6-11] Waveform interpretation can be challenging and this article is meant to serve as an introduction to the process for the interested reader.

Types of Waveforms

General

Ventilator waveforms are typically divided into those wherein a single parameter plotted over time (scalars) or 2 parameters plotted simultaneously (loops). Scalar waveforms generally take on 6 characteristic shapes (Fig 1): square, ascending ramp, descending ramp, sine, exponential rise, and exponential decay. Ramp and exponential waveforms are functionally similar enough that exponential waveforms can be often lumped into the ramp category, leaving 3 characteristic shapes: square, ramp, and sine. Sine waveforms are characteristic of patient efforts such as is seen with spontaneous breaths in continuous positive airway pressure or synchronized intermittent mandatory ventilation (SIMV). Square waveforms indicate that the given parameter changes abruptly, but is then held at a near constant value for a period of time. Ramp and exponential waveforms indicate that a parameter is changing gradually over time, with a rate of change that is either constant (ramp) or variable (exponential). Scalars are made up of a series of these waveforms plotted above or below the axis over time (Fig 2). Many modern ventilators can display multiple different scalars simultaneously (Fig 2). Deflections below the axis can indicate either that values are lower than a reference point (e.g., pressure below baseline) or directionality (e.g., flow into or out of the patient). Determining which waveform to monitor most closely depends on the setting and clinician need. As a rule of thumb, the scalar that represents the dependent variable would have the information that most directly reflects the patient's respiratory mechanics. For example, if the patient is being ventilated in a pressure-control mode, then the flow and volume scalars would contain useful information, whereas the pressure scalar should appear however the clinician set it to appear. This rule does not wholly apply to PVD, however, as patient effort in this setting often leads to subtle alterations in the plot of the independent variable.

Waveforms in Different Ventilation Modes

The scalar waveforms take on characteristic shapes depending on the mode of ventilation employed. Ventilator waveforms associated with commonly employed modes of ventilation are shown in Figs 2 and 3. In Fig 2, the characteristic shape of the waveforms seen with volume control modes (volume-assist/control ventilation [V-ACV] and SIMV-volume control [SIMV-VC]) are

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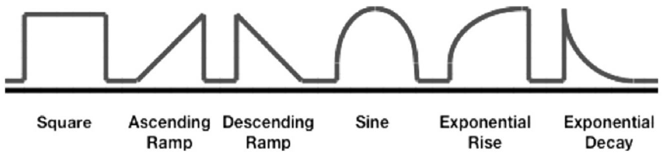

Fig. 1. Characteristic shapes of ventilator waveforms. The 6 basic forms that make up standard ventilator scalar graphics are shown. Ascending ramp and descending ramp are functionally equivalent to exponential rise and exponential decay, respectively. Sine wave form is typically associated with spontaneous breathing efforts.

shown.[12] Two successive machine-delivered breaths are shown with no patient triggering or spontaneous breaths. The pressure waveforms have the characteristic exponential rise shape ("shark fin"). The highlighted area denotes a period of inspiratory hold, which allows time for intrapulmonary redistribution of gas ("*pendelluft*") with a resultant pressure decline from peak inspiratory pressure (PIP) to plateau inspiratory pressure (Pplat).[13] If the inspiratory hold was removed, then this concavity would not be present and expiration would begin once the preset tidal volume had been achieved. It should be noted that the flow profile in this setting is constant (square) throughout inspiration. The delivery of flow at a constant rate allows for meaningful assessment of airway resistance (Raw). However, some ventilators allow for the delivery of flow during volume control modes with a descending ramp profile, which has several potential benefits. The inspiratory hold also results in a prominent plateau in the volume waveform as is shown in Fig 3; the characteristic shape of the waveforms seen with pressure-control modes (pressure-ACV [P-ACV] and SIMV-PC) and support modes are shown. In pressure-control modes, the pressure waveform is now the one with the characteristic shape whereas the flow waveform typically assumes the shape of an

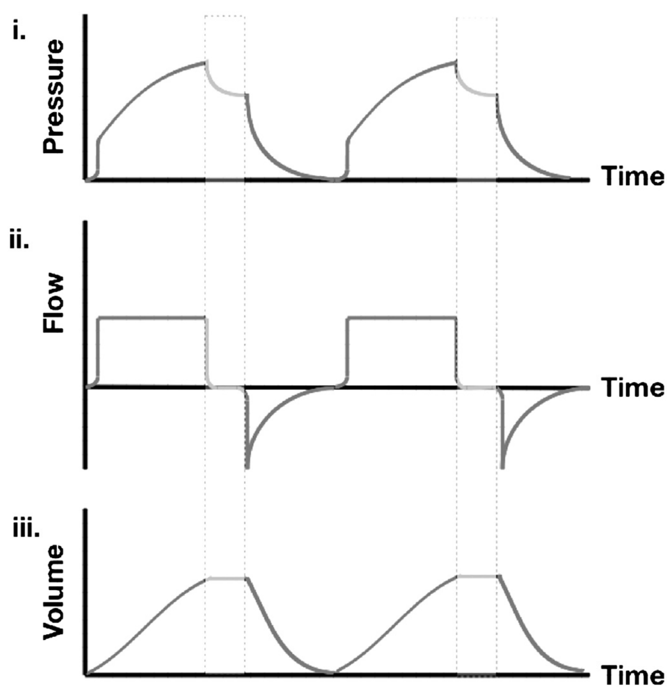

Fig. 2. (i-iii) Scalar waveforms typical of volume control modes of ventilation. The pressure, flow, and volume scalars are shown as they typically appear when volume control modes of ventilation are employed. An inspiratory hold is in place (shaded zones), which gives the pressure scalar (i) the classic appearance of a shark fin with a bite taken out of it. The inspiratory hold results in a period of zero flow before exhalation on the flow scalar and a prominent plateau in the volume scalar. In this example, a constant flow delivery option has been selected (square wave in (ii)) instead of a descending ramp which is an option on many modern ventilators.

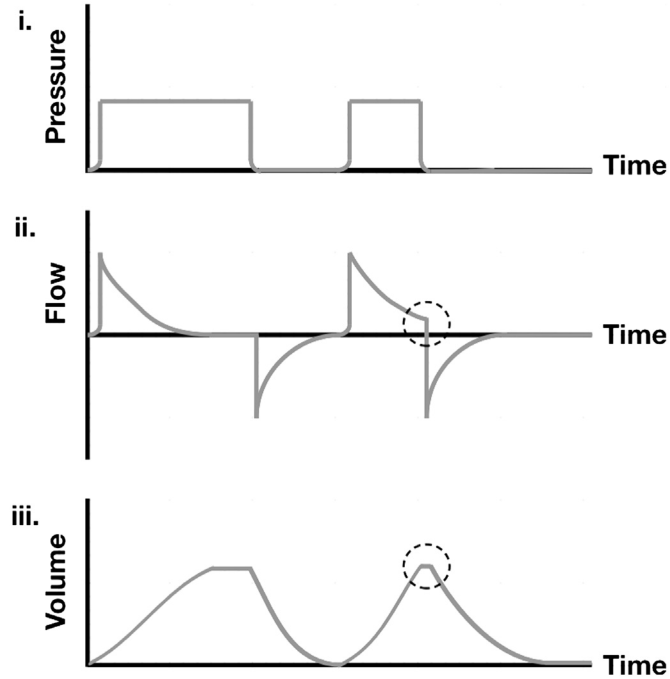

Fig. 3. (i-iii) Scalar waveforms typical of pressure-control modes of ventilation. The pressure, flow, and volume scalars are shown as they typically appear when pressure-control modes of ventilation are employed. In contrast to the appearance of the scalars in volume modes (Fig 2), in this context, it is the pressure that is constant during inspiration (i) whereas the flow scalar takes on an exponential decay form. An inspiratory hold may still be prescribed and this again results in plateau of the volume scalar (iii). The scalars for the second breath are typical of pressure support modes of ventilation. Patient effort effects have been omitted to improve clarity. In the pressure support mode, inspiratory flow (ii) cycles off when a target flow rate is reached (e.g., 30% of peak flow) and this is reflected by the flow not reaching zero before exhalation begins. As such, the previously seen volume scalar plateau is no longer observed (iii).

exponential decay.[14] The volume waveform may be indistinguishable from those observed with volume control modes. The series of waveforms to the right in this figure show typical profiles for pressure support modes (e.g., SIMV with PSV). In this setting, inspiratory flow is not expected to reach zero before expiration begins. In these instances, the inspiratory flow is set to cycle off once a preset percentage of peak flow is achieved (e.g., 30% of peak). This point is reached within the upper dashed circle in the figure. Because the termination of inspiratory flow occurs when the flow is low but not zero, the volume waveform shows a minimal plateau (lower dashed circle).

