CHAPTER 4
MONITORING PRESSURE AND VOLUME VENTILATION

I. Introduction
II. Volume Versus Pressure Ventilation Scalars
III. Inspiratory Pause During Volume and Pressure Ventilation
IV. Effects on Increased Airway Resistance on Volume- and Pressure-Targeted Ventilation
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INTRODUCTION

Mechanical ventilation has evolved from early volume-targeted ventilators such as the Emerson Post-op and Bennett MA-1 to providing the now common approach of combining volume- and pressure-targeted controls. Traditional volume ventilation has been found not to be the most protective approach for fragile patients such as those with ARDS. Some now advocate starting with pressure-targeted ventilation when possible (Marini) (Houston), but the consensus recommendation is to at least use low tidal volumes (see bibliography).

Volume-targeted ventilation refers to the delivery of a preset volume to the patient. Upon delivery of this volume the ventilator terminates inspiration (volume cycling). On the other hand, pressure-targeted ventilation delivers a preset pressure for a preset inspiratory time (pressure cycling is another type of pressure-targeted ventilation but is rarely used). Inspiration is terminated when the set inspiratory time elapses (time cycling). In volume ventilation, patient changes in airway resistance and lung compliance result in corresponding changes in driving pressure required to deliver a preset tidal volume. In pressure ventilation these variations in lung characteristics do not affect the preset pressure, but result in changes in the delivered volume.

Clinical applications of volume- and pressure-targeted ventilation require a thorough understanding of these modes. It is imperative that a clinician in the critical care setting be familiar with both types of ventilation. To protect the lungs from overdistension and the resulting damage from shear forces, the alveolar pressure (estimated by $P_{PLATEAU}$) should be kept below 30 cm H_2O, regardless of the mode of ventilation used (ARDSNetwork).

Pressure varies with volume-targeted ventilation, dependent on the lung characteristics and the caliber of the circuit. Setting the desired tidal volume based on ideal body weight is a common practice; however, current data indicates that higher tidal volumes even in normal range may promote overdistension and may be detrimental to the lungs. This is especially likely for conditions such as in ARDS where the majority of a set tidal volume may be delivered to the small portion of the lungs remaining with a normal compliance. Pressure ventilation is generally indicated for these patients. Volume ventilation has its role in patient populations that do not exhibit low lung compliance. It may be easier to maintain stable blood gas values with volume-targeted ventilation when patient compliance and resistance are frequently (albeit modestly) changing. Generally, short-term, post-operative patients, neuromuscular patients, and drug overdose patients can be better managed by volume ventilation, whereas patients with decreased lung compliance such as ARDS require pressure ventilation to prevent overdistension.

The goal of volume-targeted ventilation is to titrate the $PaCO_2$ to the patient's normal level and support ventilation at a minimal work-of-breathing for the patient. When appropriately set, pressure-targeted ventilation helps protect the lung from overdistension and can be programmed for recruiting maneuvers to reopen areas of collapsed alveoli. The mean airway pressure can be manipulated with less chance of overdistending the lung when using pressure-targeted ventilation. A clinician is expected to be familiar with the type of ventilation the patient is receiving and all monitoring aspects associated with the ventilator-patient interactions. This chapter compares ventilator waveforms during different volume and pressure-targeted ventilation conditions.

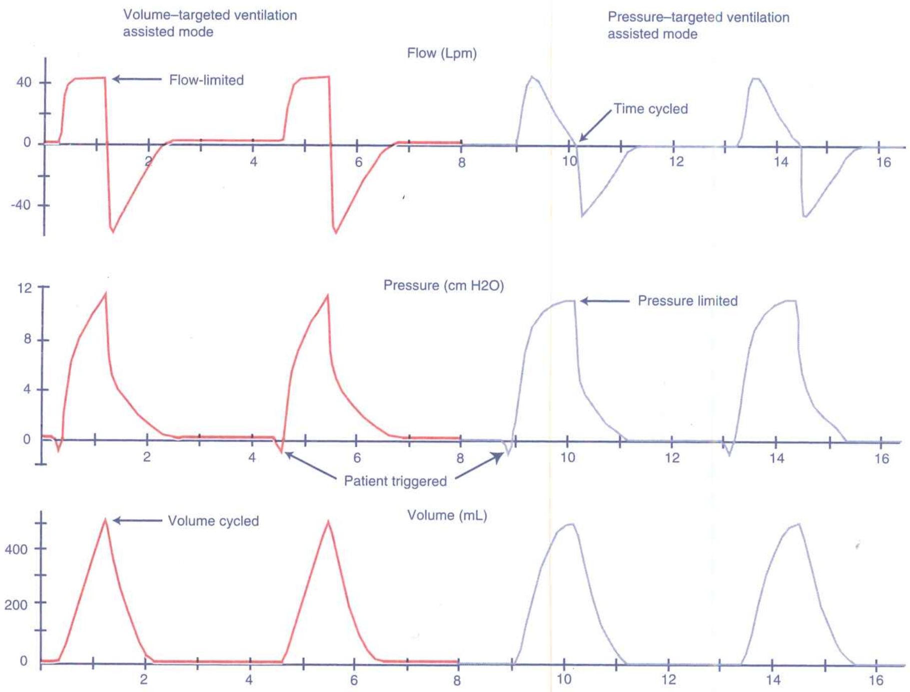

Figure 4-1. Volume vs. pressure ventilation scalars. Volume-targeted and pressure-targeted examples set to deliver similar tidal volumes at similar patient resistance and compliance values.

The examples in Figure 4-1 show flow, pressure, and volume scalars for the same patient using first a volume-targeted mode and then a pressure-targeted mode. Volume ventilation allows the use of a square, descending, or sine wave flow pattern, (some ventilators offer additional patterns). Regardless of the flow pattern, inspiration is terminated when the preset tidal volume is delivered. The graphic shows a square wave or constant flow pattern. During pressure-targeted ventilation, the clinician sets a desired inspiratory pressure and inspiratory time. The inspiration is terminated when the set inspiratory time elapses. Since the pressure gradient between the preset limiting pressure and alveolar pressure decreases as the lung begins to fill, the flow is always descending after the initial peak.

The pressure scalar for the volume-targeted breath has a curvilinear shape dependent on the lung characteristics of resistance and compliance. The peak inspiratory pressure (PIP) varies according to changes in lung characteristics. The consistent peak pressure for the pressure-targeted mode often (but not always) exhibits a square shape for the inspiratory pressure/time curve that indicates the PIP is independent of lung characteristics and will maintain the desired preset pressure.

Comparison of the volume scalar for volume-targeted ventilation vs. pressure-targeted ventilation reveals that the curve is rectilinear in volume-targeted ventilation (due to square flow pattern) whereas it has a curvilinear shape in pressure-targeted ventilation. Recognize that the delivered volume will remain relatively constant in volume-targeted ventilation, but it will vary in pressure-targeted ventilation as lung characteristics change.

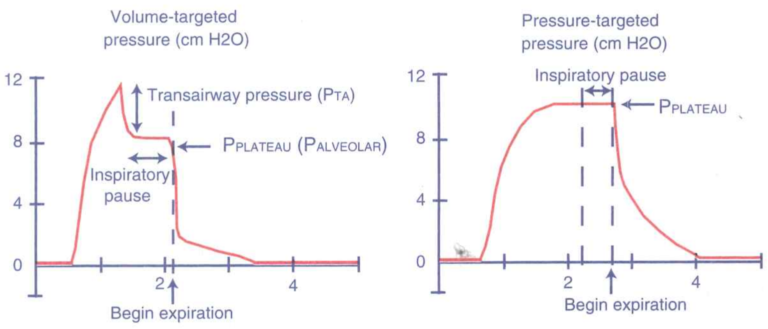

Figure 4-2. Observed inspiratory pause during both types of ventilation (zero flow during end inspiration).

Observe the gradient between PIP and $P_{PLATEAU}$ (transairway pressure) in the pressure scalar of the volume-targeted breath in Figure 4-2 when an inspiratory pause occurs. If during a pressure-targeted breath the inspiratory flow returns to baseline (zero flow) before the end of inspiration, this effectively creates an inspiratory pause. In this case, the alveolar pressure and the airway pressure have equilibrated indicating no transairway pressure gradient and therefore no associated resistance at that moment. The PIP in this circumstance is representative of the end inspiratory alveolar pressure and therefore relates to the respiratory system compliance.

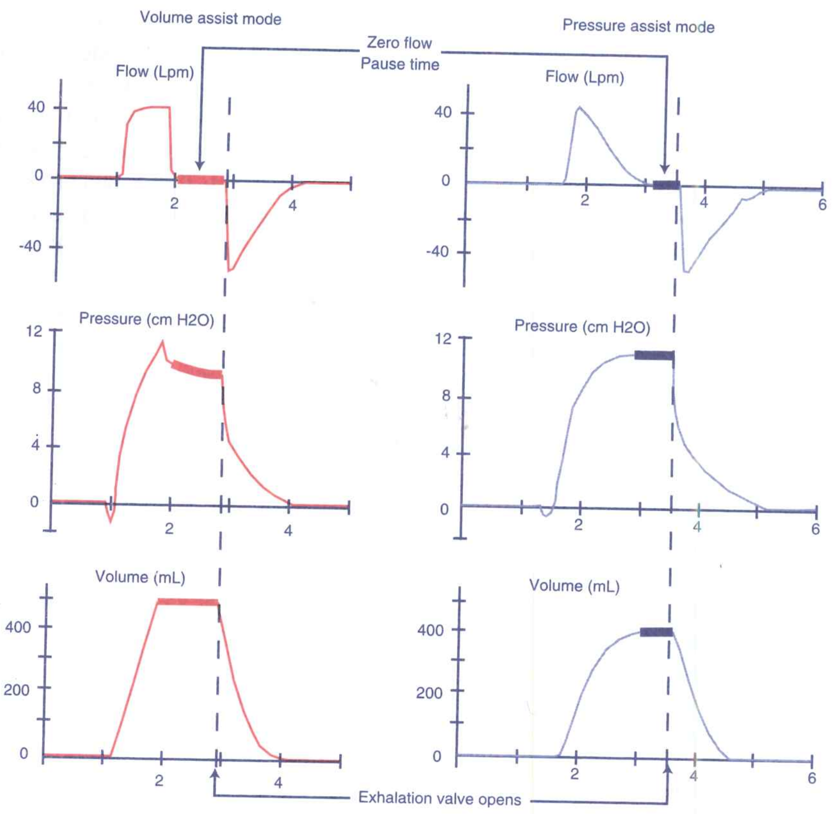

Figure 4-3. A contrast of ventilator scalar changes in volume-targeted vs. pressure-targeted ventilation with an inspiratory pause.

During volume-targeted ventilation, an inspiratory pause causes a rapid decrease of flow to the baseline, and it stays at a zero state until the pause time elapses at which time the exhalation valve opens and exhalation proceeds (Figure 4-3). A zero flow state at the end of inspiration during the pressure-targeted breath is observed which corresponds with an inspiratory pause. The volume scalar shows the volume held in the lungs during the inflation hold for both the volume-targeted and pressure-targeted breaths. It is necessary to view the flow scalar to determine if an inspiratory pause is occurring during pressure-targeted ventilation, i.e., a flow of zero at the end of inspiration.

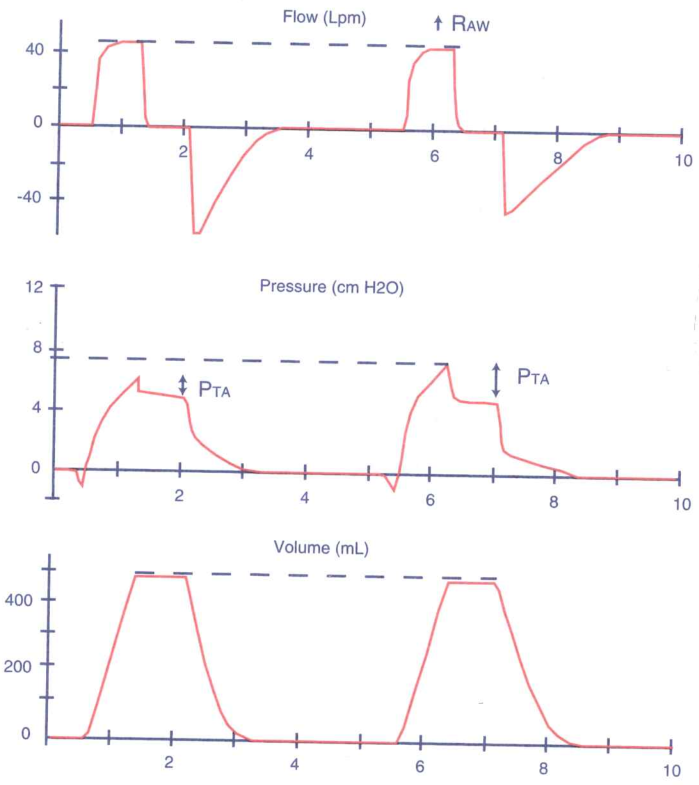

Figure 4-4. Shows the effect of increased airways resistance on volume-targeted breaths.

In Figure 4-4, the second breath shows how the gradient between the PIP and $P_{PLATEAU}$ (transairway pressure) increased as a result of the increased airways resistance. Notice that the delivered tidal volume and peak flow remained constant. An increase in airways resistance during volume-targeted ventilation promotes an increase in the PIP and no change in $P_{PLATEAU}$ (an increased transairway pressure).

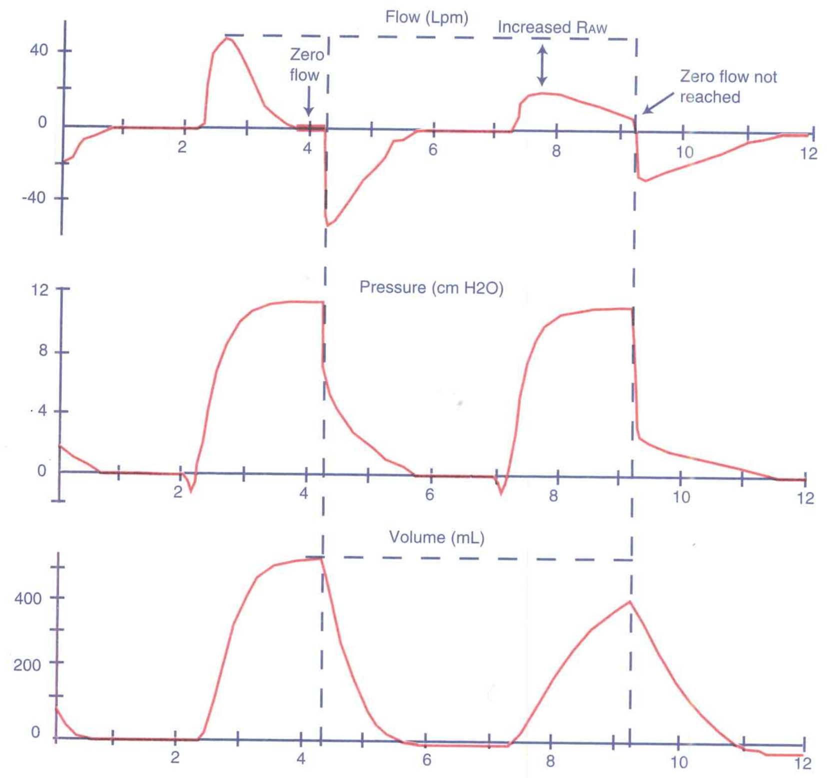

Figure 4-5. The effect of airway resistance on pressure-targeted ventilation.

EFFECTS OF INCREASED AIRWAY RESISTANCE ON VOLUME AND PRESSURE-TARGETED VENTILATION: An increase in airway resistance during pressure-targeted ventilation precipitates several changes: a slower rate of flow deceleration and a decreased peak flow due to resistance and delivery of smaller tidal volume. Notice in the second breath of Figure 4-5, the flow does not return to the baseline in the flow scalar and the volume scalar indicates a decreased tidal volume. A volume plateau is reached with the lower resistance (first breath), but the volume of the second breath (higher resistance) continues to increase throughout inspiration.

