Essentials of ventilator graphics

Ruben D Restrepo*, Felix Khusid

Email: restrepor@uthscsa.edu

Abstract

Respiratory function monitoring involves the integration of information such as airway pressures, flow and volume to evaluate changes in pulmonary mechanics. Ventilator graphics are an essential and valuable tool in the care of mechanically ventilated patients. Clinicians responsible for both setting up the ventilators and managing the patients should have a thorough understanding of the different waveforms to be able to recognise mechanical and/or clinical abnormalities. The scalar graphics allow the assessment of each variable (pressure, flow and volume) over time. Despite the ability to customise graphics on modern ventilators, scalars are typically displayed together in the same screen. There are an innumerable number of changes that can be detected in the scalars that may facilitate the management of the mechanical ventilator, and thus optimise the care of the ventilated patient. The loops provide a two-dimensional view of two variables plotted against each other. Understanding how the patient and the ventilator interact must be considered a critical component of the overall assessment of patients undergoing any type of mechanical ventilation since detection and management of asynchrony impacts important clinical outcomes in the ICU.

Abbreviations and definitions

Throughout this chapter the following words and abbreviations are used.

- PIFR — Peak inspiratory flow rate
- PEFR — Peak expiratory flow rate
- PIP — Peak inspiratory pressure
- PEEP — Positive end expiratory pressure
- P_{plat} — Plateau pressure
- R_{aw} — Airway resistance
- P_{aw} — Airway pressure
- V_T — Tidal volume
- T_I — Inspiratory time, in seconds
- T_E — Expiratory time, in seconds
- TCT — Total cycle time, in seconds
- I:E Ratio — Inspiratory to expiratory time ratio
- Scalar graphic — A single variable plotted against time
- Loop — Two variables plotted simultaneously
- Hysteresis — Widening of a pressure-volume loop
- Inflection Point — The point of change in the slope of a line
- Tracing — Used interchangeably with loop or curve
- Opening Pressure — The point where pressure delivered begins to induce a corresponding volume change
- WOB — Work of breathing
- C_L — Lung compliance
- FRC — Functional residual capacity

Ruben D Restrepo, MD, RRT, FAARC
Professor, Department of Respiratory Care, The University of Texas Health Sciences Center at San Antonio, San Antonio, Texas.

Felix Khusid, BS, RRT-ACCS, NPS, RPFT, FAARC
Administrative Director, Respiratory Therapy Department/ Pulmonary Physiology Center New York Methodist Hospital, Brooklyn, New York.

Introduction

Ventilator graphics have become an essential tool in managing patients on mechanical ventilators. All newer mechanical ventilators are equipped with a graphic package that displays selected ventilator waveforms facilitating assessment of the patient's condition. These graphics are displayed in two forms-scalars and loops.

The purpose of this article is to provide clinicians with the specific knowledge and interpretive skills necessary to recognise various aspects of patient and ventilator interaction, in both text and graphical format.[1,2] This article identifies typical tracings

How to cite this article: Restrepo RD, Khusid F. Essentials of ventilatory graphics. Ind J Resp Care 2014;3(1): 396-404.

and analysis of commonly encountered waveforms during mechanical ventilation.

Description

A graphic display where any of the three variables that make up the ventilator graphics, flow, volume and pressure are plotted against time is known as a '*scalar'* graphic. Time is conventionally shown on the horizontal (x) axis whereas flow, volume, and pressure are plotted on the vertical (y) axis. The scalars used in this chapter reflect the use of mechanical volume cycled ventilation with a constant (preset) flow.

'Loops' are the two-dimensional graphic display of two scalar values. The most common loops available for interpretation are: pressure-volume loop and flow-volume loop.[3-5]

When viewing the flow-volume loop, the horizontal (x) axis is used to indicate volume whereas flow is displayed on the vertical (y) axis. As indicated in the flow-volume loop below, the inspiratory curve is plotted above the baseline and the expiratory curve is traced below the baseline. However, it is not unusual to see a completely reverse pattern where the inspiratory component is presented below the baseline.

When viewing the pressure-volume loop, pressure is usually displayed on the horizontal (x) axis while volume is displayed on the vertical (y) axis.

Analysis of scalar graphics

Flow *vs* time

Spontaneous *vs* mechanical breath

Observe that the inspiratory flow is traced above the baseline whereas expiratory flow is indicated below the baseline (*Figure 1*). The flow *vs* time curve for a spontaneous breath resembles a sine wave flow pattern. The flow *vs* time for a mechanical volume-targeted breath shows a square-wave pattern.