The use of synchronized intermittent mandatory ventilation (SIMV) as mode of ventilation may be preferred in some clinical settings; however, it represents an additional level of complexity when it comes to ventilator waveform interpretation. Four archetypal sorts of SIMV breaths are displayed in Fig 4 for comparison.[15] The vertical series labeled "A" depicts the typical waveforms associated with a mandatory breath in SIMV-VC. In this setting, the shark fin pressure tracing and square wave flow tracing are evident. No inspiratory hold has been prescribed, so expiration begins once the target tidal volume is achieved. Before the initiation of inspiratory flow, there is no evidence of patient effort (triggering). The second breath (vertical series "B") is a spontaneous breath with characteristic sine wave appearance. It should be noted that the negative portion of the pressure tracing is associated with inward flow because this is a spontaneous breath and not a positive pressure machine-delivered or assisted or supported breath. The tidal volume the patient achieves is lower than that seen with the preceding mandatory breath, which is

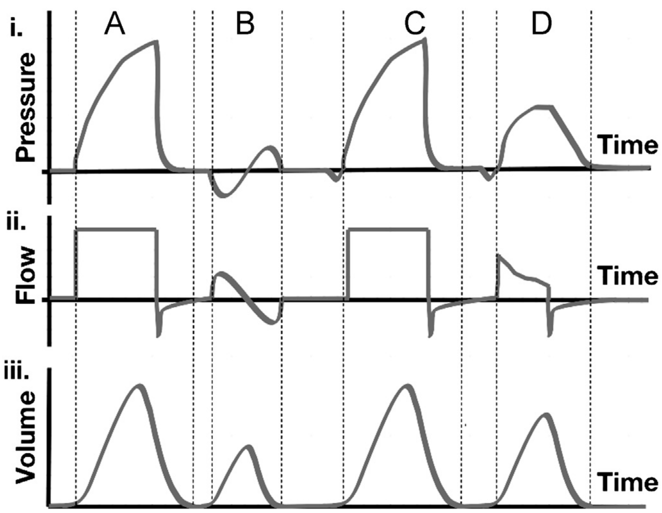

Fig. 4. (i-iii) Scalar waveforms typical of SIMV breaths. The pressure, flow, and volume scalars are shown as they typically appear when SIMV modes of ventilation are employed. The first 3 breaths shown (A-C) are depicted as they would appear for SIMV-VC. Inspiratory flow rates are constant for breaths A and C. The pressure scalar for breath A and C have the shark fin appearance typical of volume control modes without an inspiratory hold. The difference between the 2 is that A is a fully mandatory breath whereas C is a patient-triggered, synchronized, machine-delivered breath as illustrated by the patient-generated decline in airway pressure preceding breath C (but not A). The tidal volume and flow patterns are identical for these 2 breaths, the only difference is the trigger (time vs. patient effort). Breath B is typical of spontaneous breathing efforts during the interval between mandatory breaths. A typical sine wave pattern is seen. A smaller tidal volume is achieved in this example. The breath D tracings are typical of SIMV with pressure support. Patient triggering is evident on the pressure tracing (iD) with an accompanying descending ramp flow pattern (iiD). Inspiratory flow cycles off before zero flow is reached, which is typical of support modes. In this example, a tidal volume intermediate in value between mandatory and spontaneous breaths is achieved.

what is typically observed (but not obligatory as it depends on patient effort and capacity). The third breath (vertical series "C") represents a synchronized, patient-triggered, but machine-delivered breath. In this instance, the patient's inspiratory effort fell near to the time when the next mandatory breath was due. As such, the ventilator delivered a breath equivalent to the mandatory breath (series "A"), but did so at a time synchronous with the patient's respiratory efforts. The tidal volume is identical to that achieved with the first breath. The patient's efforts only altered the timing of the breath, not its character. The nature of SIMV is such that there are preset periods of time immediately *following* a mandatory breath wherein the patient may breathe spontaneously and small time intervals *before* a mandatory breath during which patient efforts would trigger early delivery of the next ventilator-delivered breath (thus the *synchronized* nature of SIMV vs. IMV). The fourth breath (vertical series "D") represents the waveforms typical of SIMV with pressure support. Here the patient's inspiratory efforts result in the ventilator delivering additional flow to supplement that achieved by the patient's own efforts. This pressure support is set to cease once a predetermined level of inspiratory flow is reached (e.g., 30% of peak flow). This is reflected in the flow waveform by the fact that inspiratory flow abruptly ceases at a level above zero. The tidal volume attained is larger than that the patient achieved with a spontaneous breath ("B"), but smaller than the mandatory breaths ("A" and "C"). However, equivalent tidal volumes could be achieved by increasing the level of pressure support.

Pressure Waveform

The pressure waveform typically takes on an exponential rising (volume control modes with constant flow) or square waveform (pressure control) (Fig 5iA and C). In volume control modes with an exponential decay flow profile, the pressure scalar profile often appears as less square and more rounded. As mentioned previously, when an inspiratory pause is in place, the pressure waveform takes on the shape seen in Fig 5iB and ii shows that when PEEP is being applied, it is expected that pressure never returns to baseline, but rather remains at this preset level above atmospheric pressure between breaths (dashed line). Pressure decreases below this level indicate patient effort, artifact, or circuit leaks.[16]

When an inspiratory pause is in place, inspection of the pressure waveform may reveal a great deal of information regarding the patient's lung mechanics (Fig 5iii). In this setting, (PIP; "a") and plateau pressure (Pplat; "c") can be determined; these pressures can be used to calculate dynamic and static compliances, respectively. For example, tidal volume/(PIP-PEEP) would estimate dynamic compliance whereas tidal volume/(Pplat-PEEP) would estimate static compliance. Dynamic compliance (Cdyn) is higher than static compliance (Cs) because of the increased pressure required in overcoming circuit and Raw. This pressure would be reflected by the size of the region labeled "1" in this figure. True static compliance can only be determined once bulk flow (gas delivery) and intrapulmonary flow (pendelluft) have ceased (point "c"). In many cases, clinicians may be reluctant to design a breath with an inspiratory hold of the requisite length ($\sim$1.5 seconds) to truly measure static compliance and instead design application of a more brief inspiratory hold. In such a case, the pressure drops to the point labeled "b" and compliance measurements derived using these values are termed "quasistatic" (i.e., Cqs). In Fig 5iii, the determinants of mean airway pressure (MAP) can be appreciated. The major influences on MAP values are the relative height and width of 4 distinct pressures: (1) pressure utilized to overcome circuit and airway resistances, (2) pressure used to deform the lung and expand the alveoli, (3) pressure throughout the expiratory flow phase, and (4) PEEP.[17] An increase in the surface area of any of these regions without an equivalent decrease in another would result in a higher MAP.

The PIP value on the pressure scalar can also be used in the estimation of Raw as resistance is equal to the driving pressure divided by flow. An increase in Raw is seen as an increase in PIP without an accompanying increase in Pplat (Fig 6i). Conversely, a decrease in compliance is evidenced by an increase in PIP and Pplat both, with an unchanging difference between the 2 values (Fig 6i).

Although an inspiratory hold can generate a wealth of information regarding pulmonary mechanics, an expiratory hold can also yield useful information.[18] Many ventilators come equipped with an option for performing expiratory hold maneuvers. Performing this task allows one to quantify intrinsic PEEP due to gas trapping (auto-PEEP) as long as auto-PEEP is of a value greater than set PEEP (illustrated in Fig 6ii). In the example shown, set PEEP is $+5$ cm H_2O, but auto-PEEP is present and total PEEP is actually $+10$ cm H_2O. In such situations, the auto-PEEP can have many adverse effects including making patient triggering of the ventilator more challenging. In this instance, if the trigger value was set to -2 cm H_2O below PEEP, the patient would have to drop airway pressure to -7 cm H_2O instead of -2 cm H_2O before a breath would be triggered owing to the additional airway pressure from auto-PEEP.

Flow Waveform

The flow scalar takes on either a predictable, repeatable shape or a variable shape depending on the ventilation mode employed. In volume control modes of ventilation, the flow waveform would typically be square or descending ramp in conformation.[19] Many ventilators allow the operator to choose the flow profile in this setting. In spontaneous breathing, the flow profile would be sine