In pressure-targeted ventilation, the pressure will always be limited to the set pressure and will not exceed the set pressure irrespective of increase in the airways resistance. Notice that the shapes of the inspiratory pressure curves for the two resistance conditions are similar despite the marked changes in the flow and volume waveforms. The predominant effect of increased airway resistance during pressure ventilation is the concomitant decrease in the delivered tidal volume.

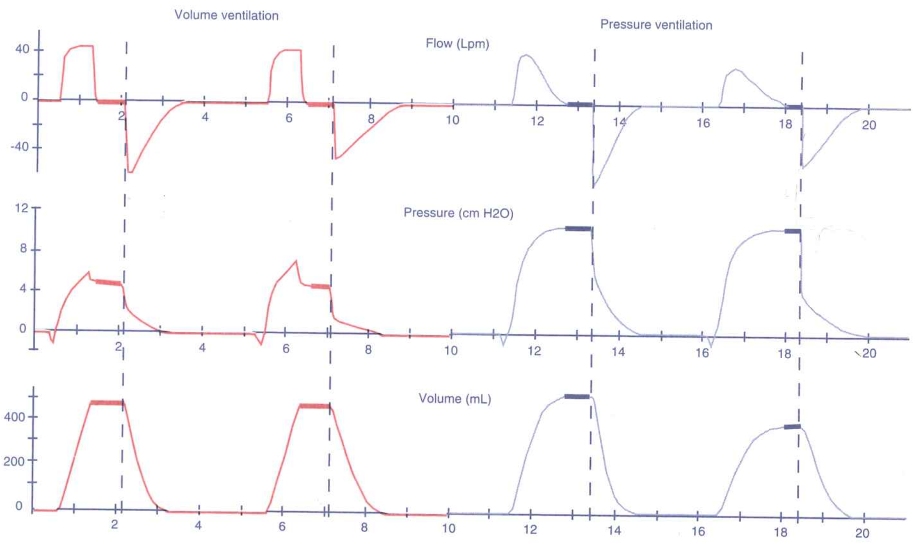

Figure 4-6. Changes due to increased resistance in volume- and pressure-targeted ventilation are contrasted.

In Figure 4-6, the inspiratory flow waveform changes for pressure-targeted but not volume-targeted breaths. The plateau pressure remains unchanged as the transairway pressure increases for the volume-targeted breath, while the pressure-targeted breath is less likely to reach zero flow and the associated inspiratory pause. The volume-targeted breath maintains a constant volume and the pressure-targeted breath yields a smaller volume.

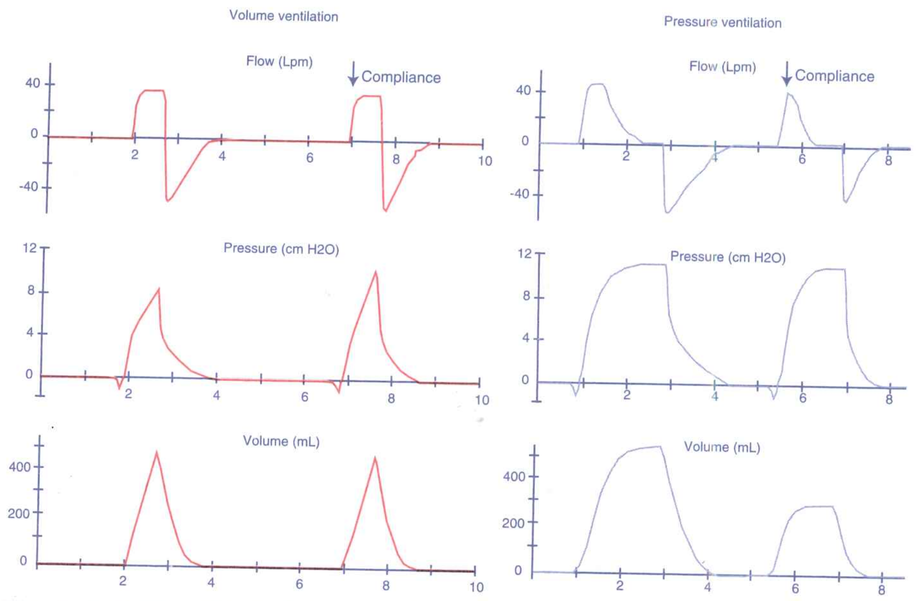

Figure 4-7. The effect of decreased compliance.

EFFECT OF DECREASED COMPLIANCE: In Figure 4-7, observe how the PIP increases in volume-targeted ventilation. The peak expiratory flow is slightly greater and returns to the baseline more quickly due to the increased lung recoil, but the delivered tidal volume is unchanged. If an inspiratory pause were activated, an increased plateau pressure would also be seen. With a pressure-targeted breath, decreased compliance hastens the descent of the inspiratory flow curve to the baseline before the set inspiratory time has elapsed, often creating a no-flow period. This creates the inspiratory pause effect previously described (Figure 4-3). In contrast to the volume-targeted breath, the pressure-targeted example does not show an increased peak expiratory flow. In addition, the tidal volume is reduced as a result of the decreased compliance.

THREE CONDITIONS IN PRESSURE-TARGETED BREATHS: Now notice the three conditions for pressure-targeted breaths in Figure 4-8. All breaths have the same inspiratory time but somewhat different flow tracings. Example A shows the flow scalar with an optimal inspiratory time for the patient conditions. Example B shows the effect of decreasing lung compliance as indicated by the return of inspiratory flow to the baseline before the inspiratory time has elapsed. Example C illustrates increased airways resistance causing slower descent of inspiratory flow resulting in termination of flow before the preset inspiratory time elapses.

It is interesting to note that the flow scalars of two other breath types appear to be similar to example C in Figure 4-8. These are the pressure support breath and a volume-targeted breath with descending ramp flow pattern in Figure 4-9.

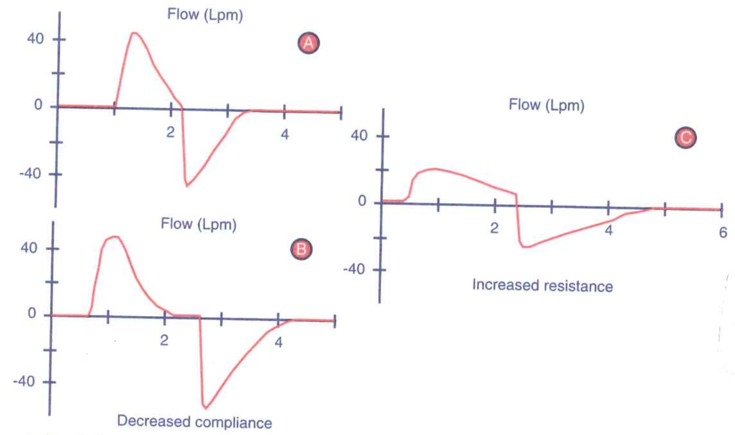

Figure 4-8. Three conditions for pressure-targeted breaths are displayed together.

The three breath types having different cycling variables can have similar flow curves depending on the patient conditions and control settings. It is important to properly set the low volume alarm during pressure-targeted ventilation since it will alert the clinician when the delivered tidal volume decreases due to increased resistance or decreased compliance (similar to high pressure alarm in volume-targeted ventilation).

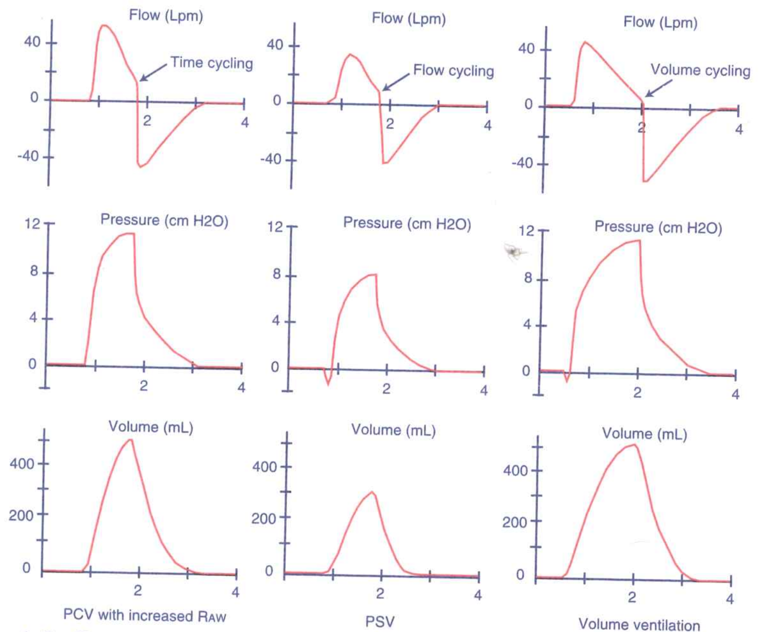

Figure 4-9. Pressure-targeted and volume-targeted breaths with decending ramp flow.

CHAPTER 5
COMMON CLINICAL FINDINGS

I. Changes in Respiratory System Compliance
    - Decreased Compliance and Inflection Points
    - Overdistension
    - Active Exhalation

II. Airway Obstruction
    - Bronchospasm: Bronchodilator Benefit Assessment
    - Air-trapping from Dynamic Hyperinflation
    - Air-trapping from Early Small Airway Collapse
    - Kinked Endotracheal Tube

III. Patient-Ventilator Dyssynchrony
    - Inadequate Inspiratory Flow Rate
    - Inappropriate Trigger Sensitivity
    - Patient and Ventilator Rates Out of Synchrony

IV. Leaks

There are many possible abnormal ventilator waveform variations but the most common findings make a relatively short list. The following specific examples are arranged under the general categories to which they relate.

CHANGES IN RESPIRATORY SYSTEM COMPLIANCE

DECREASED COMPLIANCE AND INFLECTION POINTS

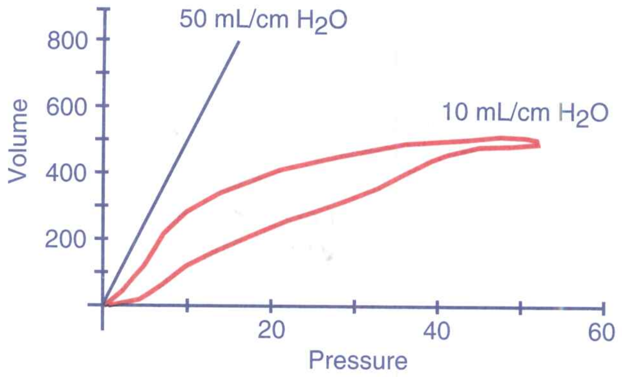

Figure 5-1. The P-V loop of a patient with severely decreased respiratory compliance.

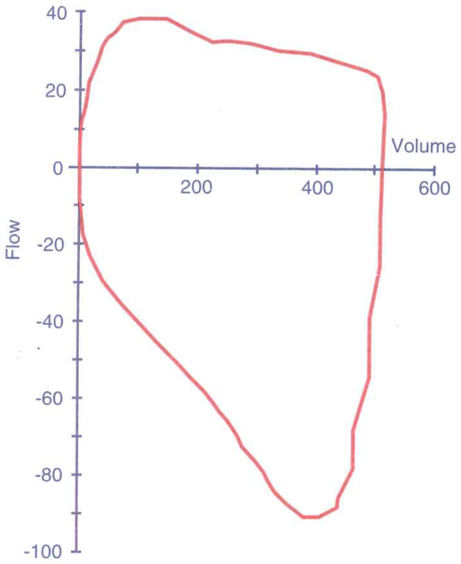

Figure 5-2. The F-V loop of a patient with severely decreased respiratory compliance.

Decreased respiratory compliance is best appreciated in the P-V loop (Figure 5-1). The blue line indicates the slope for the low end of the normal compliance range. The loop has a dynamic compliance of 10 mL/cm H_2O and is shifted downward and to the right of the normal compliance line. The F-V loop corresponding to this patient example is essentially normal except for the relatively high expiratory flow rate for a tidal volume of 500 mL (Figure 5-2). The F-V loop does not provide much information for this particular patient condition, but it is given in this instance for orientation purposes.

The goal of determining best or optimal PEEP for ventilator patients has been pursued by many approaches. It has traditionally sought the best balance between indicators of oxygenation, cardiac function, and respiratory mechanics. The lung protective approach to setting PEEP is to maximize recruitment of alveoli to restore FRC and prevent cyclic derecruitment injury without causing alveolar overdistension. PEEP is used to maintain an open (inflated) lung. As PEEP is increased, the tidal volume must be decreased to prevent excessive alveolar pressures. Many of the publications in the bibliography at the end of this book describe rationales for selecting optimal PEEP. The purpose of this text is to explain how techniques involving waveforms are performed and interpreted, not to argue the efficacy of the techniques.

The pressure-volume curves discussed in Chapter Two are dynamic waveforms. This means they are plotted as gas is flowing during a breath. Static pressure-volume plots can be created by incrementally inflating and deflating the lungs with sufficient pauses between each increment to reach a steady pressure. This is time-consuming and usually requires some form of temporary paralysis making it impractical for most clinical environments. In addition, oxygen consumption during slow inflation maneuvers (lasting more than 30 seconds) introduces significant measurement error. A more clinical-friendly variation of this can be done by inflating the lungs at a constant, very low flow (i.e., less than 10 L/min) corrected for known airway resistance so that the resulting plot is similar to a static plot (even this method may require some sedation). This "quasi-static" curve will often (but not always) reveal inflection points that possibly can be used to guide the setting of PEEP (inflection point identification can sometimes be difficult without computer-assistance). One approach is to set the PEEP level slightly above the lower inspiratory inflection (LIP) point. Some advocate setting PEEP by the expiratory curve inflection point. Still others recommend that inflexion points should not be used and that other measures such as dynamic inspiratory compliance, the linear or "best" compliance (middle portion of the inspiratory curve), or decremental PEEP trials should be used. Such debate is beyond the scope of this text, and no consensus currently exists.

The plots in Figure 5-3 show examples of dynamic, static, and quasi-static pressure-volume curves from the same patient. As previously mentioned, if this approach to setting PEEP is used, the static curve would be preferred but is often not feasible. The quasi-static curve may be a satisfactory substitute and the LIP is estimated by noting the change in compliance as indicated in the figure. The dynamic curve is shown for comparison sake to reveal its inadequacy for determining the LIP.

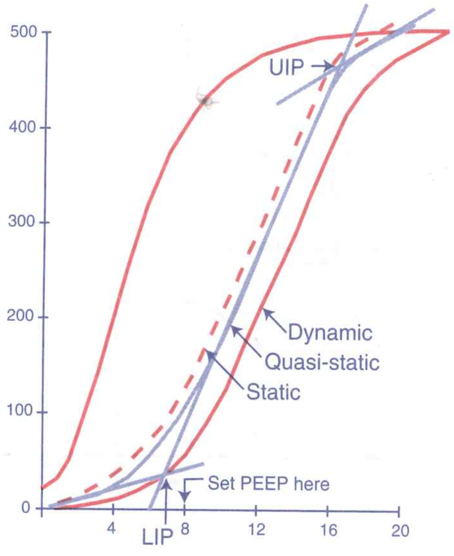

Figure 5-3. P-V loop inflection points.

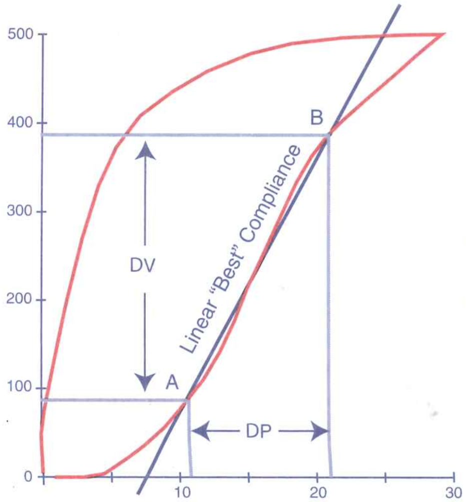

Figure 5-4. Determining linear compliance from a P-V loop.