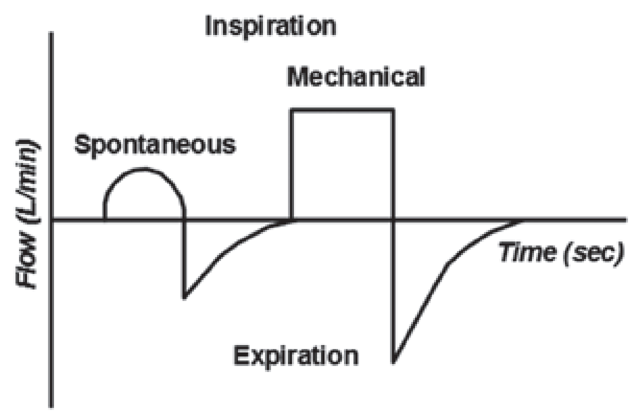

Figure 1: Components of inspiratory and expiratory flow

Expiration, whether from a mechanical breath or a spontaneous breath, is generally a passive manoeuvre. Both the inspiratory and the expiratory flows reach their peak value instantaneously and both return to the baseline.

The following points and events that can be identified on the *flow vs time* scalar are (*Figure 2a, 2b*):

- Initiation of flow at the beginning of inspiration: At this time the exhalation valve closes to permit a mechanical breath to deliver volume to the patient's lungs.
- The peak inspiratory flow (PIFR) level is reached instantaneously during a constant flow pattern. The flow remains at this level until the inspiration is terminated.
- End of inspiratory flow delivery and beginning of expiration: This event occurs when the preset tidal volume is delivered. At this time the exhalation valve opens to allow for passive exhalation.
- Initiation of expiration
- Peak expiratory flow rate (PEFR)
- Duration of expiratory flow
- Expiratory time (T_E)
- Notice the inspiratory time (T_I), expiratory time (T_E) and the total cycle time (TCT) for one mechanical breath.

Notice that the expiratory flow decays to zero before the next mechanical breath is initiated. Thus, the duration of expiratory flow may be shorter than the allocated expiratory time.

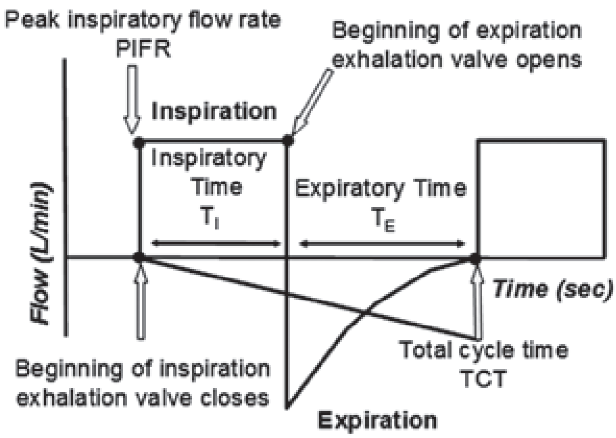

Figure 2a: Components of the flow-time scalar

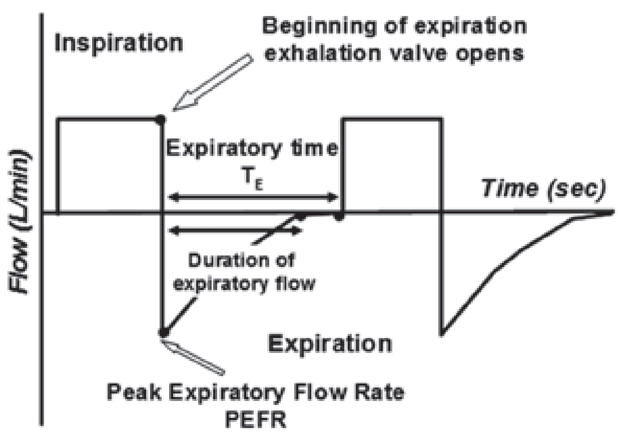

Figure 2b: Components of the flow-time scalar

Recognition of common abnormalities

Airway obstruction and response to bronchodilator: Exhalation is normally passive. The expiratory flow pattern and PEFR depend upon the changes in the patient's lung compliance and airway resistance, as well as patient's active efforts to exhale. For example, increased airway resistance due to bronchospasm or accumulation of secretions in the airway may result in decreased PEFR and a prolonged expiratory flow.

Flow vs time tracing can verify clinically suspected bronchoconstriction. In these cases, the PEFR is reduced and the expiratory flow returns to the baseline very slowly. Administration of a bronchodilator improves PEFR and allows for an expiratory flow to return to baseline within a normal time (*Figure 3*).[6,7]