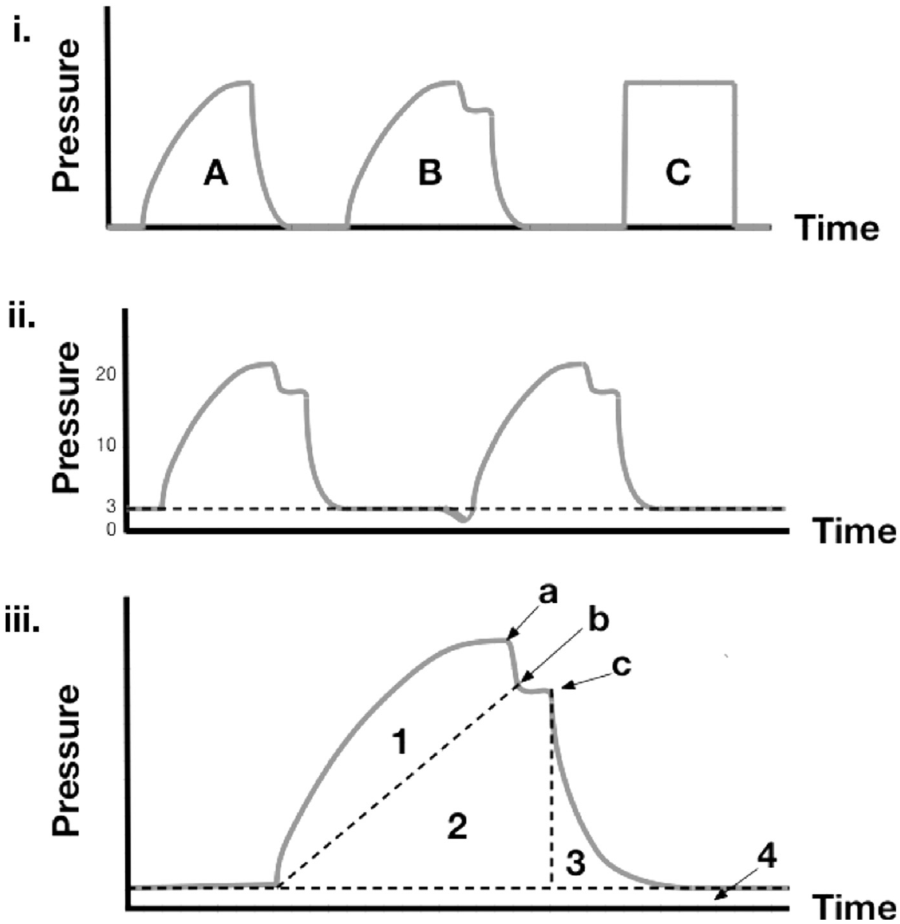

Fig. 5. (i-iii) The pressure waveform. Waveforms iA and iB are typical of volume control without and with an inspiratory hold, respectively. In pressure-control modes, inspiratory pressure remains constant (iC) and the pressure scalar assumes a square conformation. The presence of PEEP raises baseline pressure above atmospheric (dashed line in ii.) and patient triggering efforts are seen as dips in pressure below the value of PEEP. When an inspiratory hold is added, the pressure tracing can be analyzed and many aspects of lung mechanics can be quantified. Point (a) represents PIP and point (c) indicates Pplat. The drop in pressure from (a) to (c) is due to redistribution of gas from rapidly filling to more slowly filling alveoli. Compliance measurements using PIP constitute dynamic compliance whereas those using Pplat estimate static compliance. When only a very brief inspiratory hold is used, the pressure at point (b) is obtained and quasistatic compliance determined. The area of the regions labeled 1-4 each contributes to overall mean airway pressures.

wave in appearance. Lastly, in pressure-control modes, the flow waveform typically takes on an exponential decay appearance (Figs 2 and 3).[20] Using a constant flow pattern (square wave) does allow for certain pulmonary mechanics measurements to be made as one can assign an absolute value to flow, next measure pressure differential, and then finally calculate resistance. However, the constant flow approach does have some drawbacks. For a given tidal volume delivered, using a constant flow delivery would result in modestly higher PIPs than if a decelerating ramp approach is taken, as illustrated in Fig 7i and ii.[21-25] Moreover, the use of a decelerating ramp pattern allows for fine-tuning of inspiratory time (I-time). Fig 8 shows 4 different volume control mandatory breaths with 2 different flow profiles. For the breath to the far left, a constant (square) flow delivery was selected whereas for the remaining 3 a decelerating ramp flow pattern was chosen. The third breath ("c") shows the appearance of the waveform when I-time is optimal. Flow returns all the way to zero before exhalation begins. In breath "b," the I-time is too short and this may lead to flow asynchrony. In the case of breath "d," the I-time is too prolonged and there is a noticeable period of "zero-flow state" before exhalation. This zero-flow state puts the patient at risk for double triggering and other forms of PVD.[26] When one looks at breath "a," one can see that the constant flow rate option does not lend itself to the adjustment of I-time as the transition from inspiration to expiration is always abrupt when this flow pattern is selected, unless an inspiratory hold is put in place. Thus, if the clinician opts for a volume control mode of ventilation, the selection of a decelerating ramp flow pattern may allow for a

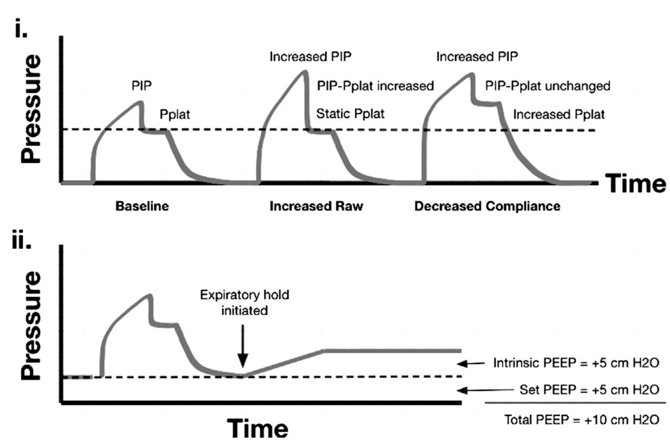

Fig. 6. (i-ii) Using the pressure waveform to assess changes in lung mechanics. (i) The characteristic changes in the pressure waveform, PIP, Pplat, or both are shown for instances of increased airway resistance and decreased compliance. (ii) An expiratory hold maneuver can be used to determine if auto-PEEP is present. Pressure rise above PEEP in this setting reflects intrinsic PEEP due to gas trapping.

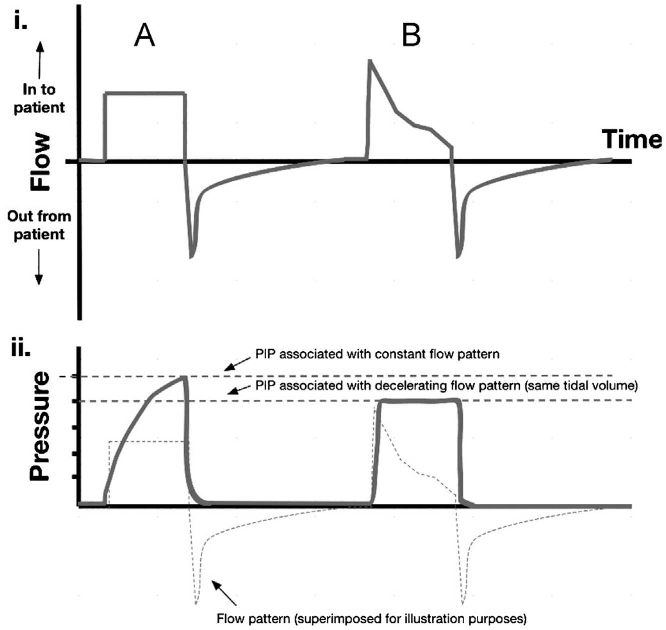

Fig. 7. (i-ii) The flow waveform. (i) The flow waveforms typically seen when volume-control modes of ventilation are employed are shown. (iA) Square wave indicative of a constant inspiratory flow pattern. (iB) Descending ramp flow patterns are also an option on many modern ventilators. (ii) Pressure waveforms for 2 breaths of equal tidal volume delivered in volume control mode. One advantage of using the descending ramp flow pattern is that the same tidal volume can often be achieved at a lower peak inspiratory pressure.

lower PIP as well as allow one to optimize I-time using waveform inspection methods.

The flow scalar is also a key tool in the detection of auto-PEEP without having to apply an expiratory hold. When auto-PEEP is present, the expiratory flow does not return to zero before the breath is delivered (Fig 9). That is to say, the patient is not done exhaling the last breath when the next one is applied. In this way, auto-PEEP can occur even in patients without intrathoracic airway dysfunction.

Volume Waveform

Of the 3 standard scalar waveforms, volume tracing typically contains the least information that would lead a clinician to alter ventilator settings. This is because most ventilators that can display graphic outputs also provide numeric outputs as well. As such, one often relies on numeric outputs of tidal volume and spends more time inspecting the other 2 scalars. However, there is some value to visual inspection of the volume scalar. In particular, it can provide a rapid qualitative picture of the relative size of spontaneous and mandatory breaths during SIMV or of patient effort during continuous positive airway pressure breathing. The volume waveform is inextricably linked to the flow waveform. One parameter is generally derived from the other. In many modern ventilators, the circuit flow is determined (often via a flow disruptor and differential pressure transducer) and it is the flow signal over time that is used to calculate the delivered or exhaled volume. Thus, when one looks at the volume tracing, one can see that the slope of the curve at any point reflects the instantaneous flow rate ($\Delta V/\Delta t$), as shown in Fig 10i. In this same figure, one can see that between the points labeled "a" and "b," the slope is large and positive and thus the flow scalar should have a large positive deflection at this same point. Between "b" and "c," the slope of the volume waveform is zero, thus the volume is unchanging, and thus a corresponding zero-flow period is expected on the flow scalar. Lastly, between "c" and "d," one would expect to see a large negative deflection on the flow scalar to reflect the rapidly decreasing volume in the circuit. Tidal volume can also be determined from inspection of the volume, scalar as shown in this same figure. Lastly, the other major role for volume waveform inspection is in the identification of circuit leaks or gas trapping. As shown in Fig 10ii, a volume waveform that takes a vertical plunge straight to baseline in the midexpiratory to late-expiratory phase indicates that more volume came in across the flow sensor than ultimately came back. This can mean that there is a leak in the circuit or that a given volume of gas has unexpectedly remained within the patient (e.g., gas trapping or unidirectional flow into the pleural cavity).