Figure 5-4 shows a pressure-volume plot identifying the linear compliance of the inspiratory curve. Setting PEEP to produce the highest compliance measured from this linear portion of the inspiratory P-V curve is yet another approach to setting optimal PEEP. The P-V curve can be generated by using a constant pressure increase (i.e., 3 cm H_2O/sec) or a low constant flow. Regardless of what method is used to set optimal PEEP, a lung recruiting maneuver should always be done before and after a PEEP trial (a lower PEEP is needed once the lung is opened). The more common lung recruitment methods to date involve using a CPAP level from 35-50 cm H_2O for about 30-40 seconds. Another variation on using compliance to set ventilator parameters involves using compliance based on the end inspiratory pressure in PCV mode (which is similar to a plateau pressure during an inspiratory pause) to determine optimal PIP and PEEP. First, an attempt is made to recruit as much lung volume as possible starting at a high PEEP level (15-20 cm H_2O) and then increasing PIP (in PCV mode) after a few breaths at each small step until reaching 50 cm H_2O. Once the lung is opened, the PIP is then set at a pressure that will produce a V_T of 5-7 mL/kg ideal body weight (IBW) as the PEEP is changed in small decrements. As the PEEP decreases, compliance increases because some of the overinflated alveoli are relieved. Eventually the compliance plateaus and then begins to decrease as alveoli begin to close. The PEEP is set above the point of decreasing compliance. The whole procedure takes about 10-12 minutes. The best inspiratory compliances measured during the incremental PIP and decremental PEEP maneuvers and the associated pressures are used as the new ventilator settings after repeating a briefer lung recruiting maneuver (1-2 minutes). This approach to setting PIP and PEEP can be done manually, but some ventilators have a special trending monitoring mode (as seen in Figure 5-5) to simplify the procedure. Clinical results of lung recruitment maneuvers have shown varied success but may indicate the technique works best on early stage ARDS patients.

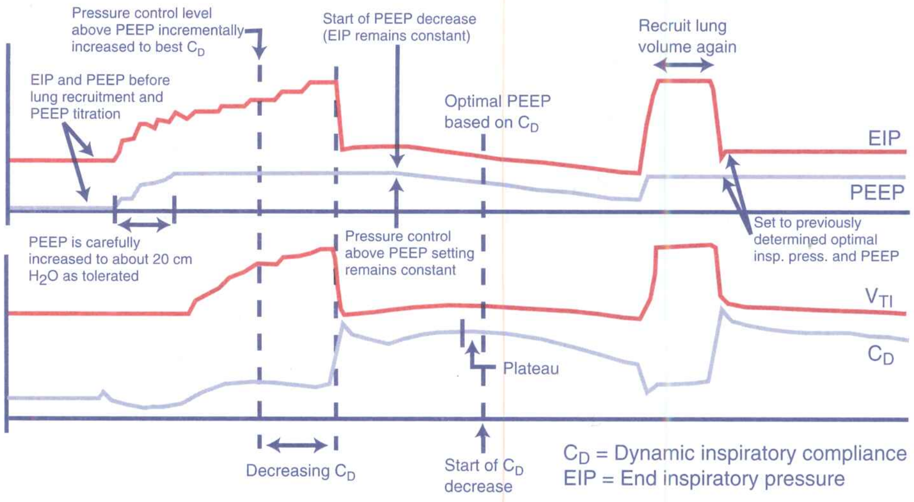

Figure 5-5 Setting optimal PEEP and EIP guided by compliance.

OVERDISTENSION

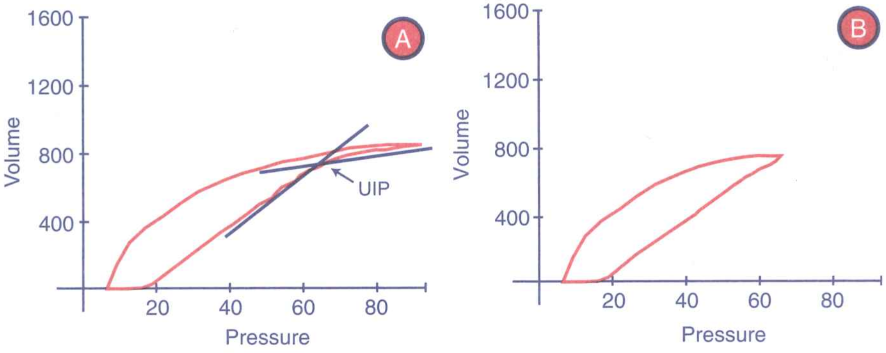

Figure 5-6. Identification and correction of overdistension as seen in P-V loops. (UIP = upper inflection point)

Overdistension occurs when the volume capacity of the lungs has been exceeded and the application of additional pressure causes very little increase in volume (loop A in Figure 5-5). The volume limit is identified on the P-V loop as an abrupt change in compliance in the terminal portion of inspiration, a second inspiratory inflection point (upper inflection point). This abnormal loop shape is commonly termed *beaking* and results in a reduced slope having a decreased dynamic compliance. Overdistension can lead to volutrauma and biotrauma (release of inflammatory mediators), particularly in lung regions with normal alveoli. Correction of overdistension involves decreasing the pressure setting in pressure-targeted ventilation or decreasing the volume setting in volume-targeted ventilation. The loop in graph B shows that a small decrease in the set tidal volume produced a large decrease in the PIP.

ACTIVE EXHALATION

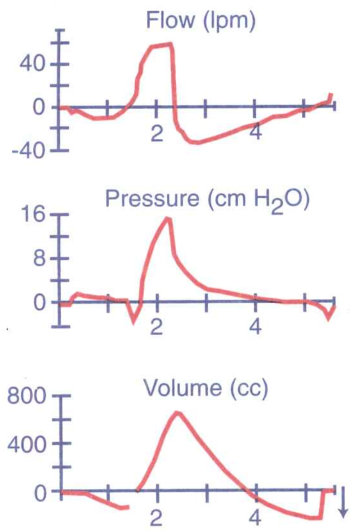

Figure 5-7. Active exhalation displayed in scalars.

When a patient exhales more than the inspiratory volume, active exhalation has occurred. The waveforms in Figures 5-7, 5-8, and 5-9 show active exhalation of an additional volume of about 200 mL. For expiratory volume to be greater than inspiratory volume, the patient has to exhale below FRC. It is normal for this to happen occasionally in the clinical setting, for example, when the patient changes position, experiences a twinge of pain, or tries to cough. It is not normal if it happens in a regular pattern. Patients with air-trapping will often show a pattern of an active exhalation occurring every few breaths in attempt to relieve the trapped volume. A larger expiratory volume than inspiratory volume on every breath indicates the expiratory flow transducer is out of calibration or some other equipment error exists.

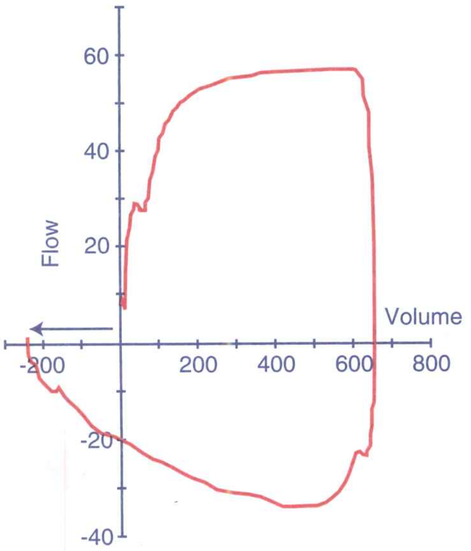

Figure 5-8. Active exhalation displayed in F-V loop.

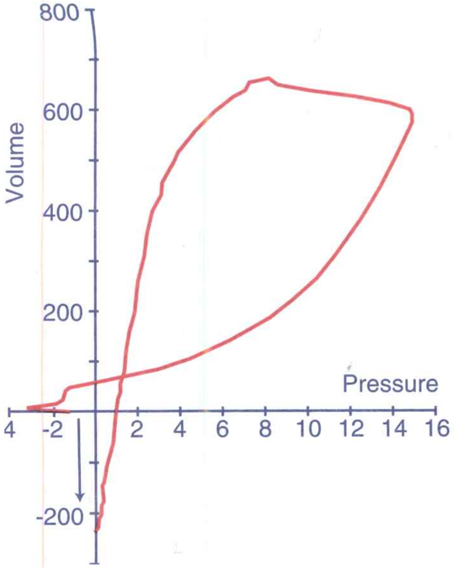

Figure 5-9. Active exhalation displayed in P-V loop.

AIRWAY OBSTRUCTION

BRONCHOSPASM: BRONCHODILATOR BENEFIT ASSESSMENT

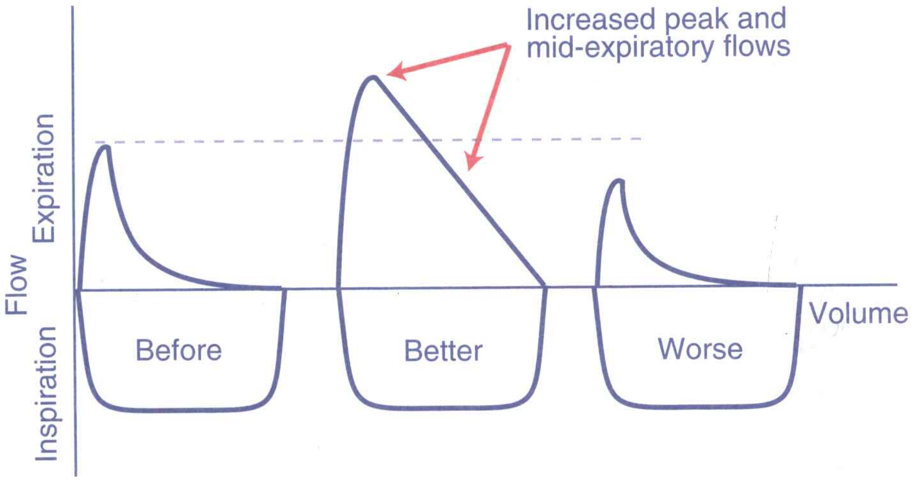

Figure 5-10. Indicators of airway improvement in the F-V loop as a result of response to a bronchodilator.

The effects of a bronchodilator are best appreciated in the F-V loop (Figure 5-10). The two major changes that indicate improvement are an increased peak expiratory flow rate and an increased mid-expiratory flow rate. Decreased mid-expiratory flow rates produce a scooped appearance in the descending portion of the expiratory curve (the Before and Worse loops in Figure 5-10). An improvement from bronchodilator will yield an increased tidal volume in pressure-targeted ventilation and sometimes in volume-targeted ventilation. An example of a positive bronchodilator response is given in Figure 5-11. Loop B shows increased peak and mid-expiratory flow rates compared to the pretreatment loop A.

Response to bronchodilator can also be seen in P-V loops. Loop B in Figure 5-12 shows decreased loop hysteresis compared to loop A. The maximal volume is slightly increased in this volume-targeted breath. Pressure-targeted ventilation tends to show similar and often more pronounced pre- and post-bronchodilator changes in the P-V loop given the same lung conditions. It is very useful to store a pre- and post-bronchodilator F-V loop in computer memory or print them for comparison. Comparing pre- and post-bronchodilator loops in one's memory is unreliable. It is best to keep the same axis scaling for both measurements if possible for ease of comparison.

Lack of response to bronchodilator may indicate that increased airways resistance is not due to bronchospasm. Airway narrowing may be due to fluid in the airways or swelling of the mucosa due to an inflammatory process not responsive to beta$_2$ agonists, or parasympatholytic agents. Pre- and post-loops after a trial of steroids may be

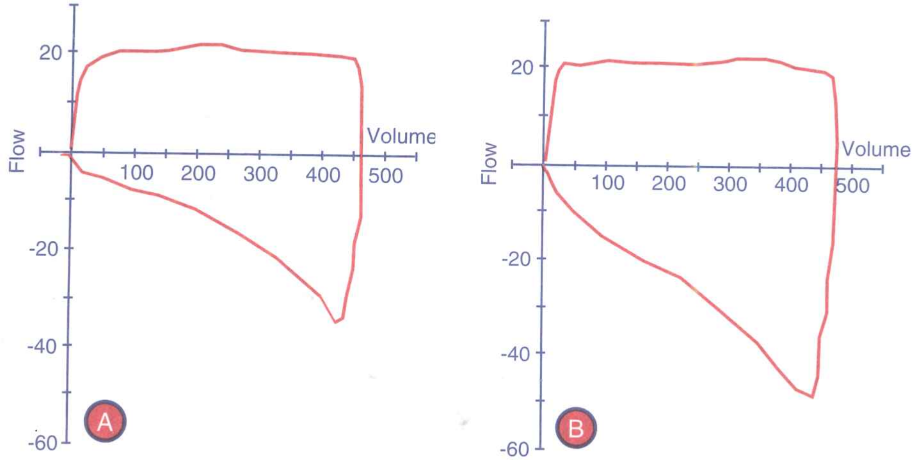

Figure 5-11. Pre- and post-bronchodilator F-V loops of volume-targeted breaths.

helpful for guiding therapy. Pre- and post loops can also be used for assessing which type of bronchodilator works best for a particular patient or if some combination of drugs has a superior effect. A post-drug loop that is worse than the pre-drug loop may indicate the patient is reacting to the drug propellent or preservative.

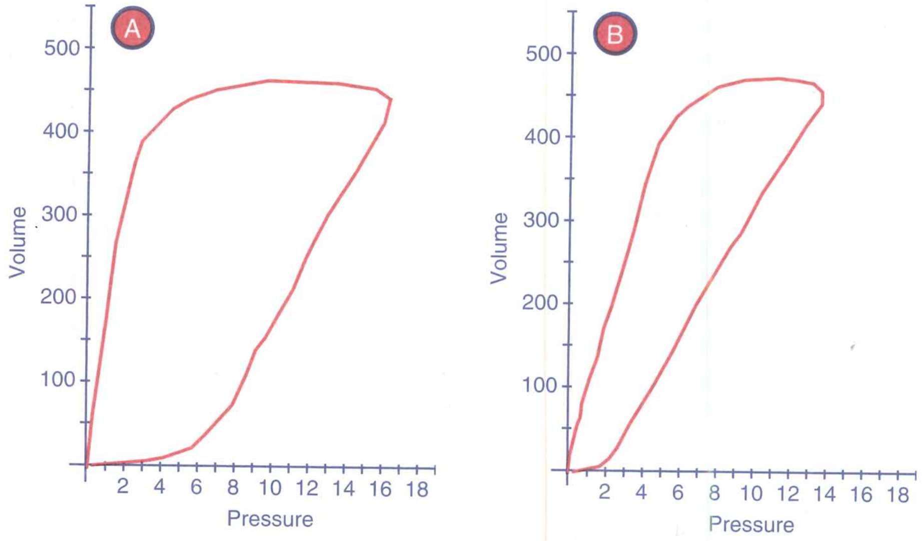

Figure 5-12. Pre- and post-bronchodilator P-V loops of volume-targeted breaths.

AIR-TRAPPING FROM DYNAMIC HYPERINFLATION

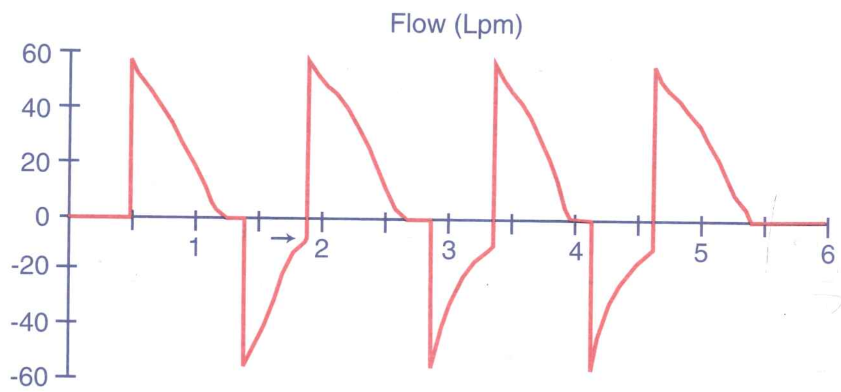

Figure 5-13. Flow scalar showing air-trapping due to dynamic hyperinflation.