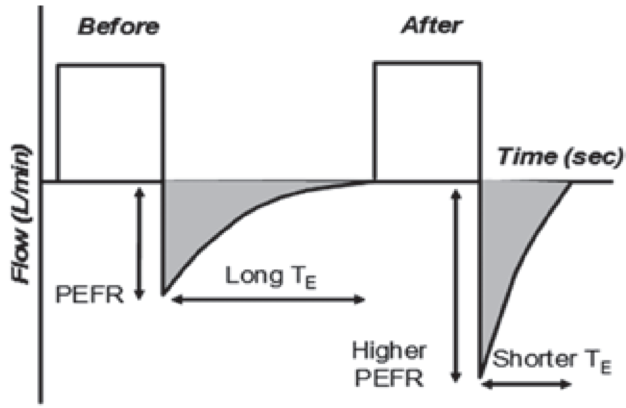

Figure 3: Flow-time scalar indicating the response to bronchodilator

Air trapping or Auto-PEEP: Normally, expiratory flow returns to the baseline prior to the next breath. If the expiratory flow does not return to zero and the subsequent inspiration begins below the baseline, auto-PEEP or air trapping is present (*Figure 4*). The presence of auto-PEEP or air trapping may result from inadequate expiratory time, rapid respiratory rates, long inspiratory time, or prolonged exhalation due to bronchoconstriction. Even though auto-PEEP is best detected from the *flow vs time* waveform, its magnitude is not directly measured from the *flow vs time* scalar. A higher inspiratory flow rate (in volume-cycled ventilators) or short T_I (in time-cycled ventilators) allows for a longer T_E and may eliminate auto-PEEP.[6,7]

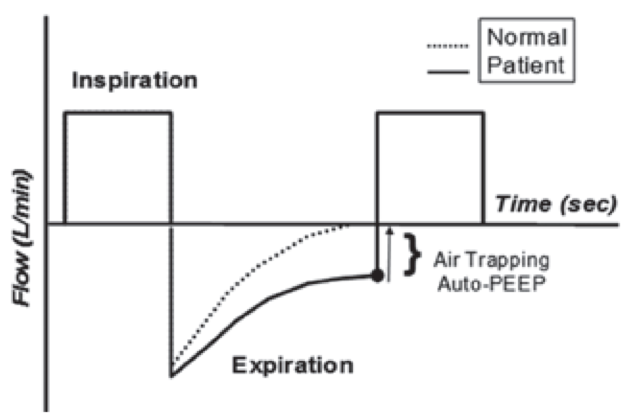

Figure 4: Flow-time scalar indicating air trapping

Volume *vs* time

Information obtained from a *volume vs time* scalar graph includes a visual representation of the inspiratory tidal volume, inspiratory phase, expiratory phase, and inspiratory time (*Figure 5*).

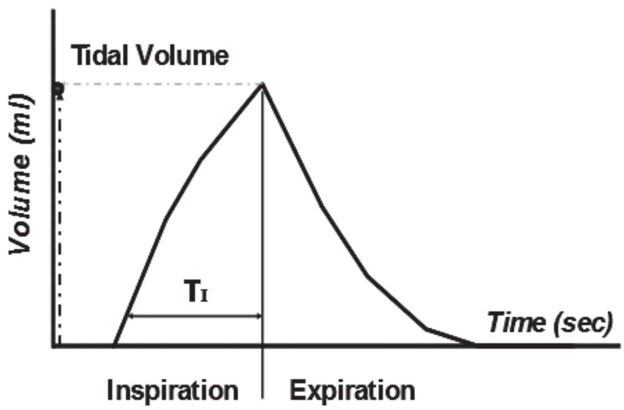

Figure 5: Volume-time graph

Recognition of common abnormalities

Presence of air leak or air trapping: A leak in the circuit or around the tracheal tube can be detected from the *volume vs time* curve. If the expiratory tracing smoothly descends, and then plateaus, but does not reach baseline, it indicates the presence of a leak in the system or air trapping (*Figure 6*). This pattern mandates that the leak should be located and fixed. The volume of the leak can be easily estimated by measuring the distance from the plateau to the end of the expiratory tracing. To confirm air trapping, look at the expiratory component of the *flow vs time* curve.

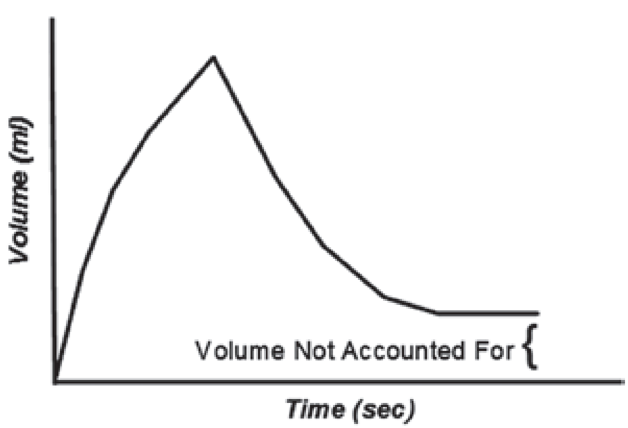

Figure 6: Volume-time graph indicating leak or air trapping

Pressure *vs* time

Spontaneous breath: Observe that unlike the *flow vs time* curve, the *pressure vs time* scalar indicates inspiration below the baseline and expiration is traced above the baseline, which is consistent with the normal spontaneous respiratory pattern. During the inspiratory phase the pressure curve shows a negative deflection and during exhalation goes above the baseline. Compare this with a mechanical breath (*Figure 7*).