Pressure-Volume Loops

Pressure-volume loops (PV loops) are graphic representations of the dynamic interconnection between changes in circuit pressure and circuit volume. Inspection of PV loops has long been used in the assessment of lung mechanics in patients on ventilator.[27] In the last 2 decades, PV loop assessment has also come to play an important role in designing protective lung strategies for the support of patients with acute respiratory distress syndrome.[28] Fig 11i shows a typical PV loop for a mandatory, machine-delivered breath in a patient on a ventilator. As the patient is receiving IPPV, inflation of the lungs corresponds with a rise in circuit pressure (inspiratory limb). It should be noted that in a spontaneously breathing patient (or one in a negative pressure ventilator or iron lung), the addition of volume to the circuit would be associated with a *decrease* in circuit pressure and thus the tracing of the loop would proceed in a clockwise fashion instead (not shown). Several features of Fig 11i are noteworthy. First, the loop does not begin at a pressure value of 0. This indicates the patient is on PEEP. Next, the pressure and volume values recorded at the highest value of the loop (upper right hand area of the plot) would correspond to PIP and tidal volume, respectively. Finally, a dashed line connecting the 2 points at which volume is not changing has been added. This line connects the starting and end-inspiratory points. As no significant circuit flow is occurring at these points, the pressure value largely reflects that required to distend the lung to that volume and not the additional pressure required to overcome airway and circuit resistance. The bowing of the inspiratory limb away from this line reflects the additional pressure required to overcome these resistances. The slope of this line is a measure of pulmonary compliance. As intrapulmonary flows have not been given enough time to cease, this form of compliance would be termed dynamic compliance (Cdyn) rather than static compliance.

Fig 11ii shows a patient-triggered PV loop for comparison. This "figure 8" type of loop is typical of patient effort.[29] In this case, the

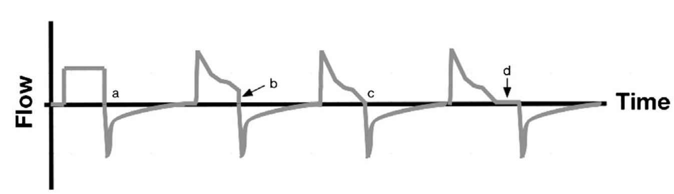

Fig. 8. Using the flow scalar to optimize inspiratory time. The flow waveform for 4 different volume control mandatory breaths with 2 different flow profiles are depicted. For breath (a), a constant (square) flow delivery was selected whereas for the remaining 3 (b-d) a decelerating ramp flow pattern was chosen. The third breath (c) shows the appearance of the waveform when I-time is optimal. Flow returns all the way to zero before exhalation begins. In breath "b," the I-time is too short. In the case of breath "d," the I-time is too prolonged and there is a noticeable period of "zero-flow state" before exhalation. When one looks at breath "a," one can see that the constant flow rate option does not lend itself to the adjustment of I-time as the transition from inspiration to expiration is always abrupt when this flow pattern is selected unless an inspiratory hold is put in place.

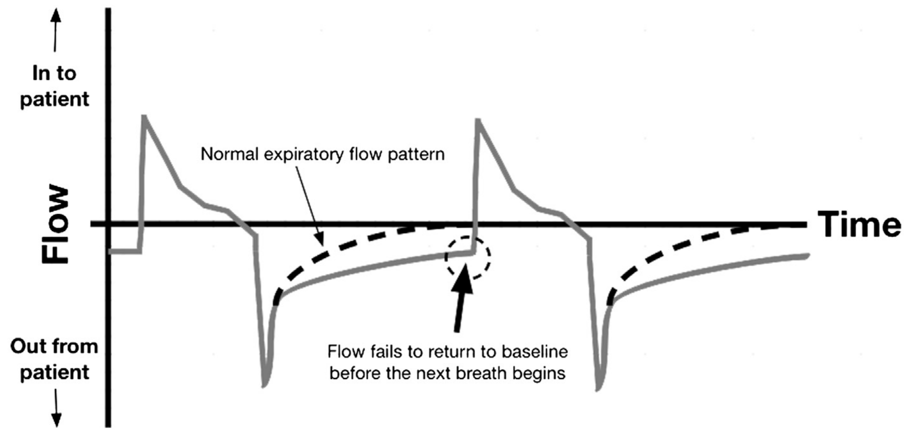

Fig. 9. (i-ii) Using the flow scalar to detect auto-PEEP. The pressure tracing from 2 successive breaths delivered in volume control mode with descending ramp flow patterns is depicted. In this example, expiratory flow fails to return to zero before the next breath is delivered, indicating that auto-PEEP is present.

patient effort is triggering or initiating activity and thus the small loop lies in the lower left aspect of the tracing. PVD may result in small patient-generated loops at other points in the tracing (e.g., the expiratory limb). The dashed vertical line and arrow indicate the PEEP value and one can note that the patient efforts bring airway pressure below this resting value. Once the triggering threshold is reached, a machine-delivered breath proceeds. The size of the shaded area of the patient effort loop indicates the work done by the patient to trigger the breath. If the trigger sensitivity is altered, then the patient would need to do more or less work to trigger the ventilator and the size of this area would change.

Changes in the orientation and area of PV loops can indicate alterations in the mechanical properties of the patient's lungs, the circuit, or both.[29] Fig 12i shows 2 loops from the same patient. The gray loop is the initial tracing whereas the black loop shows the changes expected to occur with an increase in airway or circuit resistances or both. The loop bows out farther from the dynamic compliance line indicating that relatively greater applied pressure is required to overcome resistance and reach a given volume. It should be noted that the Cdyn (as indicated by the slope of the line) has decreased. Unlike static compliance, the value of Cdyn is altered by changes in resistance because flow is not allowed to cease entirely. Increased bowing of the PV loop should prompt the clinician to investigate whether the endotracheal tube is kinked or obstructed, heat-moisture exchanger occlusion has occurred, or airway suctioning or bronchodilator administration is needed. Compliance changes also alter the shape and position of PV loops. As shown in Fig 12 ii, a reduction in compliance (e.g., pulmonary edema develops) caused the PV loop to rotate (labeled "A") as if its starting point was anchored and the loop rotated toward the *x*-axis. Conversely, if compliance increases (e.g., edema resolves) as

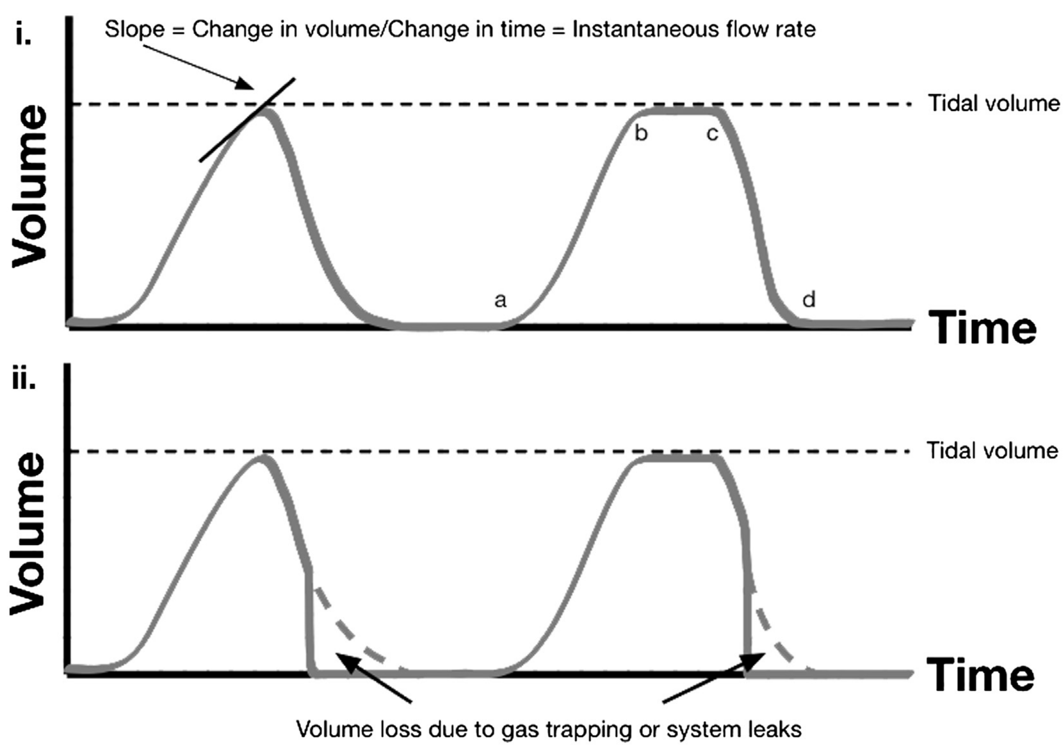

Fig. 10. (i-ii) The volume waveform. The volume waveforms from 2 successive breaths are represented. One cannot typically discern the ventilation mode employed from inspection of the volume waveform alone. (i) Tidal volume can be determined as the peak volume attained. The slope of the volume tracing at any point is equal to the instantaneous flow rate at that instance. Inspiration occurs between points (a) and (b). The plateau between (b) and (c) indicates that an inspiratory hold has been delivered. Between points (c) and (d), exhalation occurs. (ii) Inspection of the volume tracing can alert the clinician to a circuit leak or gas trapping.