Air-trapping and the associated auto-PEEP is generally caused by two mechanisms: dynamic hyperinflation and early collapse of unstable airways during exhalation. Dynamic hyperinflation occurs when the respiratory rate does not allow sufficient time for complete exhalation before the next breath. Figure 5-13 demonstrates this condition with early termination of exhalation indicated by the arrow. A similar example of early termination of exhalation is shown in the F-V loop of Figure 5-14. If dynamic hyperinflation is due to an excessive patient triggered respiratory rate it

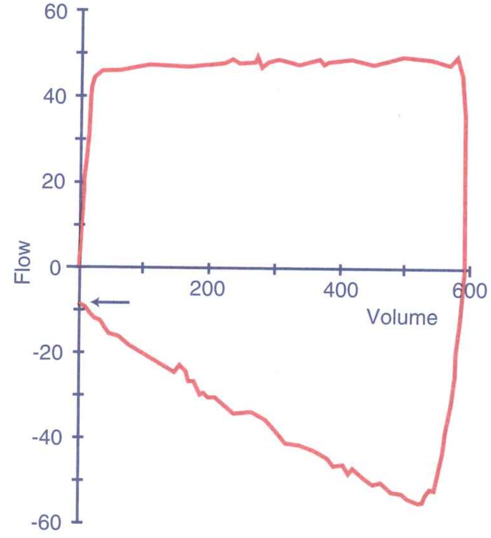

Figure 5-14. Air-trapping identified in the F-V loop of a volume-targeted breath.

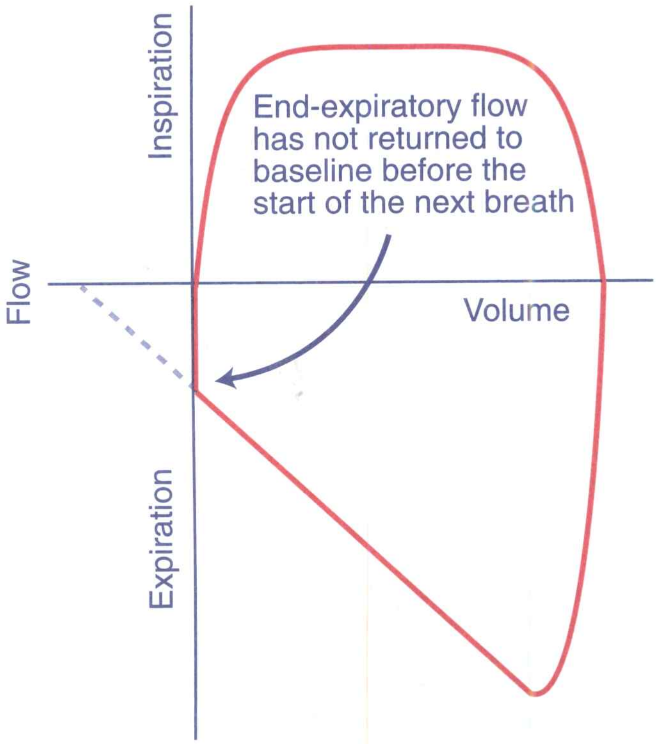

Figure 5-15. Conceptual illustration of why the F-V loop is altered by air-trapping.

may be helpful to switch to SIMV mode or, if necessary, sedate the patient. If a high respiratory rate is necessary and dynamic hyperinflation occurs, especially when bronchospasm is also present, increasing the inspiratory flow rate may yield improvement by extending the time for exhalation.

To better understand why the F-V loop changes shape at the end of exhalation, a conceptualized rendering is given in Figure 5-15. If expiratory time was extended the loop would follow the path of the light blue dashed line. Instead, the loop returns abruptly to the baseline at the start of the next breath. The potential additional volume is exaggerated in this example to clarify the concept of air-trapping. It is important to note that these examples only detect the presence of air-trapping and do not quantify it in cm H_2O.

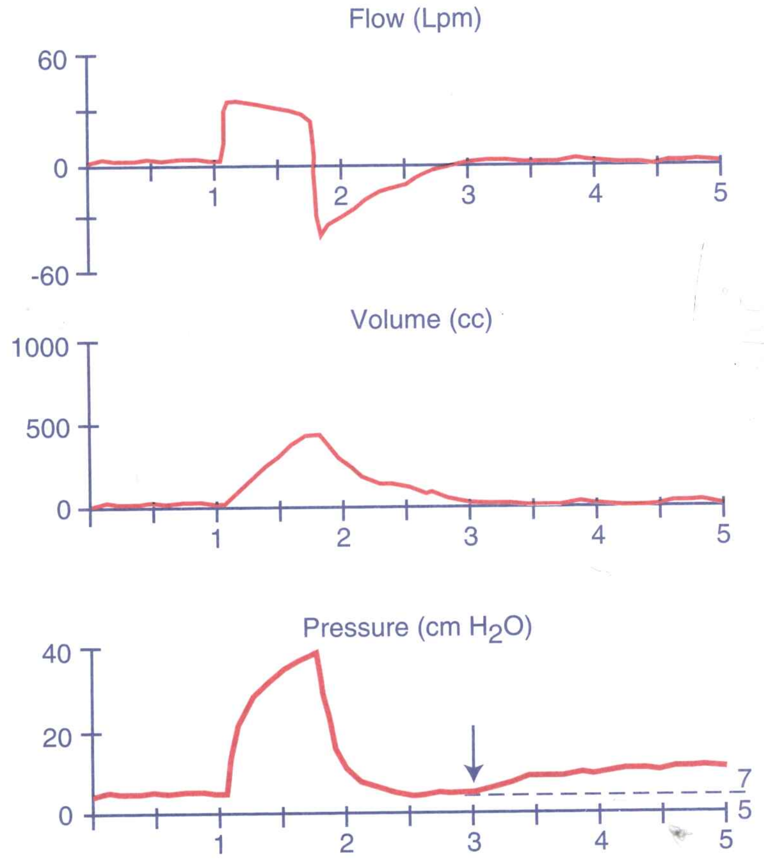

Figure 5-16. Measurement of auto-PEEP in a patient with early airways collapse during expiration. (Set PEEP of 5 cm H_2O, auto-PEEP of 7 cm H_2O, total of 12 cm H_2O.)

The other cause of air-trapping relates to the early collapse of small airways during expiration. Lung diseases that cause destruction of normal airway structure result in tissue being replaced by scar tissue that collapses more easily. This results in early airway closure during expiration. Auto-PEEP associated with air-trapping can be measured by using either of two clinical techniques. The dynamic technique requires the simultaneous measurement of esophageal pressure and will not be addressed here. The second technique involves measuring the airway pressure while occluding the expiratory side of the ventilator circuit near end exhalation (Figure 5-16). The end expiratory occlusion technique for measuring auto-PEEP requires sufficient expiratory time for the occlusion pressure to reach a plateau or the value will not be accurate. Patient respiratory efforts during the expiratory occlusion will also interfere with accurate measurements.

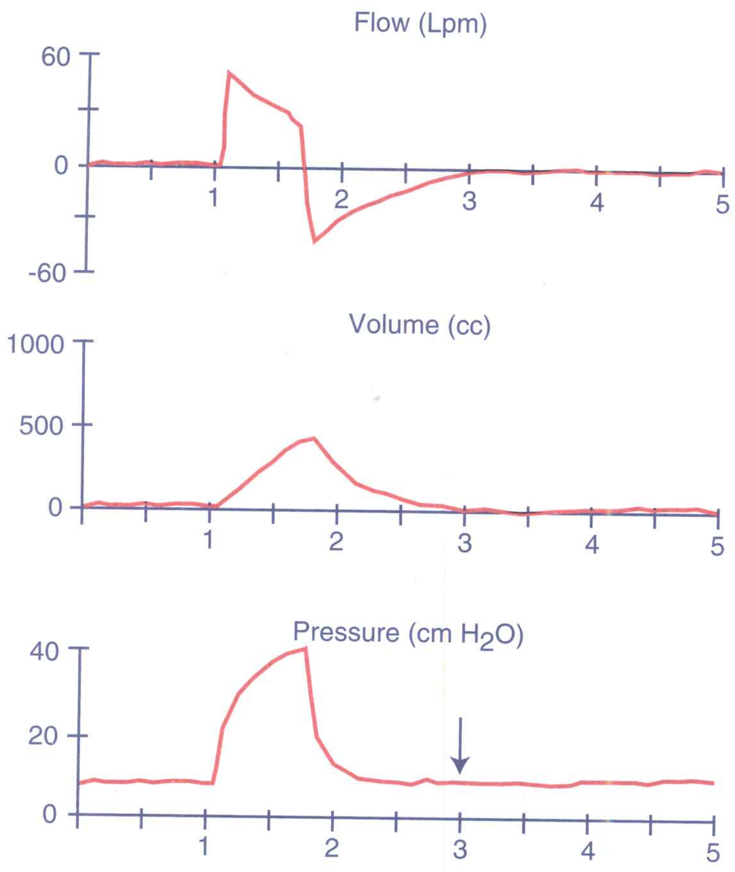

Figure 5-17. Application of external PEEP to correct auto-PEEP caused by early airways collapse during expiration.

The end expiratory occlusion technique is displayed in Figure 5-16. The arrow indicates the occlusion of the expiratory circuit after the end of the expiratory time. The airway pressure tracing rises and eventually plateaus at a level of 14 cm H_2O. This represents 5 cm H_2O of PEEP and 7 cm H_2O of auto-PEEP. Correction of this auto-PEEP is attempted in Figure 5-17. The external PEEP was increased to 8 cm H_2O in this case because the patient was known to have early small airway collapse (as in emphysema). The end expiratory occlusion measurement now indicates an acceptable 2 cm H_2O of auto-PEEP (total of 10 cm H_2O). Other causes of auto-PEEP should be addressed by other remedies such as increasing inspiratory flow, decreasing minute ventilation by frequency and/or V_T, bronchodilators, etc.

KINKED ENDOTRACHEAL TUBE

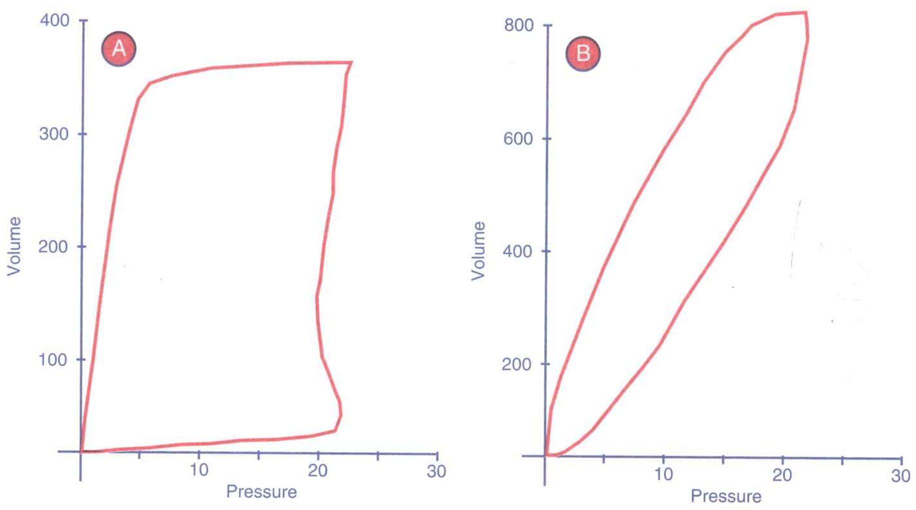

Figure 5-18. The effect of a kinked endotracheal tube on the P-V loop during pressure-targeted ventilation.

A kinked endotracheal tube (ETT) can occur suddenly or gradually. When passing a suction catheter through the ETT becomes difficult, the possibility of a partially obstructed ETT should be considered. This condition is a type of upper airway obstruction, shown in loop A of Figure 5-18. Note the considerable hysteresis and low tidal volume associated with a PIP of 22 cm H_2O. Attempts to reposition the ETT and the patient's head were unsuccessful at relieving the obstruction because a memory of bend in the tubing had developed. Loop B shows the resolution of the obstruction after replacement of the ETT. Partial obstruction of an artificial airway can also be caused by dried secretions or blood in the lumen or at the end of the tube.

PATIENT-VENTILATOR DYSSYNCHRONY
INADEQUATE INSPIRATORY FLOW RATE

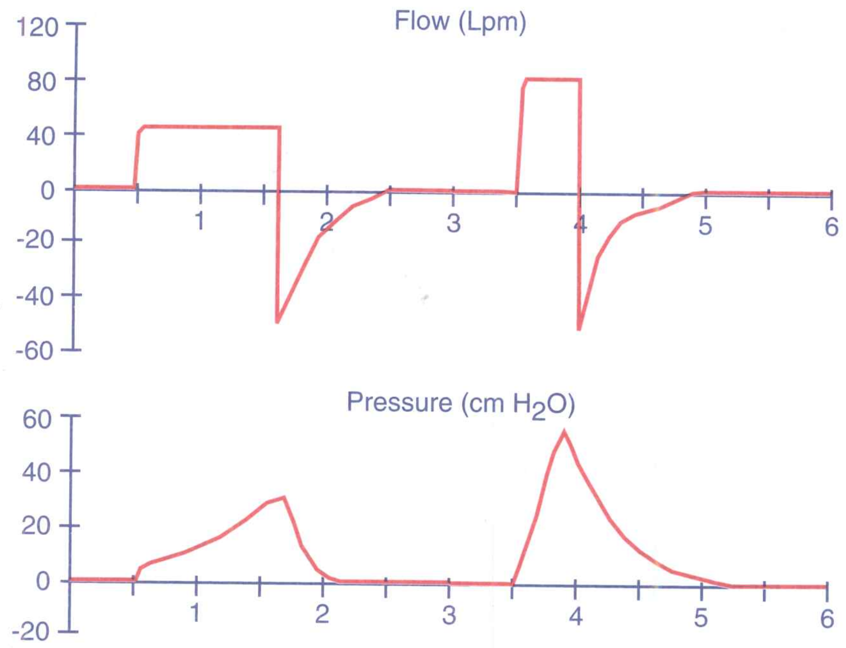

Figure 5-19. Dyssynchrony due to flow starvation.

Setting the inspiratory flow rate optimally in volume-targeted ventilation is often overlooked. This simple adjustment can improve patient comfort in general and especially when resting a patient on the ventilator who is being weaned by increasing periods of spontaneous breathing. The pressure scalar of the first breath in Figure 5-19 shows flow starvation or inadequate flow, a concave or downward scooped pressure curve during the inspiratory phase. The peak flow rate was increased in the second breath to better match the patient's inspiratory demand. Increasing the peak flow worked in this example, but setting the flow too high can produce turbulence that may lead to pressure limiting.

INAPPROPRIATE TRIGGER SENSITIVITY

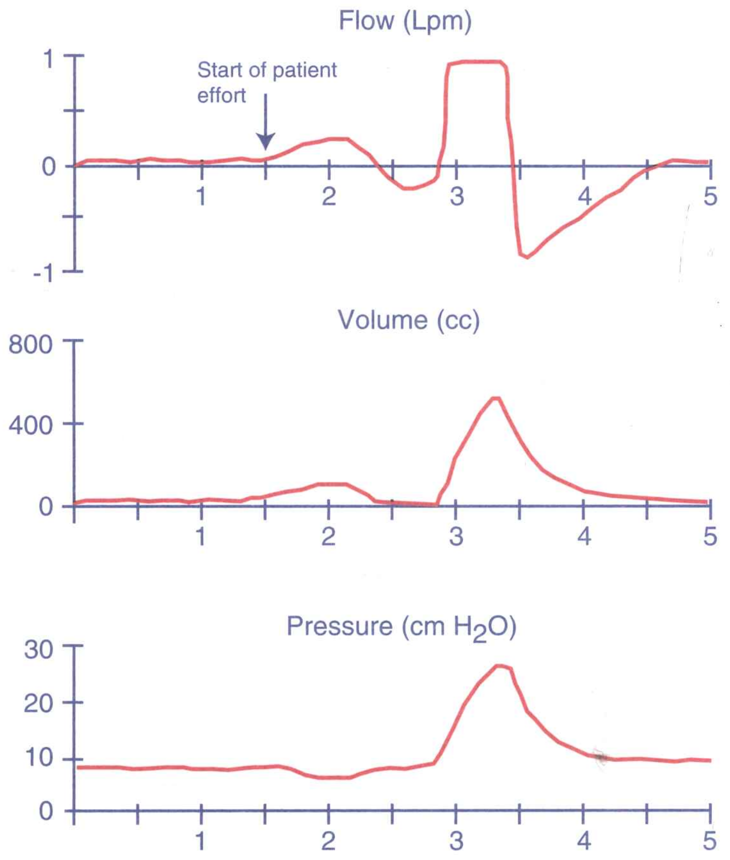

Figure 5-20. Failure to trigger a machine breath in response to patient inspiratory efforts due to an inappropriate sensitivity setting.