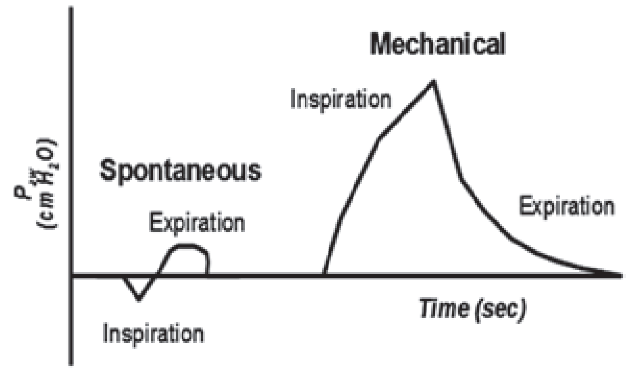

Figure 7: Pressure-time scalar during spontaneous and mechanical breaths

Mechanical breath: The *pressure vs time* scalar is one of the most useful waveforms in the clinical setting. It provides visual representations of the following (*Figure 8*):

- *Peak inspiratory pressure* (PIP) is the maximum pressure achieved during a breath.
- PIP indicates the pressure required to deliver a set tidal volume during volume ventilation.
- Increased airway resistance (R_{aw}) and/or decreased lung compliance result in an increased PIP.
- *Positive end expiratory pressure* (PEEP) is confirmed only on a pressure *vs* time scalar and a pressure-volume loop. PEEP is present when the baseline pressure is above zero.

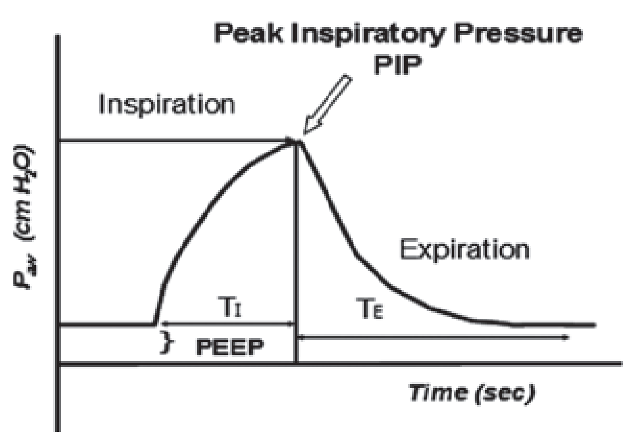

Figure 8: Components of pressure-time scalar

Assisted *vs* controlled breath: *Pressure vs time* scalar verifies the triggering mechanism of the mechanical breath. If the breaths are initiated at the baseline at fixed intervals, the mode is time triggered or a control mode. In an assist mode the patient initiates the breath by generating a negative pressure. The ventilator sensor recognises the patient's effort and delivers a mechanical breath. This event can be observed on the *pressure vs time* scalar where a small negative deflection below the baseline precedes a mechanical breath (*Figure 9*).[9,10]

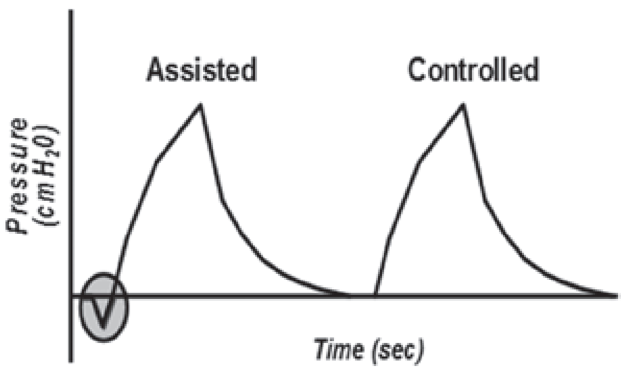

Figure 9: Trigger indicated in the pressure- time graph

Components of inflation pressure: Although dynamic lung mechanics can be observed from a *pressure vs time* curve, the addition of an inspiratory pause or inflation hold provides information to calculate static mechanics (*Figure 10*).

- *Plateau pressure* (Pplat) or alveolar pressure is obtained upon activation of an inflation hold or inspiratory pause control. The exhalation valve is kept in a closed position and the volume is held in the lungs. For clinical purposes, the plateau pressure is the same as the alveolar pressure. This measurement provides a means of measuring static lung compliance.
- *Transairway pressure* (PTA = PIP- Pplat) reflects the pressure required to overcome airway resistance. Bronchospasm, airway secretions, and other types of airway obstructions may be confirmed by an increase in the transairway pressure (PIP- Pplat).

With inflation hold, the pressure required to overcome the recoiling force (lung compliance) can be determined. The static lung compliance can be obtained by dividing the volume in the lung by the plateau pressure minus PEEP, if present.

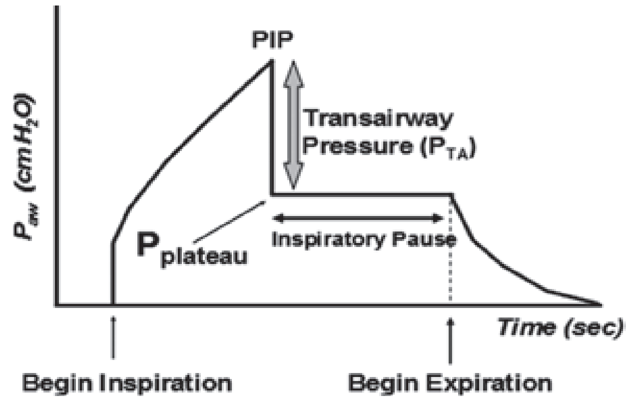

Figure 10: Components of inflation pressure

Recognition of common abnormalities: Changes in the *pressure vs time* curve have profound clinical significance. Four common clinical situations are demonstrated in the following tracings.