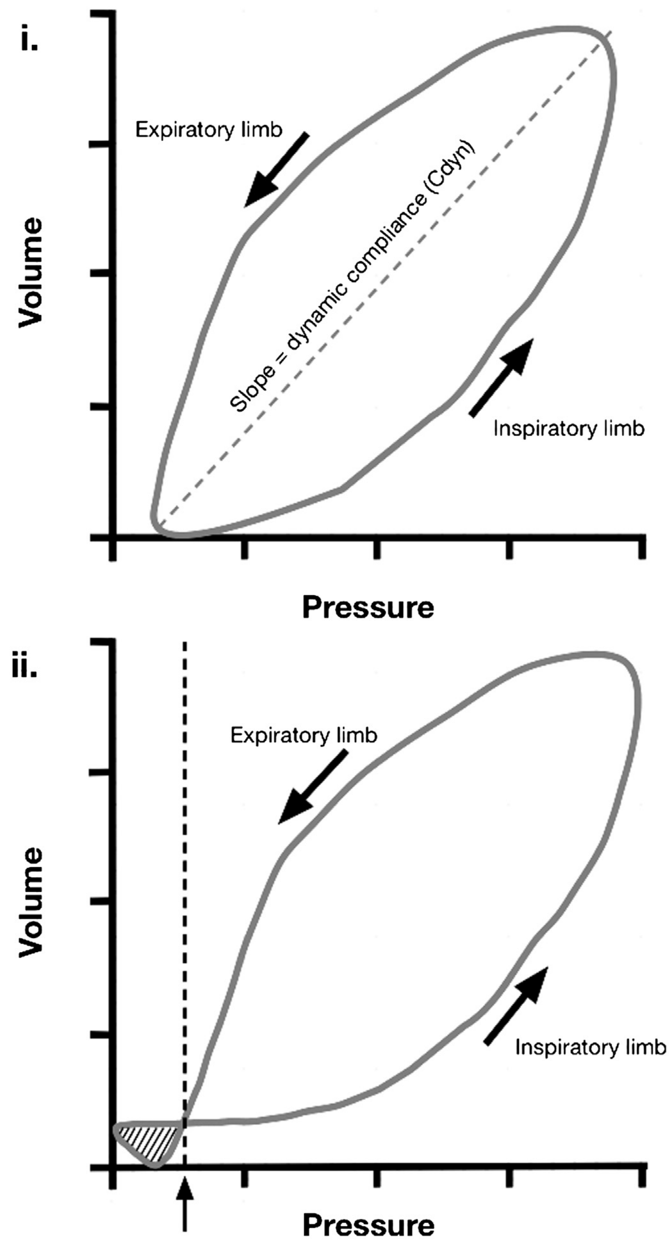

Fig. 11. (i-ii) Pressure-volume (PV) loops. Typical PV loops for machine-triggered (i) and patient-triggered (ii) breaths are depicted. PEEP is present in both examples (dotted line and arrow). The shaded area in loop (ii) is reflective of the degree of patient effort exerted during the triggering phase. A line can be drawn between the 2 points where minimal flow occurs (end exhalation and end inspiration) and the slope of this line is an estimate of dynamic compliance.

if its starting point was anchored and the loop rotated toward the *y*-axis (labeled "B"). The change in compliance can be appreciated by the significant alteration in the slopes of the Cdyn lines.

One must keep in mind that the shape of the PV loops is not entirely independent of the ventilator settings. Providing the same tidal volume with more rapid flow rates would result in increased bowing of the loop away from the compliance line. Moreover, in pressure-control modes, the latter portion of the inspiratory limb can appear nearly vertical as constant inspiratory pressure is maintained (Fig 13i). Excessively large tidal volumes can lead to alveolar overdistension and "beaking" of the terminal portion of the inspiratory limb.[27] Beaking reflects further increases in circuit pressure with minimal additional volume increase. This shape is assumed once the alveoli have been expanded excessively and can only accept additional volume with large pressure increases.

The recognition of the mechanisms underlying ventilator-induced lung injury has lead to a greater role for PV loop inspection in optimizing ventilator settings. In this setting, the clinician is advised to inspect the loop in search of 2 important inflection points (Fig 14i). The lower inflection point reflects a point at which pulmonary compliance significantly increases. This is thought to be the point at which a number of collapsed conducting or gas exchange units or both open. The cyclic opening and closing of these areas can lead to significant pulmonary damage (atelectrauma).[30] This atelectrauma can be minimized by increasing PEEP to a value greater or equal to the value at which

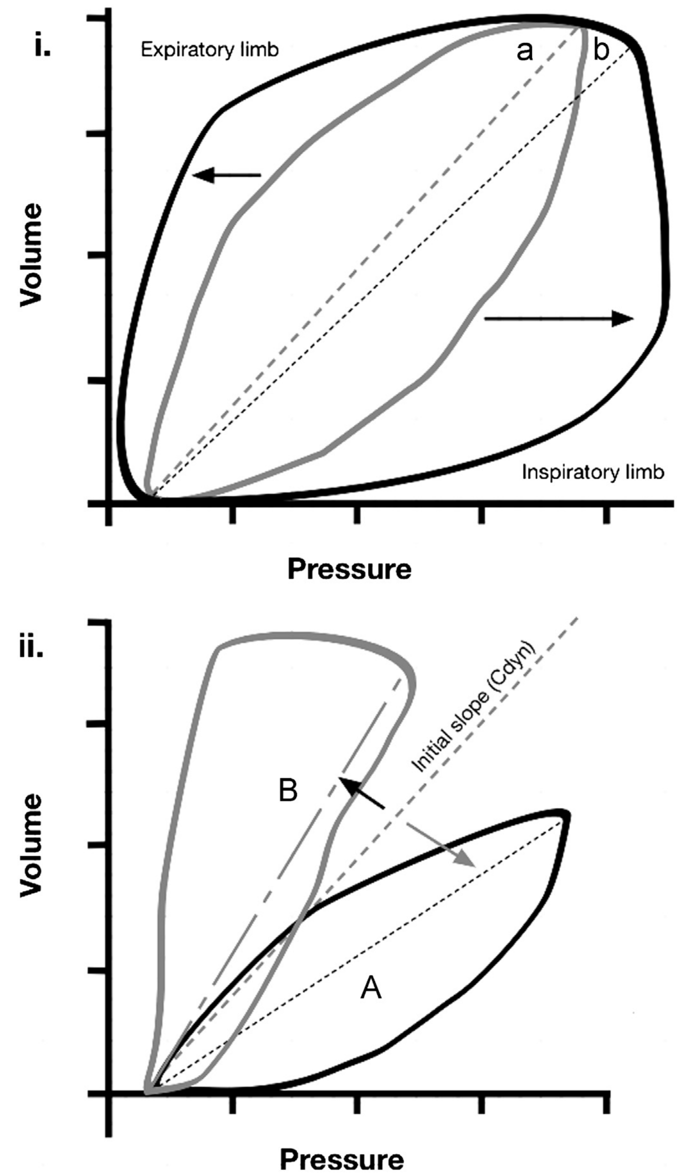

Fig. 12. (i-ii) Pressure-volume loop changes seen with alterations in pulmonary mechanics. (i) Two PV loops from the same patient are depicted. The gray loop is the initial tracing whereas the black loop shows the changes expected to occur with an increase in airway or circuit resistances or both. The loop bows out farther from the dynamic compliance line indicating that relatively greater applied pressure is required to overcome resistance and reach a given volume. Note that the Cdyn decreased (as indicated by the slope of line "a" vs. line "b"). (ii) A reduction in compliance (e.g., if pulmonary edema develops) would cause the PV loop to rotate (labeled "A") as if its starting point was anchored and the loop rotated toward the *x*-axis. Conversely, if compliance increases (e.g., edema resolves), the PV loop would rotate as if its starting point was anchored and the loop rotated toward the *y*-axis (labeled "B"). The change in compliance can also be appreciated by the significant alteration in the slopes of the Cdyn lines.

the lower inflection point is observed. In contrast, the upper inflection point reflects the point at which pulmonary compliance significantly decreases owing to alveolar overdistension and the risk of alveolar injury (volutrauma) is increased.[31] It is generally advised to keep PIP below the pressure at which the upper inflection point is noted. It must be noted that in small patients (<2 kg), the flow signal (and thus volume changes) may be difficult to acquire using all but the most sensitive equipment. When the monitoring equipment cannot acquire the signal, many models continue to plot the last recorded value. The plot of a rising pressure with an absolutely constant volume results in a sharp, narrow horizontal beak at end inspiration where flow is lowest. This signal acquisition artifact can mimic true beaking in these small patients. The clinician should remember that biological processes rarely result in biophysical relationships that are absolutely linear in nature.

A leak in the ventilator circuit can also be reflected by changes in the PV loop. Fig 14 ii shows an open, broken, incomplete loop that is typical of a circuit leak. Monitoring for leaks is important for ensuring proper cuff inflation, ensuring delivery of targeted tidal volume, and alerting the clinician to the possibility of air leakage from the respiratory tract to the pleural space.