The three scalars in Figure 5-20 all show signs of patient effort around the two second time mark, but no machine breath was triggered. Although the pressure drop due to the patient's effort was not large, it was sustained for nearly a second. The patient's diaphragmatic strength may be marginal. Continued unsatisfied patient efforts can lead to patient anxiety further compromising of the diaphragm.

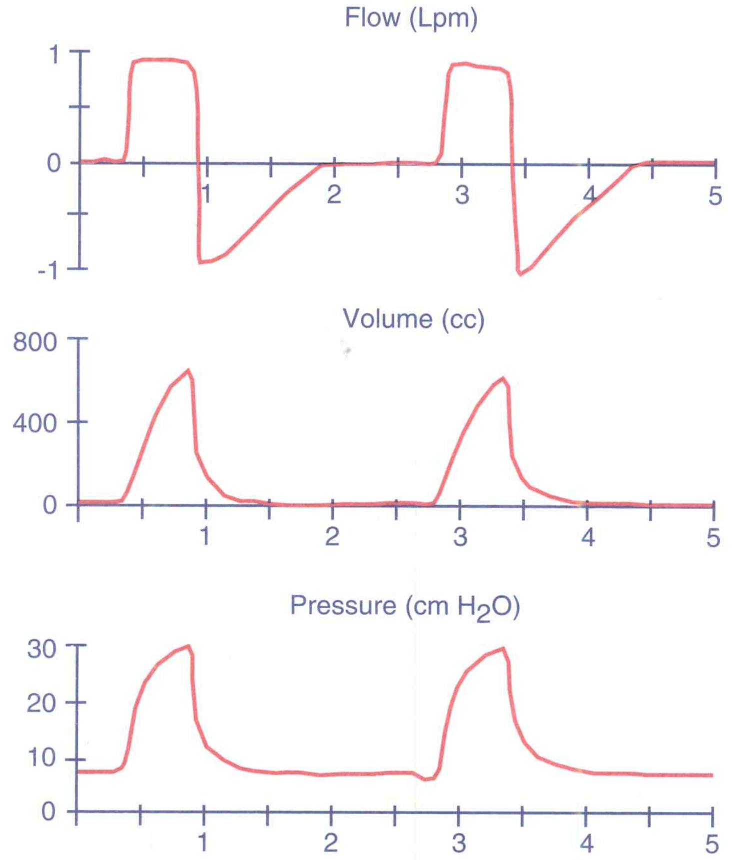

Figure 5-21. Ventilator sensitivity increased to allow for ventilator response to patient inspiratory efforts.

The first breath in Figure 5-21 was untriggered, indicated by the lack of pressure or flow change immediately prior to the machine breath. The second breath is an assisted breath as indicated by the slight pressure deflection before the machine breath. The sensitivity has been increased so that a machine breath is triggered before the patient can generate the magnitude of spontaneous effort observed in Figure 5-20.

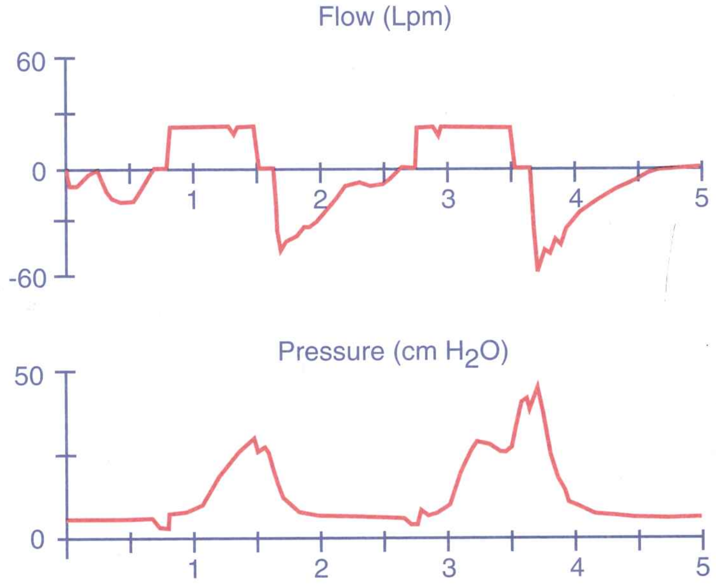

Figure 5-22. Patient rate and ventilator rate out of synchrony.

Patient ventilator rate dyssynchony can have several causes. A patient may have a very high spontaneous rate due to a sensation of air hunger or as a result of a neurologic injury. Aside from the acid base and air-trapping problems that can occur from supporting a high respiratory rate, if compliance and resistance are normal the machine breaths may remain synchronous with the patient up to a point. Beyond that point, patient and machine patterns become uncoupled. Patients with neurologic injury can become uncoupled from the ventilator pattern even at normal spontaneous rates.

Clinicians sometimes confuse rate dyssnychrony with flow starvation (Figure 5-19). Unlike flow starvation, the scalars in Figure 5-22 show abnormal patterns in the expiratory phase as well as the inspiratory phase. Also, the abnormal pattern changes from breath to breath, whereas the pattern for flow starvation is typically similar for each breath.

Choosing a ventilatory mode with rapid initial delivery such as PCV with PSV can often help minimize this type dyssynchrony. Fine-tuning the ventilator to the patient in this fashion will hopefully decrease the need for patient sedation. Some patients requiring full ventilatory support are difficult to synchronize even with using PCV and may respond best to just PSV. The pressure level can be titrated to best match the patient's pattern within the range needed for adequate gas exchange. Apnea ventilation parameters must be properly set before attempting such a trial.

LEAKS

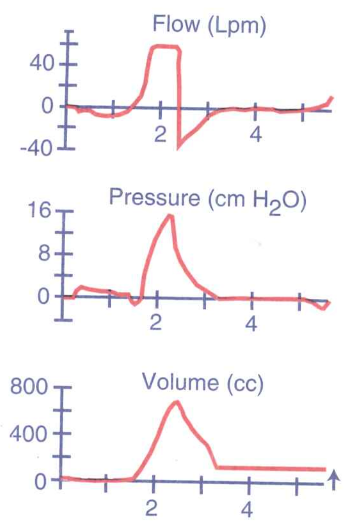

Figure 5-23. Volume loss displayed in a volume scalar.

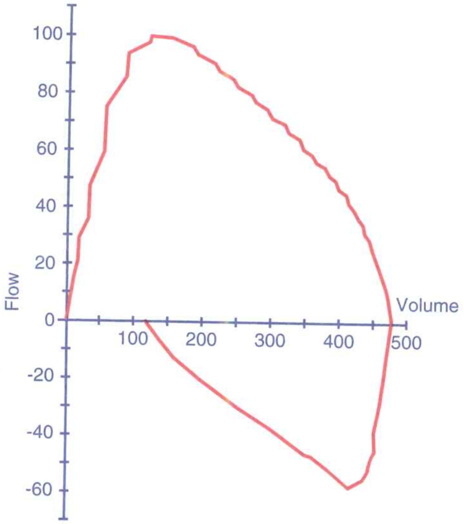

Figure 5-24. Volume loss displayed in a F-V loop.

Volume leaks can be easily detected in the volume scalar, F-V loop, and P-V loop. The volume scalar of Figure 5-23 does not return to the baseline during exhalation for the displayed breath. A plateau above the zero volume baseline is created by the lost volume (arrow). Volume loss is detected in the F-V and P-V loops as a failure to close the loops (Figures 5-24 and 5-25). Inspiratory and expiratory volume should be the same but will vary slightly even under normal conditions due to momentary changes in patient lung conditions, cuff seal, etc. Consistent volume loss should be systematically investigated for correction. A source of leak that is sometimes hard to identify is a misplaced nasogastric tube in the trachea, especially if one is unaware the tube has been replaced. In this situation, expiratory volume loss is accompanied by the patient exerting greater effort to trigger a ventilator breath.

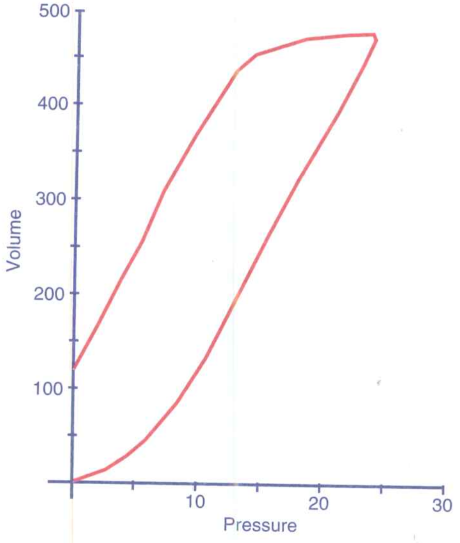

Figure 5-25. Volume loss displayed in a P-V loop.

CHAPTER 6
NEONATAL APPLICATIONS

I. Introduction
II. Normal Infant Pulmonary Functions
III. Normal Scalars, Flow-Volume (F-V), and Pressure-Volume (P-V) Loops
IV. Abnormal Waveforms
  Improper Sensitivity Scalars
  Large Air Leak and Autocycling Scalars
  A/C Pressure Control Asychrony Scalars
  A/C Pressure Control F-V and P-V Loops
 Inadequate Flow Scalars
  Inadequate Rise Time or Flow
  Excessive Inspiratory Pressure and Flow Scalars
  Effect of Excessive Inspiratory Pressure on the P-V Loop
  Reduced Compliance F-V and P-V Loops
  Excessive Inspiratory Time Scalars
 Inspiratory Flow Termination Scalars
  Termination of Inspiratory Flow
  Breath-Stacking (Auto-PEEP) Scalars
  Breath-Stacking F-V and P-V Loops
  Obstruction to Expiratory Flow Scalars
  Obstruction to Expiratory F-V and P-V Loops
  Right Mainstem Intubation Scalars
  Right Mainstem Intubation F-V and P-V Loops
  Progression to Extubation Scalars
  Turbulent Baseline Flow Rate Scalars
  High Frequency Ventilation

INTRODUCTION

Mechanical ventilation of neonates and small infants is commonly applied by a time triggered, pressure limited, time cycled ventilator. These ventilators have a continuous flow that delivers a specific F_IO_2. During spontaneous breathing, the continuous flow provides a fresh gas source to the patient. Mandatory or controlled breaths are based on setting of the inspiratory time (time cycled) and frequency (time triggered). When the ventilator time triggers a breath a signal is sent to the exhalation valve to close. Flow (decelerating flow curve) enters the patient's lungs through the inspiratory limb of the patient circuit for the set inspiratory time. When pressure reaches the set limit, the remaining pressure is diverted to a limiting device. As the ventilator cycles the exhalation valve opens and allows the patient volume and continuous flow to exit. Tidal volume delivered by the ventilator depends on the pressure limit, inspiratory time and flow rate. The amount of volume entering the lungs depends on lung and chest wall compliance, resistance of the endotracheal tube, and airways.

Over the past several years, neonatal ventilation has become more sophisticated. The first step was the adaptation of well established modes of adult ventilation into the Neonatal Intensive Care Unit (NICU) environment, such as synchronize intermittent mandatory ventilation (SIMV) and synchronized assist control as well as the ability to monitor bedside respiratory mechanics. Due to more recent technological advances, ventilators with sophisticated modes and features which had been reserved for use in the adult intensive care unit are frequently utilized in the NICU. Pressure control ventilation (PVC) and pressure support ventilation (PSV) with decelerating flow rates controlled by the ventilator are now an option. Volume-targeted ventilation is now possible as we are no longer limited to only pressure-targeted ventilation. Breath initiation and breath termination can be adjusted to more closely suit each individual patient's needs. As more ventilator modes and options become available to the clinician, the ability to monitor and assess through ventilator graphics becomes an even more valuable and essential tool.

The benefits of bedside respiratory monitoring include recognition of:

a. Asynchronous breathing
b. Breath-stacking, air-trapping and auto-PEEP
c. Expiratory grunting, prolong expiratory time
d. Change in dynamic compliance from lung disease or administration of surfactant
e. Inadvertent extubation
f. Excessive inspiratory pressure
g. Inappropriate inspiratory flow rate
h. Inappropriate sensitivity setting
i. Excessive inspiratory time
j. Excessive inspiratory flow rate
k. Excessive endotracheal tube leak
l. Identification of airway obstruction and the need for suctioning

NORMAL INFANT PULMONARY FUNCTIONS

Measurement	Units	Normal	RDS	BPD
Tidal volume	mL/kg	5-7	4-6	4-7
Respiratory rate	breaths/min	30-60	50-80	45-80
Minute ventilation	mL/kg/min	200-300	250-400	200-400
Function residual capacity (FRC)	mL/kg	20-30	15-20	20-30
Compliance (static)	mL/cm H_2O/kg	1-4	0.1-0.6	0.2-0.8
Compliance (dynamic)	mL/cm H_2O/kg	1-2	0.3-0.5	0.2-0.8
Resistance	cm H_2O/mL/sec	0.025-0.05	0.06-.15	0.03-0.15
Resistance	cm H_2O/L/sec	25-50	60-150	30-150
Work-of-breathing	gram/cm/min/kg	500-1000	800-3000	1800-6500
VD/VT ratio	percent	22-38	60-80	35-60
Dead space	mL/kg	1.0-2.0	3.0-4.5	3.0-4.5
Pulmonary capillary blood flow	mL/kg/min	160-230	75-140	120-200
Oxygen consumption	mL/kg/min	6-8		
CO_2 production	mL/kg/min	5-6		
Respiratory quotient		0.75-0.83		
Calories	kcal/kg/day	105-183		

(Adapted from SensorMedics Corporation, Yorba Linda, California)

NORMAL SCALARS, FLOW-VOLUME (F-V), AND PRESSURE-VOLUME (P-V) LOOPS

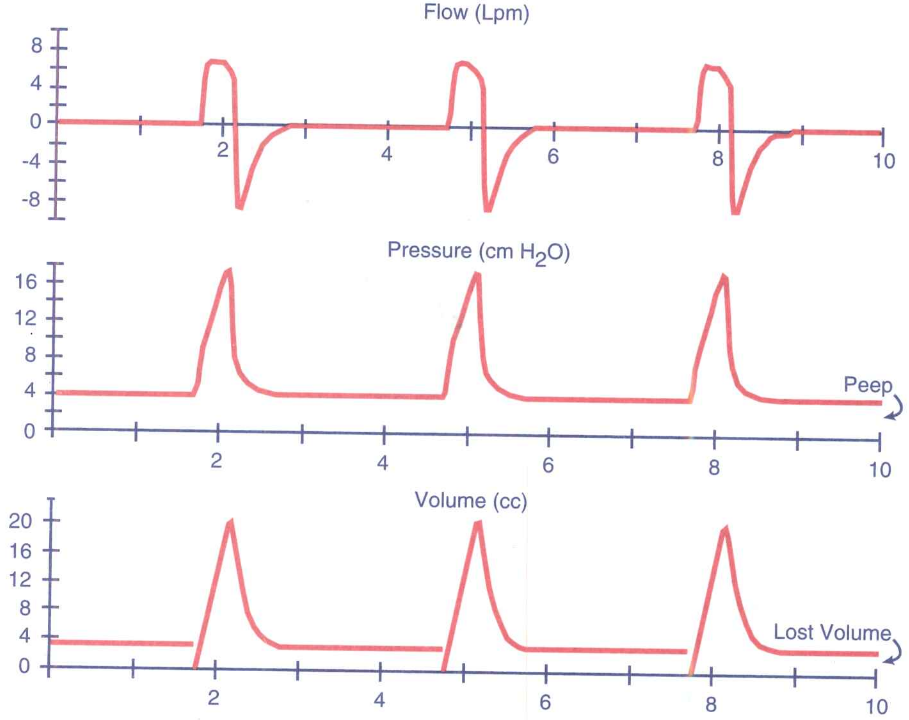

Figure 6-1. Neonatal control ventilation scalars.