- *Normal* curve: Indicates PIP, Pplat, P_{TA}, and T_I.
- *High* R_{aw}*:* A significant increase in the P_{TA} is associated with increased in airway resistance.
- *High flow:* Notice that the inspiratory time is shorter than normal indicating a higher inspiratory gas flow rate.
- *Decreased lung compliance:* An increase in the plateau pressure and a corresponding increase in the PIP are consistent with decreased lung compliance.

Analysis of loops

Loops are the two-dimensional graphic displays of two scalar values.

Pressure-volume loop (P/V loop)

Observe the direction of the tracing of the loop. When the tracing is counterclockwise, the breath delivered is a mechanical breath. On the other hand, a clockwise tracing indicates a spontaneous breath. The angle, shape and size of the loop impart pertinent information to the clinician. In an assisted mechanical breath, the tracing begins clockwise indicating patient's effort and resumes in counterclockwise fashion for the mechanical delivery (*Figure 11*).

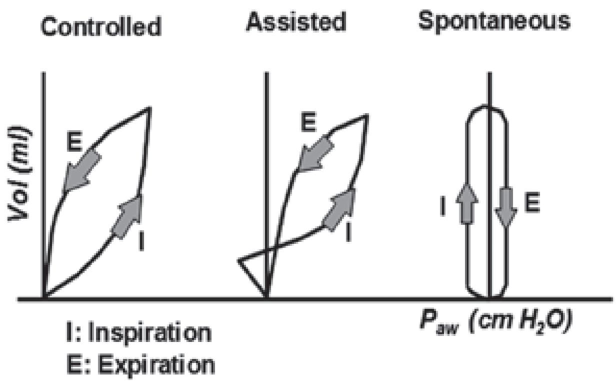

Figure 11: Pressure- volume loop

Components of a P/V Loop

A *P/V loop* traces changes in pressures and corresponding changes in volume. Inspiration begins from the FRC level and terminates when the preset parameter (volume or pressure) is achieved. The tracing continues during expiration and returns to FRC at end of exhalation. PIP and delivered tidal volume can readily be obtained from the Pressure-Volume loop (*Figure 12*).

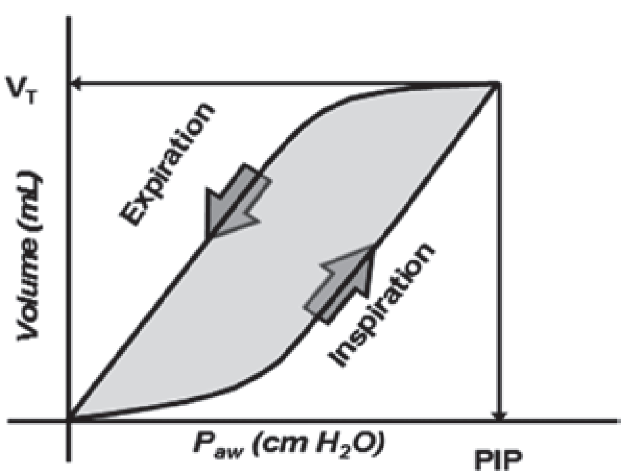

Figure 12: Components of pressure-volume loop

Presence of PEEP and inflection points

When PEEP is applied, the *P/V* loop shifts to the PEEP level on the horizontal scale. Inflection point is the point of change in the slope of a line. The inflection points represent sudden changes in alveolar opening and closing. The lower inflection point (LIP) represents the opening pressure, whereas the upper inflection point (UIP) represents the point at which overdistension starts occurring (*Figure 13*). The higher the opening pressure, the stiffer the lung, as indicated by the curve moving laterally to the right along the pressure axis. Setting PEEP levels at the level of the LIP is recommended to optimise alveolar recruitment and prevent repeated opening and closing of alveoli. Tidal volume and PIP should be set between the LIP and the UIP to avoid de-recruitment and overdistension.

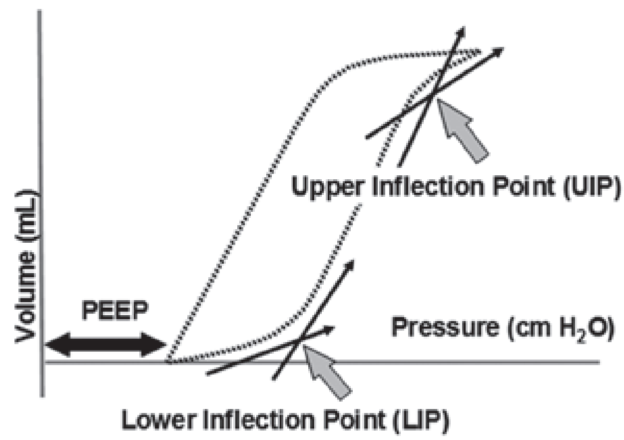

Figure 13: Inflection points on the pressure- volume loop

Recognition of common abnormalities

Decreased lung compliance: In volume-targeted ventilation, PIP is the changing variable. Therefore, the lower the C_L, the higher the PIP displayed for the preset V_T (*Figure 14*). In pressure-targeted ventilation the PIP is the constant variable, and V_T changes according to the C_L (*Figure 15*).