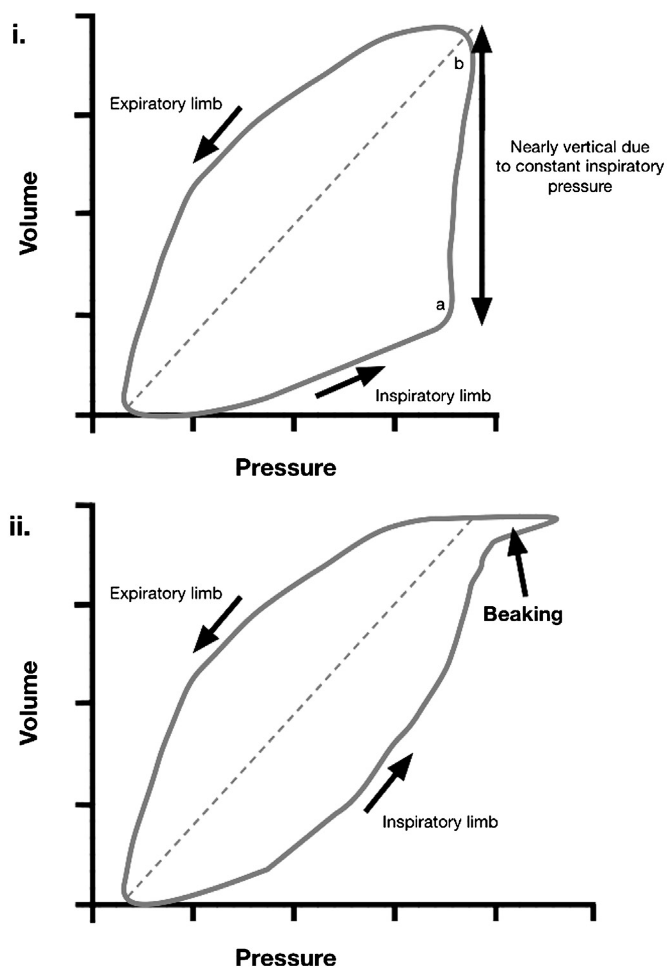

Fig. 13. (i-ii) Pressure control and overdistension effects on PV loops. (i) The constant pressure applied during inspiration can lead to a more square-shaped PV loop. (ii) Overdistension of the alveoli by excessively large tidal volumes can result in a beaklike extension of the portion of the PV loop found near end inspiration.

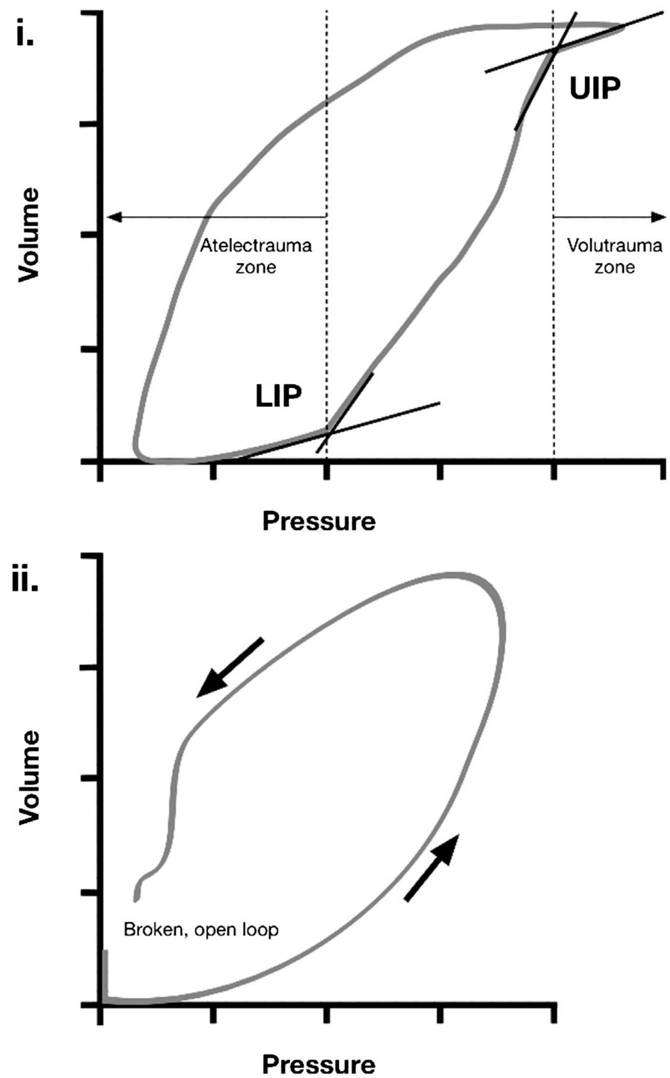

Fig. 14. (i-ii) Upper or lower inflection points and circuit leaks on PV loops. (i) On some (but not all) PV loops, an upper or lower inflection point, or both, may be identified. Maintaining airway pressures between the pressures at which these inflections occur can help to reduce ventilator-induced lung injury. (ii) Circuit leaks result in broken, open PV loops in which the expiratory limb fails to return fully to the starting point.

Flow-Volume Loops

Flow-volume loops are related to the flow scalar and the inspiratory and expiratory limbs should roughly match the shape of the flow scalar portions above and below the *x*-axis, respectively (Fig 15i and ii).[29] The morphology of the waveforms does not match precisely as one is plotting flow against time and the other against volume, but the waveforms should be qualitatively similar. Flow-volume loops are particularly important in the assessment of excessive Raw and in alerting the clinician to the presence of copious airway secretions or circuit leaks. Flow asynchrony can also be detected via flow-volume loops as has been discussed in the PVD section later.[10]

In ventilator waveform presentation, the flow-volume loop is typically presented with the inspiratory limb above the *x*-axis (Fig 16). In pulmonary function testing, the flow-volume loops are more typically presented with the expiratory limb above the *x*-axis and end inspiration closest to the *y*-axis (i.e., upside down and inverted; picture the loop in Fig 16 rotated clockwise 180°). In Fig 16, "a" denotes the start of inspiration. Inspiration continues to point “b” and then ceases. The overall shape of the inspiratory limb is square, suggesting a constant flow-volume control mode is being employed in this instance. The expiratory limb begins with the transition from point “b” to point “c.” Peak expiratory flow is achieved early in exhalation and is patient effort dependent (usually not relevant in anesthetized patients on full assist-control ventilation). After peak flow is achieved, the expiratory limb tracing progresses to the effort-independent portion of the curve (“d”). The portion of the curve labeled “d” is the most relevant to the assessment of Raw changes, although peak flow is also often altered as well. In the case of a significant increase in Raw, a “scooped-out” appearance of the middle to late portion of the expiratory limb is noted with an accompanying reduction in peak expiratory flow (Fig 17i).[32] Such changes should prompt the clinician to investigate whether airway suctioning or bronchodilator administration is needed.

Circuit leaks can also be detected on flow-volume loops (Fig 17 ii). In each case, the key feature is that inspiratory and expiratory volumes are not equivalent. Much as was seen with the PV loop, the effect of a circuit leak on a flow-volume loop is to create a broken, incomplete appearance.[29]

Excessive airway secretions can also be detected via flow-volume loop inspection. Fig 17iii shows an example of a flow-volume loop with a sawtooth appearance to the effort-independent portion of the expiratory limb. This finding (along with auscultation of the trachea) is considered one of the most reliable indicators of the need for tracheal suction, whereas auscultation of crackles over the thorax is less predictive of suctioning need.[32]

PVD

PVD (also called patient-ventilator interactions (PVI) or patient-ventilator asynchrony) is increasingly recognized as an important contributor to outcomes in patients requiring long-term mechanical ventilatory support.[6-11]

In the case of a patient on a ventilator, the respiratory cycle can be divided into 4 distinct phases (Fig 18). PVD may occur during any of them and more than 1 form of PVD may be detected concurrently. The first (phase 1) is the “initiation of inspiration,” which is also called “the trigger mechanism.” PVD during phase 1 is often referred to as “trigger asynchrony.” Trigger asynchrony has been shown to be by far the most common form of PVD in

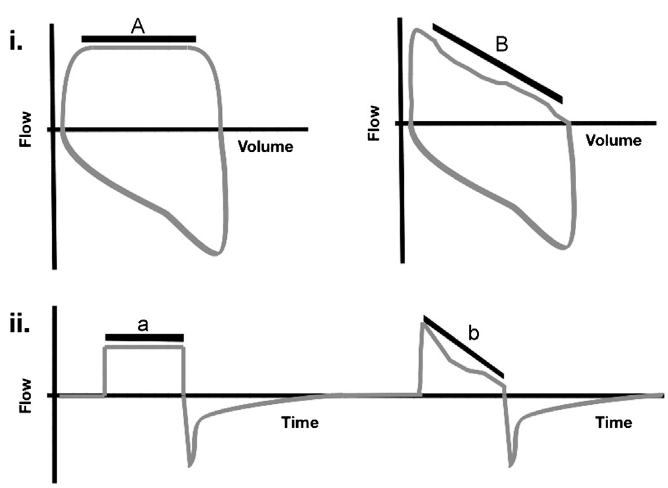

Fig. 15. (i-ii) The flow-volume loop. The general profile of the flow tracing should be very similar on the flow-volume loop (iA and iB) and their corresponding flow scalar waveforms (iia and iib).