The scalars in Figure 6-1 show mandatory or controlled breaths delivered by a time triggered, pressure limited, time cycled ventilator. The pressure scalar following a positive pressure breath (PPB) returns to baseline pressure of 4 cm H_2O representing PEEP. The driving pressure is 14 cm H_2O (18 cm H_2O - 4 cm H_2O = 14 cm H_2O). These breaths being mandatory breaths show no drop in pressure below baseline that would indicate a spontaneous inspiratory effort by the patient.

The flow scalar shows a flow rate of 8 L/m with a decelerating flow. The exhalation portion of the flow curve returns to baseline before the next breath is delivered. The volume scalar returns to baseline of 3 mL indicating lost volume. This is normal for a patient with a cuffless endotracheal tube where some volume leaks around the tube as a PPB is delivered to the lungs. Lost volume should not exceed 20% of the total volume delivered. Lost volume here represents 15%.

The F-V loop in Figure 6-2 shows a flow rate of 8 L/min and a delivered volume of 20 mL. The loop rises as flow rate enters the lung and a volume of 20 mL is achieved. That pressure is maintained for the set inspiratory time. When inspiratory time is complete, exhalation is represented by a downward loop. This corresponds to the flow scalar on the expiration side. The loop then returns to baseline. The return volume (exhalation portion of the loop) returns to 3 mL. This represents lost volume that corresponds to the volume scalar.

The P-V loop in Figure 6-3 shows a pressure of 18 cm H_2O (driving pressure is 14 cm H_2O) delivery and an exhaled volume of 17 mL (20 mL – 3 mL). The P-V loop starts at 4 cm H_2O representing the level of PEEP set on the ventilator.

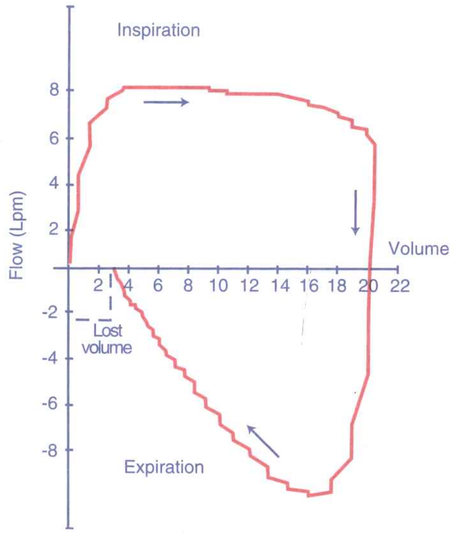

Figure 6-2. Control ventilation F-V loop.

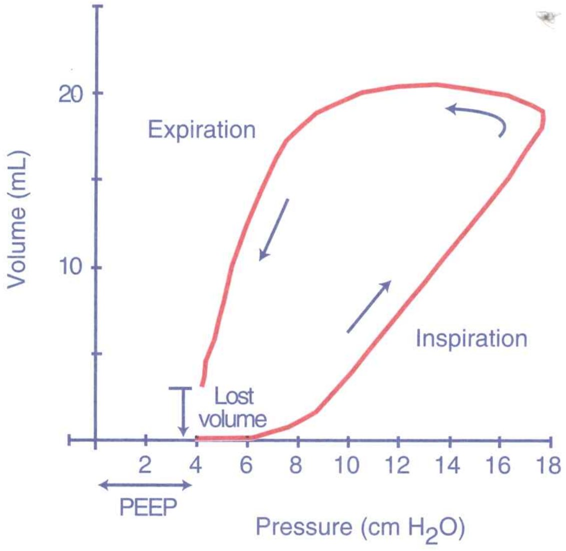

Figure 6-3. Control ventilation P-V loop.

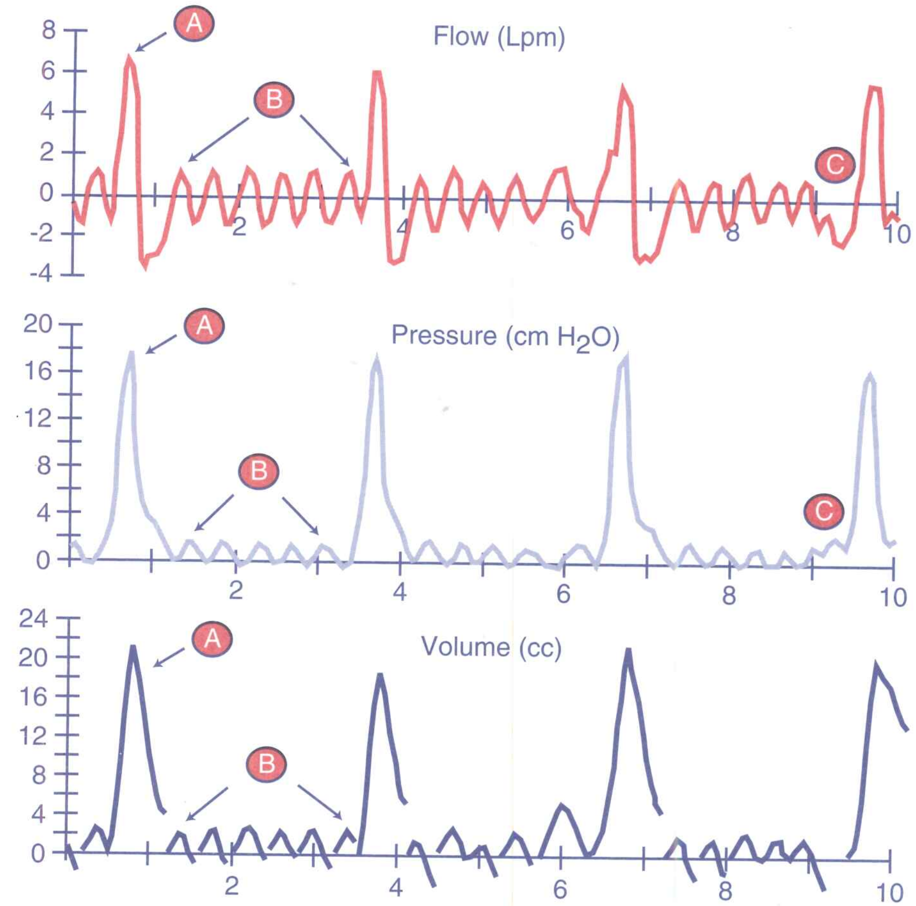

Figure 6-4. IMV scalars.

A patient is receiving pressure limited, time cycled, continuous flow ventilation in intermittent mandatory ventilation (IMV) mode (Figure 6-4). Point A represents a positive pressure breathing, and B represents spontaneous breaths on the flow, pressure, and volume scalar. The first three positive pressure breaths are delivered in synchronous with the patient's inspiratory effort. At point C, the patient begins to exhale but before complete exhalation occurs a positive pressure breath is delivered. Compare this with SIMV scalars in Figure 6-7.

Figure 6-5 shows F-V loops for the segment of breathing shown in Figure 6-4. The mandatory machine breaths are shown in red and blue, and spontaneous breaths are represented in light blue. Because the ventilator in this example used a simple interruption of constant flow to generate breaths, the machine breaths were susceptible to slight alterations by the patient's respiratory efforts.

The P-V loops for respirations in Figure 6-4 are given in Figure 6-6. Note the change in volumes as patient compliance changes from breath to breath.

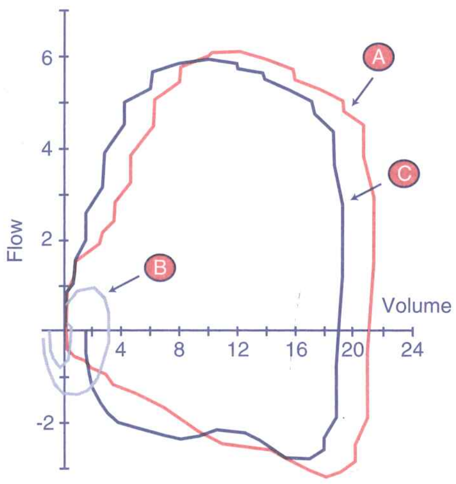

Figure 6-5. IMV F-V loops.

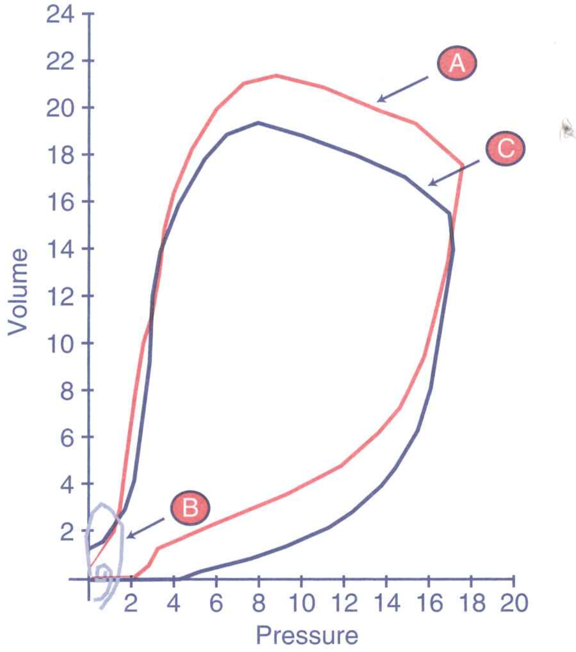

Figure 6-6. IMV P-V loops.

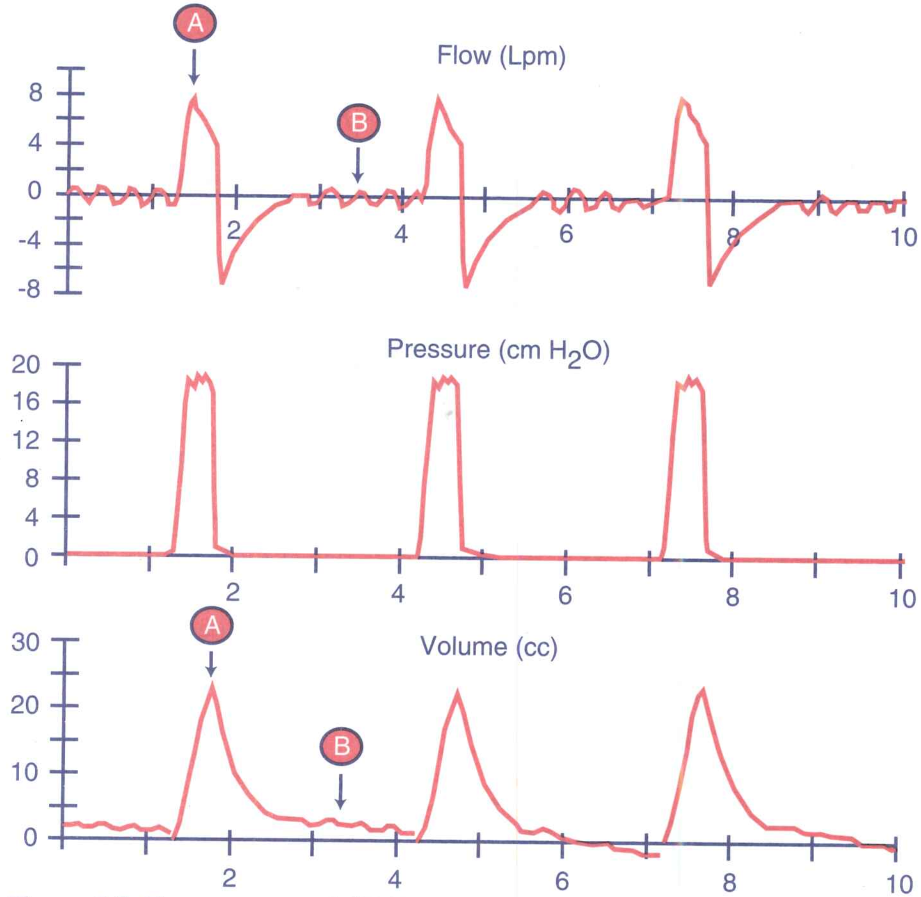

Figure 6-7. Pressure control SIMV scalars.

The patient in Figure 6-7 is receiving pressure-targeted ventilation in the SIMV mode. Point A represents a positive pressure breath. Point B represents spontaneous breaths. Note that at the end of each series of spontaneous breaths, the next positive pressure breath is delivered at end exhalation as seen on the flow scalar as the exhalation portion of the flow curve returns (resets) to baseline.

The F-V loops in Figure 6-8 were created with a ventilator in a pressure-targeted mode synchronized with the patient's inspiratory efforts, which yielded more uniform machine breaths. Although the volume was fairly constant in the example, it can vary according to amount of patient effort in a pressure-targeted mode.

The machine P-V loops in Figure 6-9 clearly indicate a pressure-targeted mode is being used. Inspiratory pressure quickly increases to the set limit and is maintained until the end of the inspiratory period.

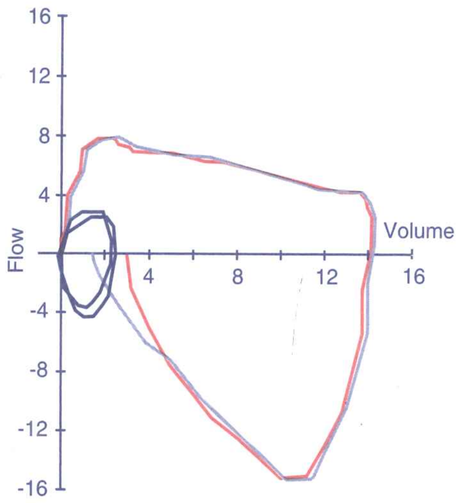

Figure 6-8. Pressure control SIMV F-V loops.

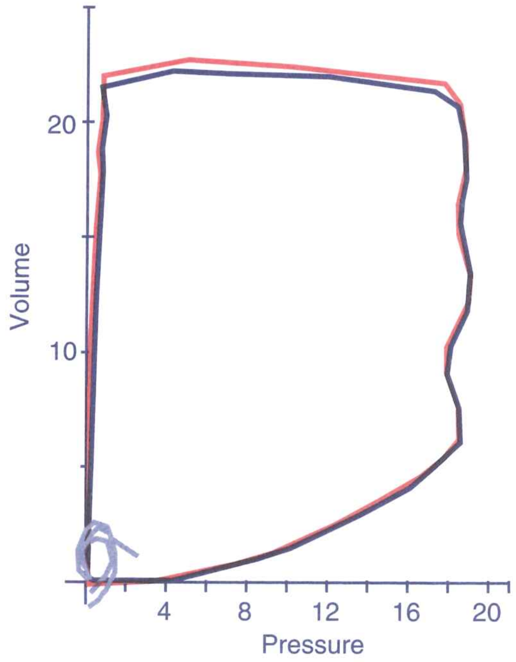

Figure 6-9. Pressure control SIMV P-V loops.