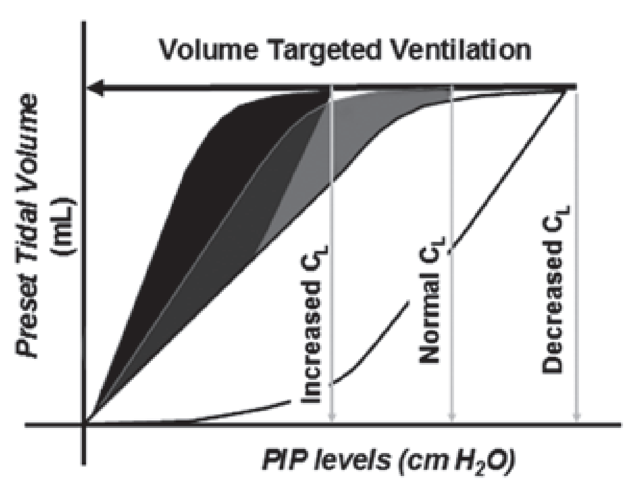

Figure 14: Compliance changes in volume targeted ventilation

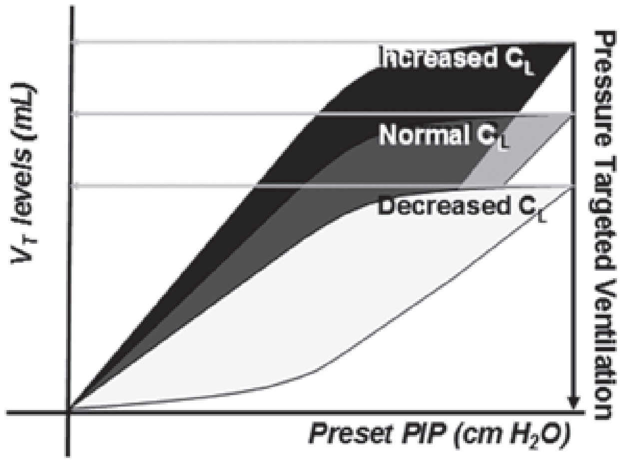

Figure 15: Compliance changes in pressure targeted ventilation

Increased airway resistance: An increased R_{aw} is associated with an abnormal widening of the *P/V loop* (*Figure 16*). This abnormal widening of the shape of the *P/V loop* is referred to as an increased "hysteresis".

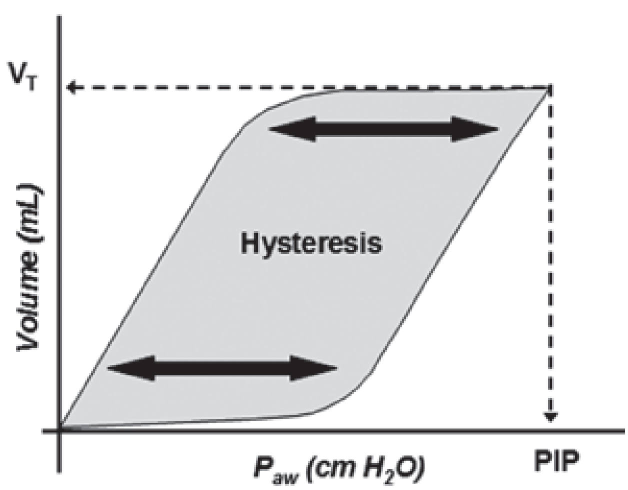

Figure 16: Pressure- volume loop indicating increased airway resistance

Alveolar overdistension: Alveolar distension is often seen during ventilation of patients with ARDS on a volume-targeted mode but should be avoided. The classic sign, known as "beak effect" or "duckbill" shows an increase in airway pressure without any appreciable increase in volume (*Figure 17*). A switch to pressure targeted ventilation, at appropriate safe pressure level, or a reduction in V_T are indicated.