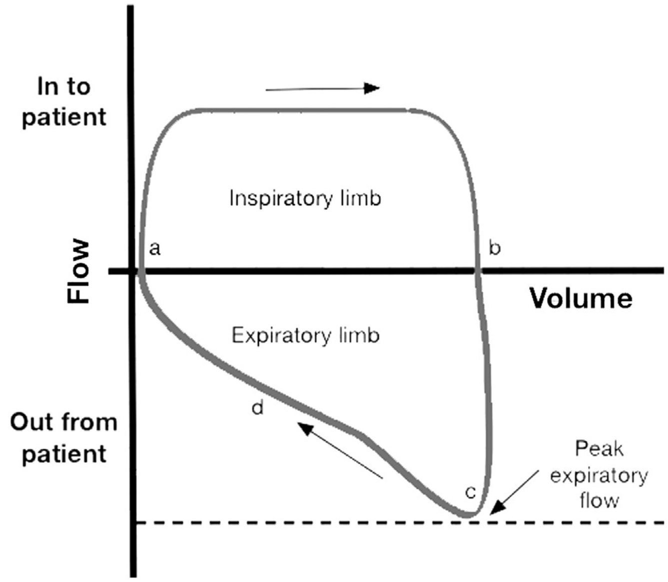

Fig. 16. Typical appearance of a flow-volume loop. For ventilator graphics, the inspiratory limb (point “a” to “b”) is generally depicted above the *x*-axis. Peak inspiratory flow is achieved in early expiration (c). As expiratory flow progresses from peak rates to zero, a period of effort-independent maximal flow is observed.

human patients.[11] The predominant types of trigger asynchrony include *ineffective triggering*, *autotriggering*, and *double triggering* (Fig 19i, ii, and iii, respectively).[33] Ineffective triggering involves a patient-generated decrease in airway pressure with a simultaneous increase in airflow without triggering a machine-delivered breath. This form of PVD is often the result of an inappropriately

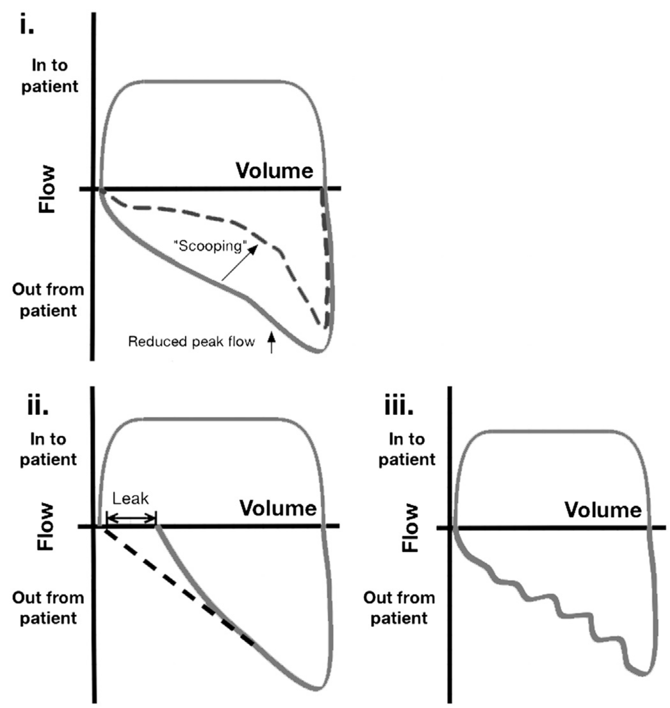

Fig. 17. (i-iii) Flow-volume loops with increased Raw, circuit leaks, and excessive secretions. (i) Increased airway resistance can result in a scooped-out appearance to the expiratory limb of a flow-volume loop. (ii) Much as is seen with PV loops, circuit leaks produce open, broken flow-volume loops. (iii) Excessive tracheal secretions often produce a sawtooth appearance to the expiratory limb of the flow-volume loop. This is generally considered a reliable indicator that tracheal suctioning is required.

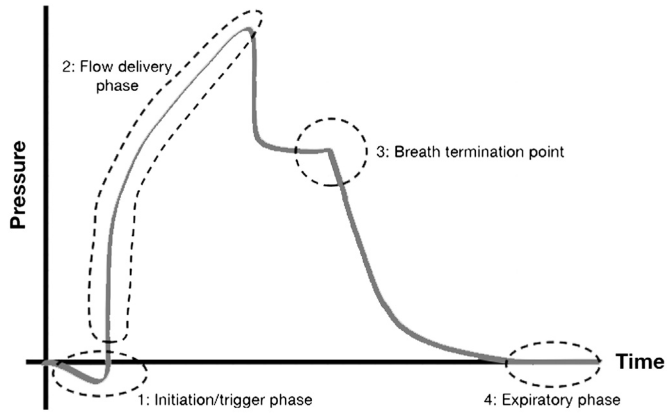

Fig 18. Phases of the machine-delivered breath. The 4 phases of a patient-triggered, machine-delivered breath are depicted and labeled on a pressure scalar waveform. The shape of the waveform is indicative that the breath was delivered in a volume-control mode with an inspiratory hold.

set sensitivity setting on the ventilator. However, it has been shown that increasing levels of pressure support suppress respiratory drive and lead to increased frequency of ineffective triggering.[33-35] Triggering delay and ineffective triggering are often easier to identify on the *flow* scalar than on the *pressure* scalar owing to the larger relative change in that parameter (i.e., bigger relative change in flow than pressure with ineffective efforts to trigger inspiration). When ineffective triggering is detected, the clinician should look for evidence of an improper triggering threshold, auto-PEEP (PEEPi), significant muscle weakness or fatigue, reduced respiratory drive, or an excessively deep level of sedation or anesthesia. Not all forms of trigger asynchrony may be corrected solely by adjusting the threshold. Autotriggering is another form of trigger asynchrony and occurs when a breath is delivered by the ventilator because of a change in airway pressure or flow *not* caused by patient effort. Most often, autotriggering is due to an inappropriately small threshold or sensitivity setting. Alternatively, flow or pressure distortions may be due to other factors including circuit leaks, fluid or secretions within the circuit, or cardiac oscillations. Autotriggering is more frequent when there are prolonged periods of no expiratory flow between breaths. Double triggering is defined as 2 delivered breaths separated by an expiratory time less than half the mean expiratory time. It occurs when a patient's inspiratory effort continues throughout the ventilator's preset I-time and thus remains present after the I-time has been completed. This prolonged effort triggers another breath. The end result is the patient receiving a tidal volume twice the desired or preset size. This carries with it risk of overdistention and alveolar trauma. This type of trigger asynchrony may be due to exceptionally high ventilatory demand on the part of the patient, low tidal volumes, and an I-time that is too short, or when the flow-cycle threshold is set too high.

Flow asynchrony is the result of ventilator supplying fresh gas to the inspiratory circuit either too fast or too slow for the individual patient. Flow asynchrony may be recognized using ventilator waveforms during either volume control or pressure control, but manifests somewhat differently in each circumstance. In volume-controlled modes with constant inspiratory flow rates, it is easiest to detect flow asynchrony by comparing passive and patient-triggered breaths on both the pressure and flow scalars. In patients with flow asynchrony, the triggered breaths often have a “scooped-out,” concave appearance on the upswing of the pressure tracing (Fig 20i, labeled “A”) and a sawtooth appearance to the plateau phase of the flow tracing (Fig 20 ii, labeled “B”) relative to the convex mandatory breaths. Flow asynchrony may also be evident on flow-volume and pressure-volume loops and may manifest as irregular concavities of the inspiratory limbs (Fig 20iii and iv, labeled “C” and “D”). Such findings should prompt the clinician to increase inspiratory flow until the 2 types of breaths have similar appearing waveforms. In pressure-control (with variable inspiratory flow), one should look at the pressure-time scalar. When inspiratory flow is inadequate, the pressure-time scalar assumes a “scooped-out” appearance during the inspiratory plateau. When inspiratory flow is excessive, one may see an early overshoot in the airway pressure waveform (Fig 21iii). The clinician should adjust rise time in this setting until the pressure waveforms appear nearly square, have no plateau concavity, and have no evidence of overshoot.