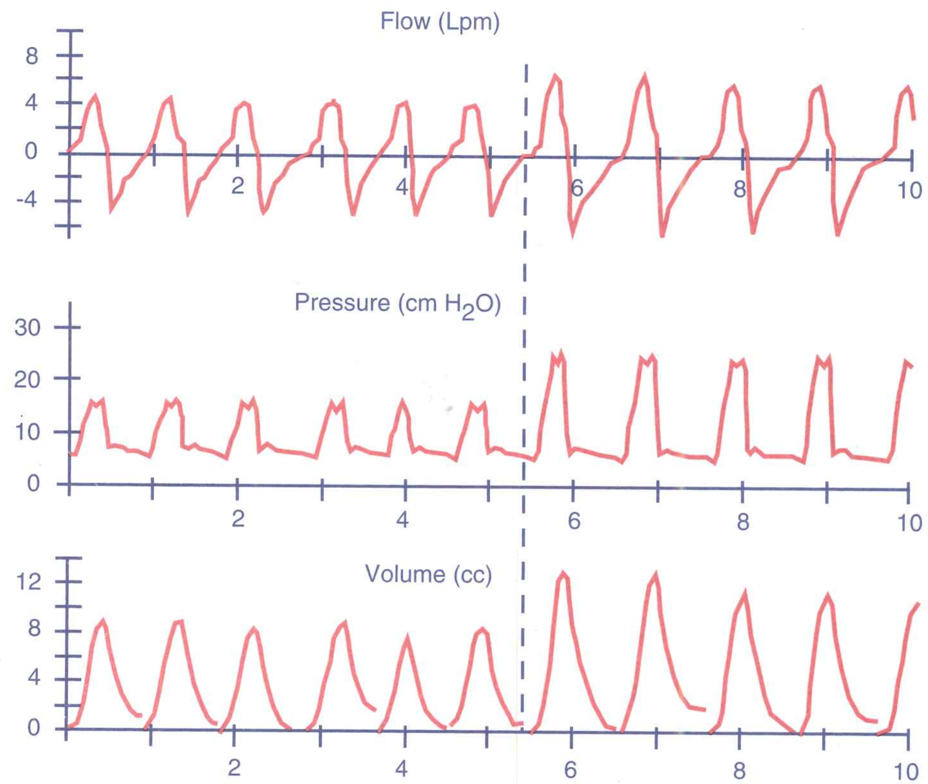

Figure 6-10. Pressure support ventilation of 10-20 cm H_2O with CPAP of 5 cm H_2O scalars.

The scalars in Figure 6-10 represent a change in PSV from 10-20 cm H_2O with a baseline CPAP of 5 cm H_2O. A PSV level of 10 cm H_2O with a baseline of 5 cm H_2O yields a total pressure of 15 cm H_2O with a driving pressure of 10 cm H_2O (15 cm H_2O - 5 cm H_2O = 10 cm H_2O). When PSV level is increased to 20 cm H_2O, flow and volume increase due to the increase in driving pressure to 20 cm H_2O (25 cm H_2O - 5 cm H_2O = 20 cm H_2O).

IMPROPER SENSITIVITY SCALARS

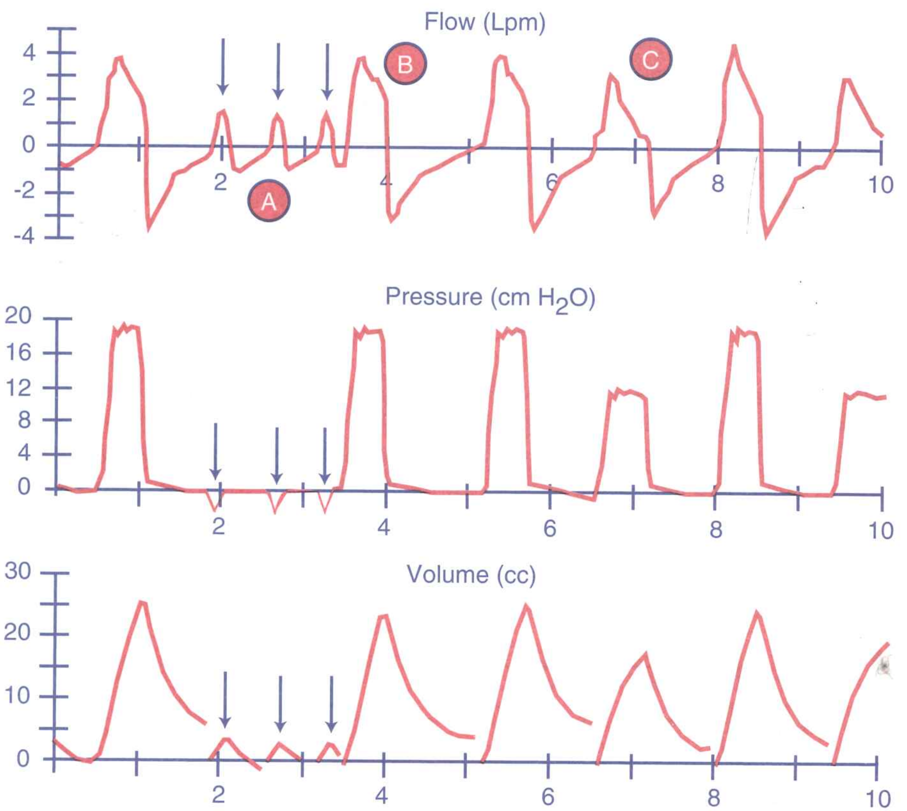

Figure 6-11. Improper sensitivity setting scalars.

The patient in Figure 6-11 is in SIMV mode with PSV. The flow, pressure, and volume scalars indicate spontaneous breaths at point A. Each arrow represents a spontaneous breath. Note on the pressure scalar there are negative pressure deflections that are not followed with a delivered pressure support breath. The sensitivity of the ventilator is improper for the inspiratory effort of the infant. Point B represents delivery of a positive pressure breath after which the sensitivity was increased. Point C represents a PS breath being delivered as a result of the new sensitivity setting.

LARGE AIR LEAK AND AUTOCYCLING SCALARS

Air leaks can have a variety of causes. They can be either mechanical in origin, such as a leak in a ventilator circuit, around a patient's endotracheal tube, or a large chest tube leak. They can also be of a patient origin, such as a bronchopleural fistula. Uncuffed endotracheal tubes are routinely used in the Neonatal and Pediatric ICU, therefore an endotracheal tube leak is the most common situation causing an air leak in children. A small leak is usually very manageable for a skilled clinician, but a large leak can be very problematic. In an air leak situation, the ventilator may not adequately maintain the baseline PEEP. The ventilator may inaccurately sense the PEEP baseline drift as a patient effort and respond with a supported breath. This is called autocycling. Some of the dangers of autocycling include air-trapping, auto-PEEP, asynchrony, hyperventilation, and delayed ventilator weaning. Large air leaks may also lead to a poor ventilator response to true patient respiratory efforts leading to an increase in the work-of-breathing and patient agitation.

Some of the signs you may observe on the scalar graphics that may demonstrate the presence of a large air leak include the inability to maintain PEEP on the pressure scalar, the presence of supported breaths without an obvious trigger such a pressure or flow change, and the tidal volume scalar not returning to baseline as demonstrated in Figure 6-12.

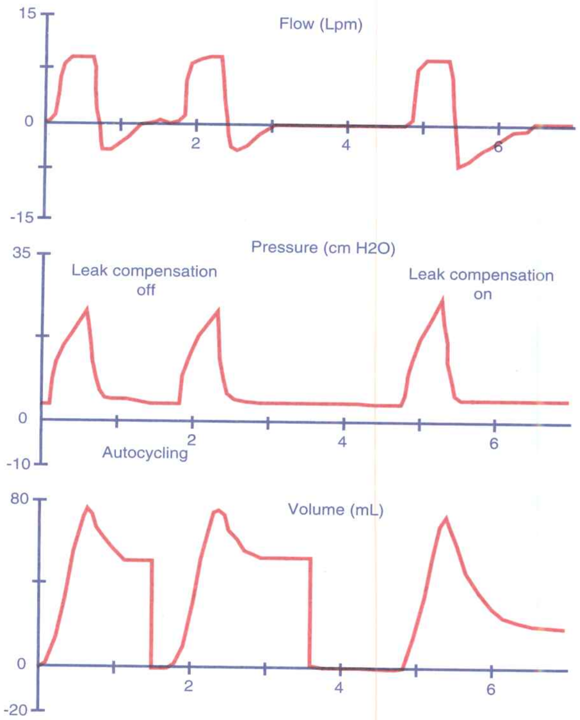

Figure 6-12. Large air leak and autocycling scalars.

ASSIST MODE PRESSURE CONTROL ASYNCHRONY SCALARS

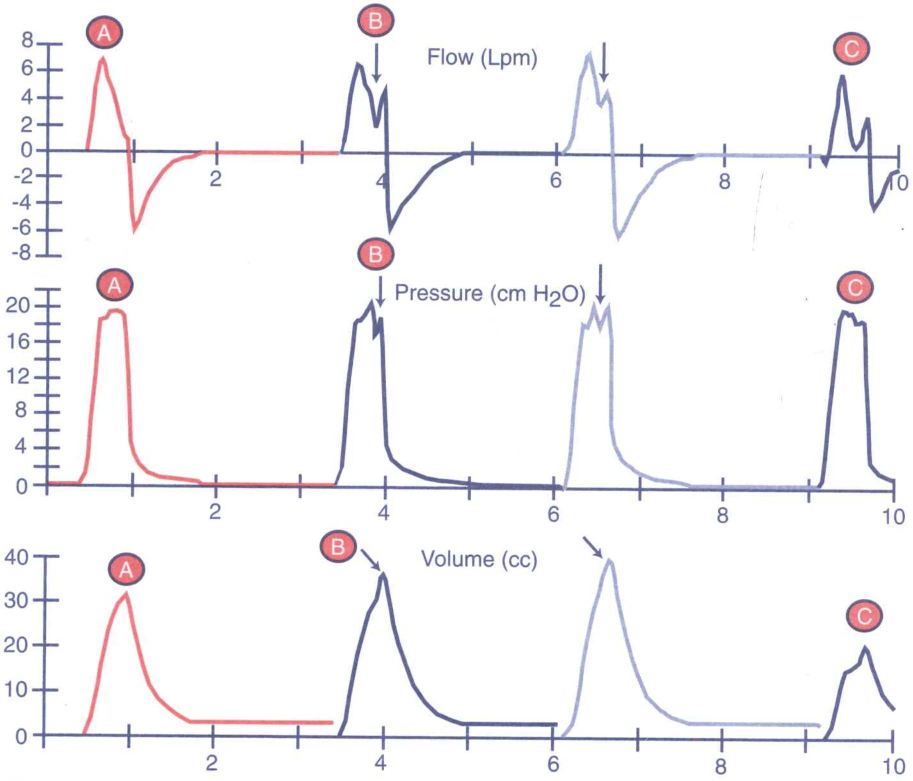

Figure 6-13. Assist mode pressure control asynchrony scalars.

The first breath A on the flow, pressure, and volume scalars represents normal synchronous breathing (Figure 6-13). Compare these waveforms to the next three waveforms on each scalar. On the flow scalar, arrows pointing to the notched area during inspiratory phase indicates an inspiratory effort. Fluctuation in pressure occurs during the inspiratory effort as seen on the pressure scalar. This coincides with fluctuation in flow as the infant inspires. The volume scalar demonstrates fluctuation in volume. The second and third volume waveforms show increases in volume as a result of the inspiration taken during the positive pressure breath. The third volume waveform shows a reduction due to asynchrony. To improve synchrony the clinician could either shorten inspiratory time or increase inpiratory pressure.

ASSIST MODE PRESSURE CONTROL ASYNCHRONY F-V AND P-V LOOPS

The loops and numbers in Figures 6-14 and 6-15 correspond with those in Figure 6-13. Inspiratory flow normally follows a decreasing pattern after reaching a peak flow (red loop). Figure 6-14 shows flow increasing and decreasing twice during the inspiratory phase due to patient-ventilator asynchrony (blue and light blue loops). Asynchrony is seen where flow is decreasing and then an upswing in the flow-volume curve occurs. This is due to the patient initiating another inspiratory effort near the end of the ventilator's inspiratory period. Note the alteration in volume with each breath.

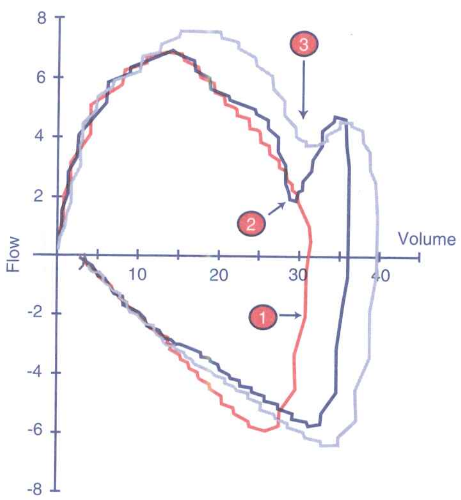

Figure 6-14. Assist mode pressure control asynchrony F-V loops.

The P-V loops in Figure 6-15 show a rapid initial rise in pressure as volume enters the lung. Change in the loop occurs as the infant inspires during the inspiratory phase of the positive pressure breath. Each P-V loop can be compared to the scalars in Figure 6-13. Note the change in volume of each P-V loop from 1 to 2, and 2 to 3. The continual rise in pressure to the set point indicates flow is adequate for the patient (red loop).

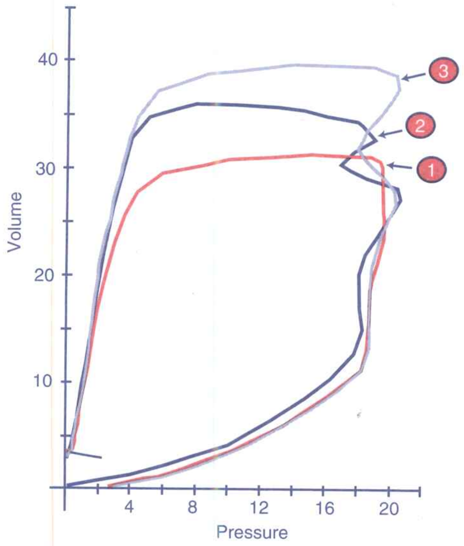

Figure 6-15. Assist mode pressure control asynchrony P-V loops.

INADEQUATE FLOW SCALARS

INADEQUATE RISE TIME OR FLOW

In some ventilator modes, the flow at the onset of inspiration phase can be determined by the setting of the rise time. The rise time is the time required to reach the set pressure level. The rise time is clinician adjusted and is often utilized to improve patient comfort. Rapid rise time may decrease the patient's work-of-breathing, the feeling of dyspnea, and the need for sedatives. Rise times that are either too fast or too slow may be detrimental. Flow rates that are too fast may prematurely terminate the inspiratory phase of a breath, since some breath termination criteria utilize a calculation based on a percentage of the peak flow. High flow rates may also potentially activate an inspiratory termination reflex, resulting in brief, shallow respirations. Flow rates that are too slow may cause flow starvation and dyssynchrony, increased work-of-breathing, inadequate mean airway pressure, and lead to the increase of peak airway pressure to attain tidal volumes.

Inadequate rise time produces inadequate flow for the patient as illustrated in the pressure and flow scalars of Figure 6-16.

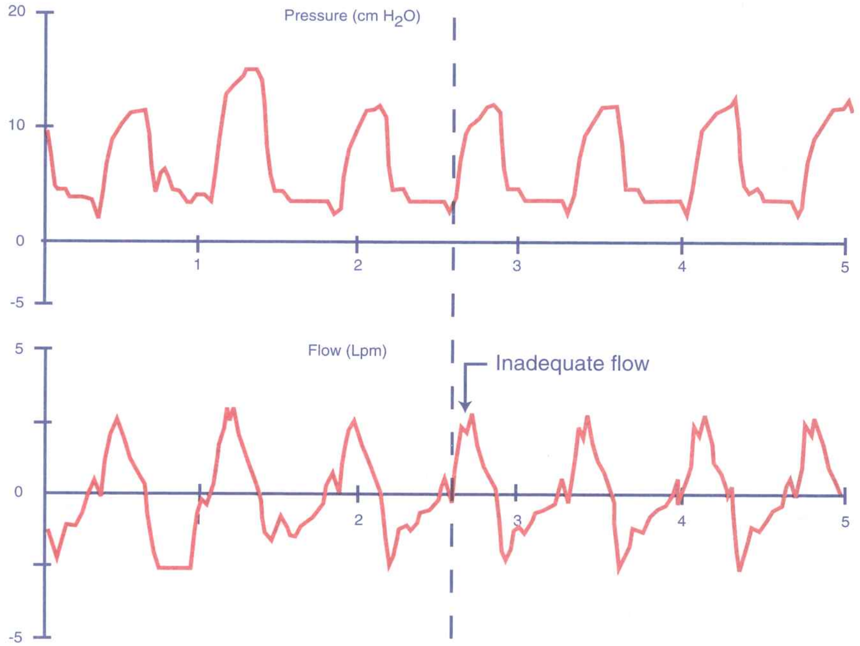

Figure 6-16. Inadequate flow scalars.