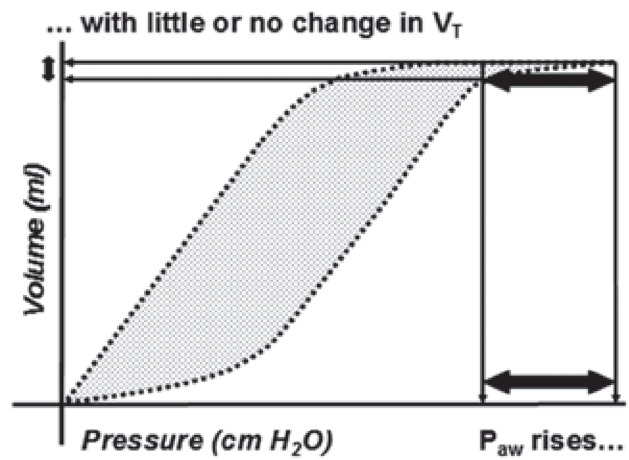

Figure 17: Pressure-volume loop indicating alveolar overdistension

Increased work of breathing (WOB): Normally the *P/V loop* traces in a counterclockwise direction. A significant clockwise deflection prior to the initiation of a mechanical breath indicates patient's effort (*Figure 18*). Adjusting the sensitivity and providing adequate inspiratory flow can minimise the patient's WOB.[11]

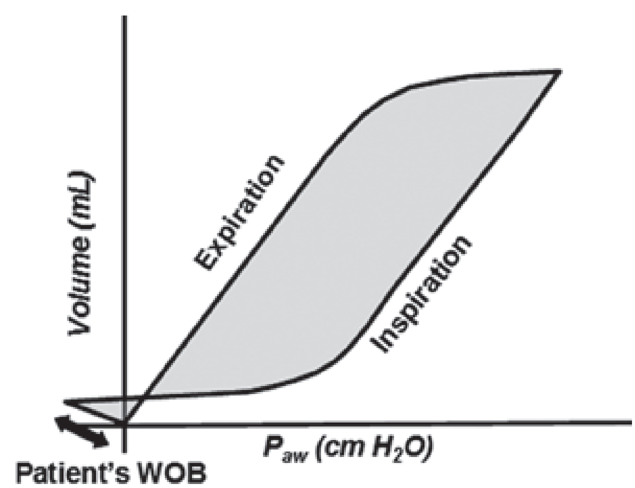

Figure 18: Pressure-volume loop indicating increased work of breathing

Flow-volume Loop (F/V loop)

There is no set convention in assigning the inspiratory and expiratory quadrants on a *F/V loop*. Some ventilators produce *F/V loops* with inspiration on the upper quadrant and expiration on the lower quadrant. Other ventilators plot inspiration on the lower side of the volume axis and expiration on the upper side. In this chapter, inspiration is shown on the upper quadrant and expiration in the lower quadrant (*Figure 19*). The *F/V loop* provides the following information: PIFR, PEFR, and V_T.

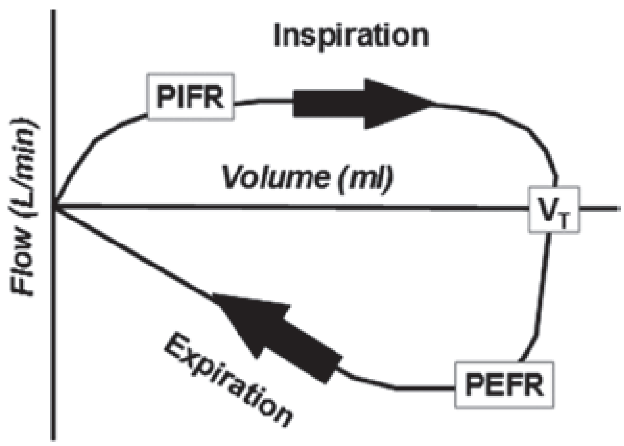

Figure 19: Components of flow-volume loop

Recognition of common abnormalities

Air leak: Ideally, expired volume should be equal to the inspired volume. With an air leak, however, expired volume is less than inspired volume. This is commonly observed in situations such as a leak around the endotracheal tube, and circuit leak, and leaks *via* chest tube (s). When the expiratory volume on a F/V loop does not return to the zero volume level, the deficit of volume indicates the magnitude of air leak (*Figure 20*).

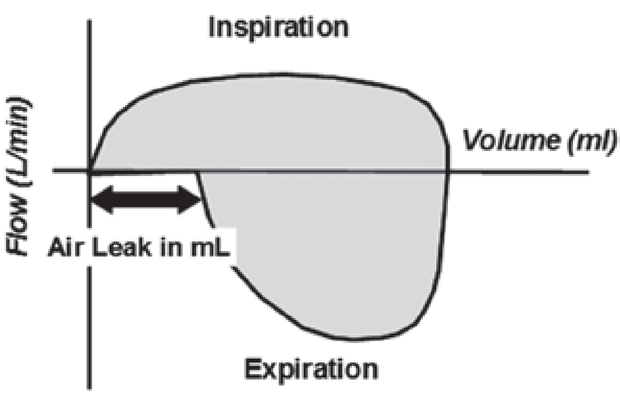

Figure 20: Flow-volume loop indicating air leak

Increased Airway Resistance: The typical pattern of increased R_{aw} due to bronchospasm, such as in asthma, is reflected on the *F/V loop* as a decreased PEFR and a "scooped out" pattern on the expiratory tracing (*Figure 21*). Effective administration of bronchodilator will show an improvement on both the PEFR and the configuration of the expiratory tracing.[12]