Termination asynchrony is also termed cycling asynchrony. The 2 main types of termination asynchrony involve inspiration being terminated too early (premature cycling; Fig 21i) or too late (delayed cycling; Fig 21ii). In the first instance, the patient is

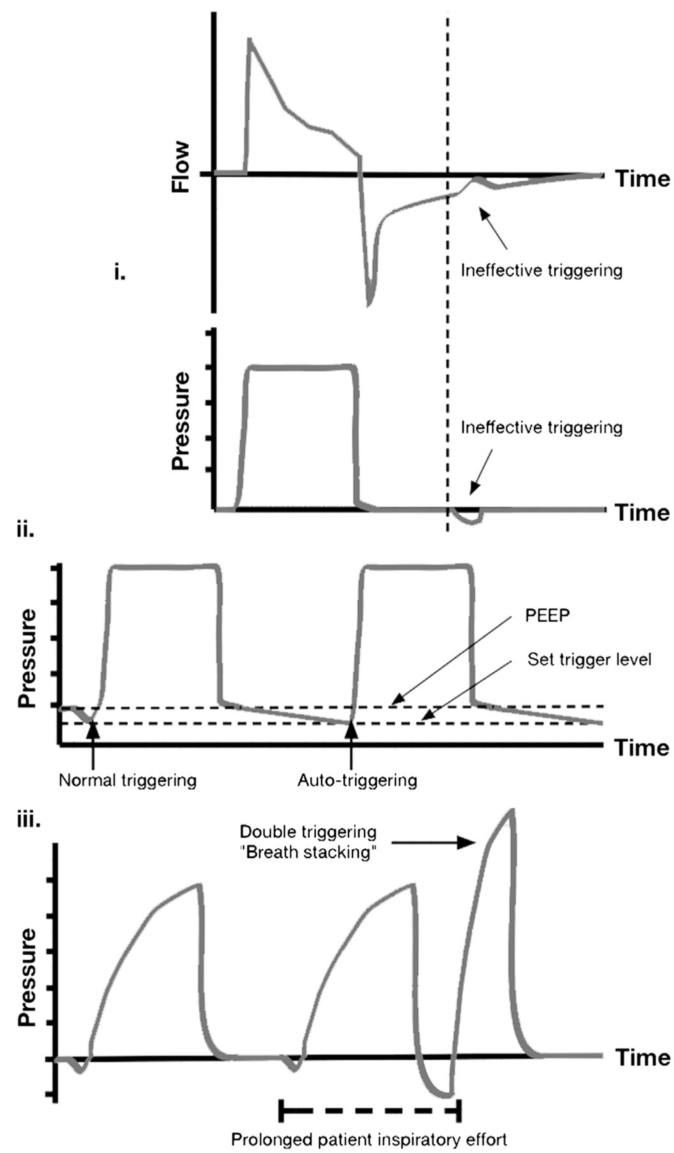

Fig 19. (i-iii) Evidence of various forms of trigger asynchrony on ventilator waveforms. (i) Inneffective triggering is evidenced by the small inversion of flow and pressure during the expiratory phase without a resultant machine-delivered breath. (ii) Autotriggering due to a circuit leak is depicted. The leaks lead to a loss of circuit pressure following the first breath that is sufficient to trigger breath delivery independent of patient effort. (iii) Double triggering can occur when the patient's inspiratory effort extend beyond the set inspiratory time.

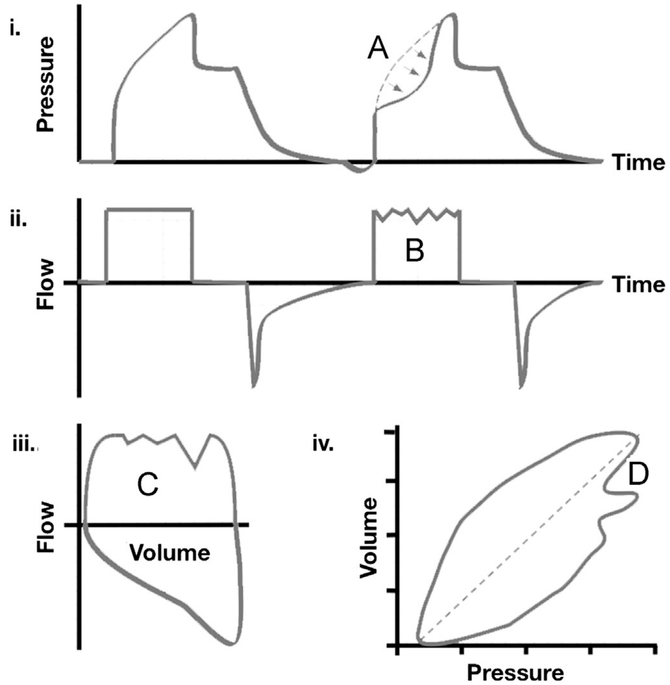

Figure 20. (i–iv) Flow asynchrony. (i) On the pressure scalar waveform, flow asynchrony may be indicated by a scooped-out appearance during inspiration (A). On the flow scalar waveform flow, asynchrony may be indicated by a series of scooped-out concavities appearing in the inspiratory flow waveform when flow is meant to be constant during this period. The waveforms in (i) and (ii) are those that would be obtained in a volume-control ventilation mode. (iii) Flow asynchrony also may be indicated when such a series of scooped-out concavities appears in the inspiratory limb of the flow-volume loop. (iv) On the pressure-volume loop tracing, flow asynchrony may distort the inspiratory limb of the loop substantially.

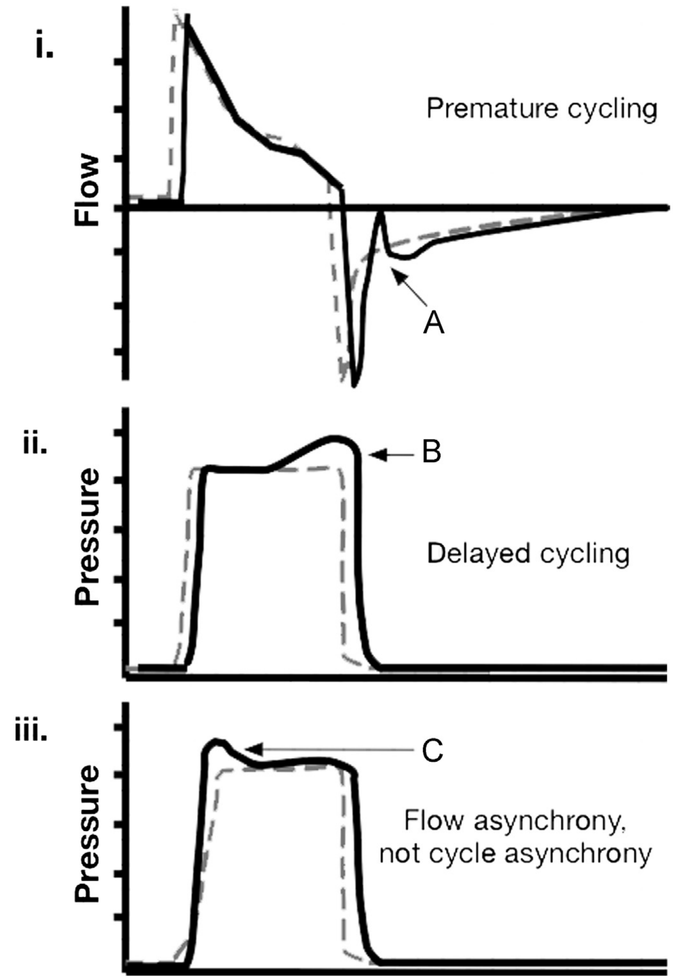

Figure 21. (i–iii) Cycle asynchrony. (i) Premature cycling leads to a transient inversion (A) of flow in the expiratory portion of the flow waveform. (ii) Delayed cycling leads to a spike in pressure in late inspiration on the pressure scalar waveform. (iii) Flow asynchrony leads to a spike in pressure on the pressure scalar waveform in early inspiration and should not be confused with delayed cycling.

continuing to make inspiratory efforts at the time the ventilator cycles off. In the latter circumstance, the patient initiates active expiratory efforts while the ventilator is continuing to deliver inspiratory flow. Premature cycling may be associated with double triggering (Fig 19iii) if the inspiratory efforts are sufficient to trigger a second breath after the first has been terminated. On the ventilator waveforms, premature cycling may be detected by visualizing an abrupt initial reversal in the expiratory flow waveform (often with a concurrent concavity in the pressure waveform). Increasing I-time or tidal volume should address premature termination. On the ventilator waveforms, delayed termination manifests as a pressure spike on the pressure scalar during middle to late inspiration (Fig 21ii). On the flow scalar, one sees an abrupt, rapid decline in inspiratory flow near end inspiration. This type of asynchrony is managed by reducing I-time or tidal volumes. It is important to not confuse the early plateau change seen with flow asynchrony and the late plateau change seen with delayed cycling, as the adjustments needed to address each of these are quite different. The waveforms for each of these forms of PVD are placed together in Fig 21ii and iii to assist direct comparison.

Expiratory asynchrony typically manifests as auto-PEEP (gas trapping), which has been described previously in the section on the flow scalar (Fig 9). If auto-PEEP is detected, then a number of parameters may be adjusted nearly all of which serve to prolong expiratory time (i.e., trigger sensitivity, peak flow, flow pattern, rise time, I-time, cycle threshold, I:E ratio, and respiratory rate).[36] One major adverse aspect of auto-PEEP is the effect that it has on triggering (refer to the aforementioned discussion of trigger asynchrony). Auto-PEEP increases the difficulty the patient faces in reaching the triggering threshold. Increasing PEEP to account for auto-PEEP may improve triggering sensitivity and efficacy.

Summary

In conclusion, ventilator waveforms should be inspected hourly in any patient on long-term mechanical ventilatory support and immediately whenever the patient appears to be “fighting” the ventilator. Ventilator waveforms can be crucial in recognizing system leaks, the need for suctioning, and changes in respiratory mechanics. The waveforms can also help place blood gas values into a more meaningful context and help with disease monitoring, in addition to evaluating the response to bronchodilators. The frequency with which PVD is recognized is largely dependent on how frequently one looks for it.[11] A systematic, step-wise approach evaluating all 4 phases can help the clinician to optimize ventilator settings and avoid overanesthetizing patients with its associated adverse effects.

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