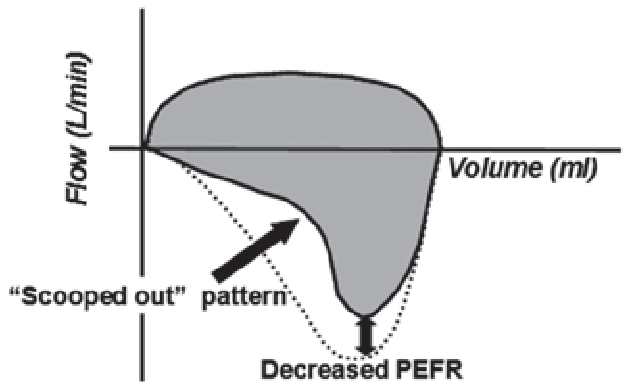

Figure 21: Flow-volume loop indicating increased airway resistance

Summary and conclusions

Respiratory function monitoring involves the integration of information such as airway pressures, flow and volume to evaluate changes in pulmonary mechanics.

The scalar graphics allow the assessment of each variable (pressure, flow and volume) over time. Despite the ability to customise graphics on modern ventilators, scalars are typically displayed together in the same screen. The initiation, limit and termination of the breath can be easily determined when analysing these three tracings.[13] There are an innumerable number of changes that can be detected in the scalars that may facilitate the management of the mechanical ventilator, and thus optimise the care of the ventilated patient. Problems with triggering, volume leaks, presence of air trapping, and changes in compliance are just some of the abnormalities that clinicians can learn to recognise when looking at these variables plotted against time.

The loops provide a two-dimensional view of two variables plotted against each other. While the preference of clinicians for scalars or loops to evaluate patient-ventilator interaction vary, many find in loops the best way to assess triggering issues, the presence of overdistension, or the presence of airway obstruction.

Ventilator graphics are an essential and valuable tool in the care of mechanically ventilated patients. Clinicians responsible for both setting-up the ventilators and managing the patients should have a thorough understanding of the different waveforms to be able to recognise mechanical and/or clinical abnormalities. It is only with a good foundation that one can understand how the patient and the ventilator interact. This understanding must be considered a critical component of the overall assessment of patients undergoing any type of mechanical ventilation since detecting and management of asynchrony impacts important clinical outcomes in the ICU.[14-18]

References

1. de Wit M. Monitoring of patient-ventilator interaction at the bedside. *Respir Care* 2011; **56**:61-72.
2. Guntupali K, Restrepo RD. ACCP Mechanical Ventilation 1. iPad application available at: https://itunes.apple.com/us/app/accp-mechanical-ventilation/id730853947?mt=8.
3. Waugh J, Deshpande V, Harwood R. Rapid Interpretation of Ventilator Waveforms. Upper Saddle River, NJ: Prentice-Hall; 1999.
4. Deshpande V, Chandrashekar TR. Mechanical Ventilation. Clinical Application. 1st ed. 2012.
5. Restrepo RD, Deshande V. Essentials of Ventilator Graphics. Compact Disc 1st ed. Atlanta: Respimedu; 2000.
6. Blanch L, Bernabe F, Lucangelo U. Measurement of air trapping, intrinsic positive end-expiratory pressure, and dynamic hyperinflation in mechanically ventilated patients. *Respir Care* 2005; **50**:110-23.
7. MacIntyre NR, McConnell R, Cheng KC. Applied PEEP reduces the inspiratory load of intrinsic PEEP during pressure support. *Chest* 1997; **111**:188-93.
8. Sassoon CS, Gruer SE. Characteristics of the ventilator pressure- and flow-trigger variables. *Intensive Care Med* 1995; **21**:159-68.
9. Sassoon CSh. Triggering of the ventilator in patient-ventilator interactions. *Respir Care* 2011; **56**:39-51.
10. Nilsestuen J, Hargett K. Using ventilator graphics to identify patient-ventilator asynchrony. *Respir Care* 2005; **50**:202-34.
11. Dhand R. Ventilator graphics and respiratory mechanics in the patient with obstructive lung disease. *Respir Care* 2005; **50**:246-61.
12. Gentile MA. Cycling of the mechanical ventilator breath. *Respir Care* 2011; **56**:52-60.
13. Pierson DJ. Patient-ventilator interaction. *Respir Care* 2011; **56**:214-28.
14. Tobin MJ, Jubran A, Laghi F. Patient-ventilator interaction. *Am J Respir Crit Care Med* 2001; **163**:1059-63.
15. Georgopoulos D, Prinianakis G, Kondili E. Bedside waveforms interpretation as a tool to identify patient-ventilator asynchronies. *Intensive Care Med* 2006; **32**:34-47.
16. Epstein SK. How often does patient-ventilator asynchrony occur and what are the consequences? *Respir Care* 2011; **56**:25-38.
17. Gilstrap D, MacIntyre N. Patient-ventilator interactions. Implications for clinical management. *Am J Respir Crit Care Med* 2013; **188**:1058-68.