EXCESSIVE INSPIRATORY PRESSURE AND FLOW SCALARS

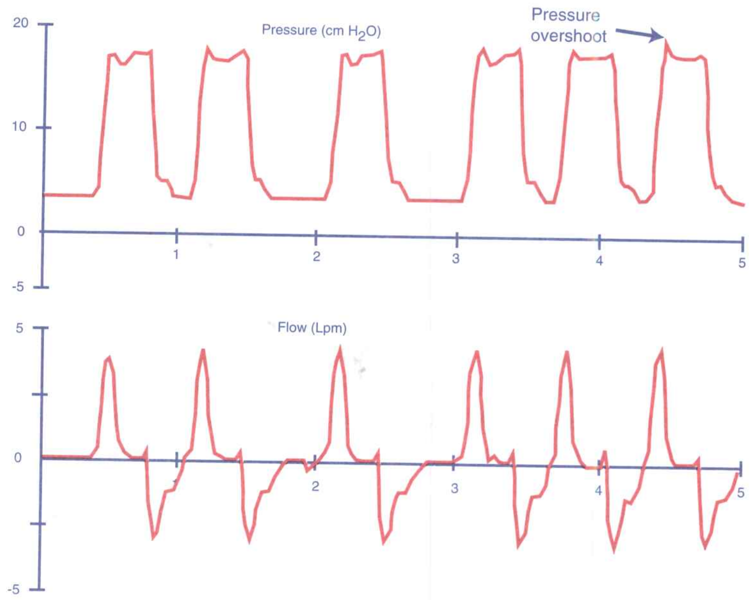

Figure 6-17. Excessive inspiratory pressure and flow scalars.

Excessive flow delivery can be caused by a rise time that is too fast. In the pressure scalar in Figure 6-17, an assist mode pressure control breath is delivered with the fastest rise time; notice the spike on the pressure scalar at the beginning of inspiration. Often this pressure spike is undesirable as it brings flow and pressure to the patient that does not translate into increased tidal volume delivery.

EFFECT OF EXCESSIVE INSPIRATORY PRESSURE ON THE P-V LOOP

Point A on the P-V curve in Figure 6-18 shows an increase in pressure with no change in volume. This is often referred to as *beaking*. At point B the pressure is decreased from 29 cm H_2O to 25 cm H_2O and the curve has a more rounded appearance at peak inspiration. Although the pressure is reduced, there is little change in the delivered volume.

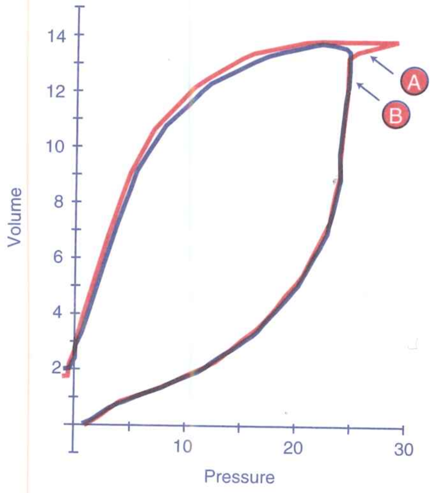

Figure 6-18. Effect of excessive inspiratory pressure on the P-V loop (beaking).

REDUCED COMPLIANCE F-V AND P-V LOOPS

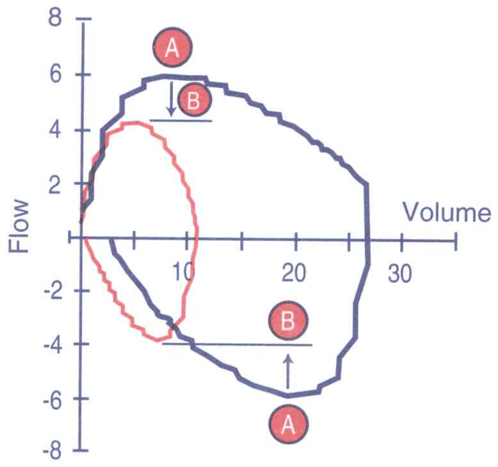

Figure 6-19. Reduced compliance F-V loop.

The F-V loop in Figure 6-19 represents a reduction in flow and volume as a result of decreased lung compliance. Loop A represents a high compliance with a 25 mL tidal volume being delivered. Loop B shows a reduction in compliance where tidal volume delivery is 10 mL. The P-V loop A in Figure 6-20 shows a similar volume as in the F-V loop A in Figure 6-19. Notice in loop B the flattening of the loop as compared to loop A, this indicates a compliance decrease.

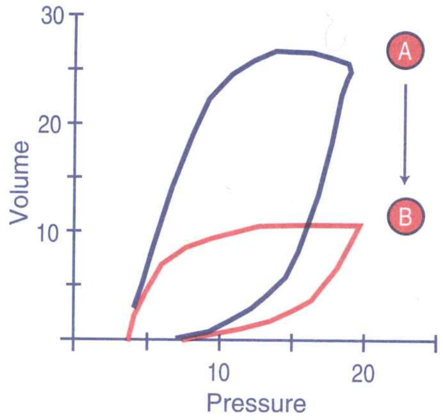

Figure 6-20. Reduced compliance P-V loop.

EXCESSIVE INSPIRATORY TIME SCALARS

Increased inspiratory time can be a valuable tool during the acute phase of the lung injury to increase mean airway pressure, treat atelectasis, and to improve oxygenation. As the lung recovers and the patient resumes spontaneous breathing, excessive inspiratory time can lead to active exhalation and dyssynchrony. Excessive inspiratory time can lead to patient agitation, increased carbon dioxide production, increased oxygen and caloric consumption, delayed ventilator weaning, increased intracranial pressure (ICP), increased risk of cerebral bleed, and a compromised cardiovascular status.

Excessive inspiratory time causes active exhalation as illustrated in the pressure and flow scalars in Figure 6-21. Notice the spiked appearance at the completion of each breath as the patient forcibly exhales due to an inspiratory time which is too long.

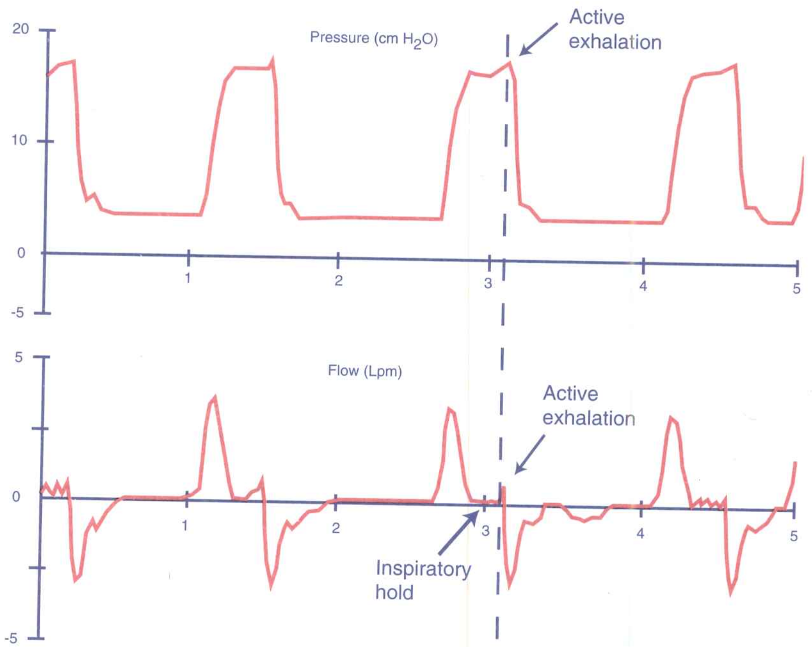

Figure 6-21. Excessive inspiratory time scalars.

TERMINATION OF INSPIRATORY FLOW SCALARS

A breath may be terminated by time or by flow. Flow termination facilitates synchrony by allowing the clinician to select the percent of peak flow at which inspiration terminates. Flow termination should be titrated by using graphics to eliminate periods of no inspiratory flow and of pressure plateau, but the patient's tidal volume should be preserved.

The addition of flow cycled termination instead of time cycled allows the transition from inspiration to expiration to occur, without a significant pressure plateau or zero flow state, as seen in the pressure and flow scalars in Figure 6-22. Notice the transition from peak inspiratory flow to peak expiratory flow is almost a straight line.

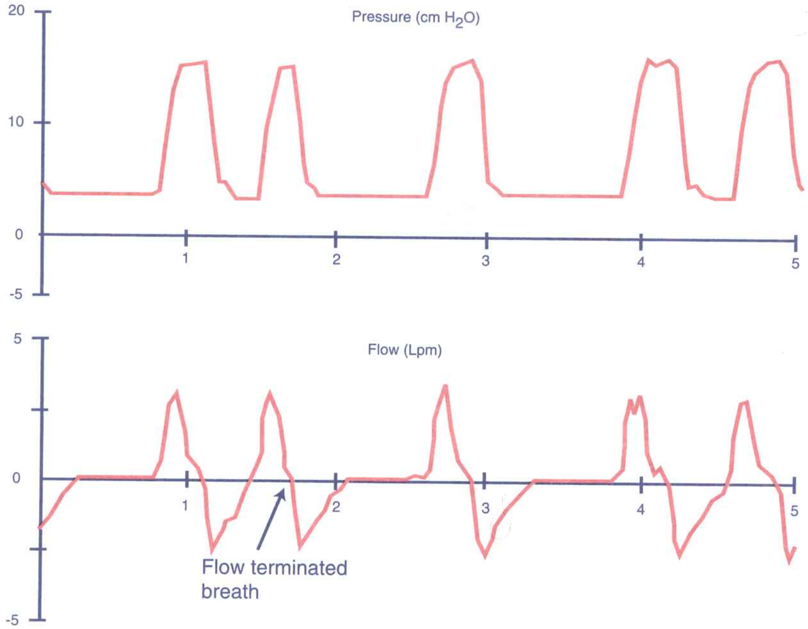

Figure 6-22. Inspiratory flow termination scalars.

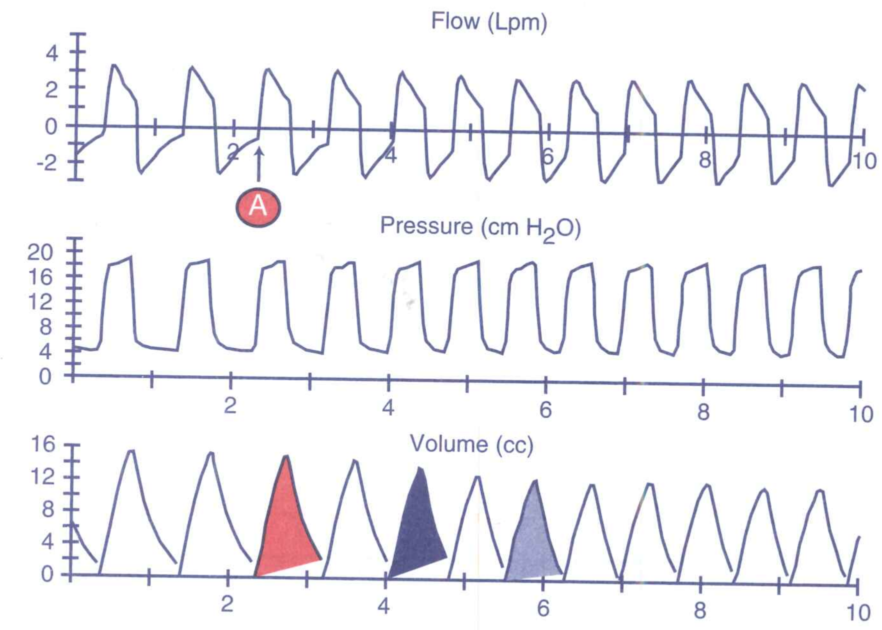

Figure 6-23. Breath-stacking (auto-PEEP) scalars.

A high mechanical ventilator rate can cause breath-stacking to occur, resulting in air-trapping or auto-PEEP. In Figure 6-23, note point A on the flow scalar how the flow does not reach baseline before the next mechanical breath is delivered. As the mechanical rate is changed (moving from left to right), note how the next positive pressure breath starts earlier. On the volume scalar, note how an increase in respiratory rate causes volume to decrease. Each new breath is stacked on top of the preceding breath causing air to remain trapped in the lung.

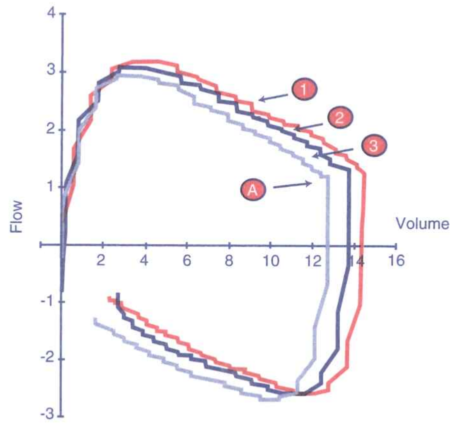

Figure 6-24. Breath-stacking F-V loops.

The F-V loops in Figure 6-24 labeled 1, 2, and 3 coincide with the shaded curves o the scalars in Figure 6-23. Note how each loop has a decrease in volume as th mechanical rate is increased and how flow does not reach baseline before the nex positive pressure breath is delivered. The P-V loop in Figure 6-25 shows the volum retained in the lung at end exhalation. Also note how with each successive breath, th tidal volume decreases due to the trapped gas in the lung. Observe the large hysteresis created by breath-stacking.

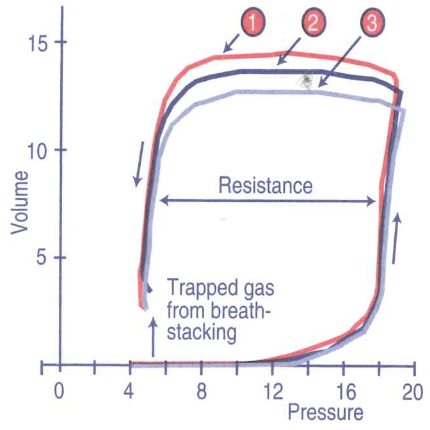

Figure 6-25. Breath-stacking P-V loops.

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OBSTRUCTION TO EXPIRATORY FLOW SCALARS

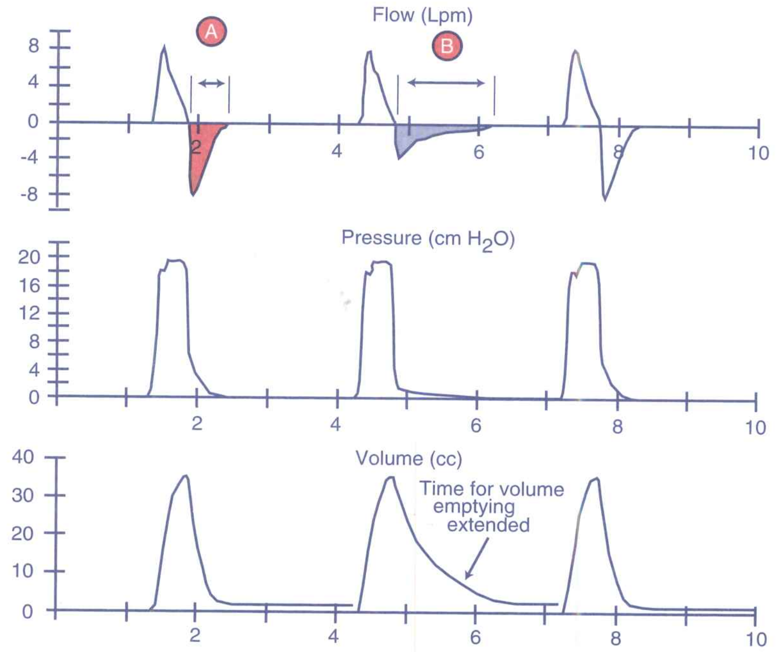

Figure 6-26. Obstruction to expiratory flow scalars.

Compare the shaded expiratory waveforms A and B in Figure 6-26. Waveform A shows a normal expiratory waveform reaching baseline in a short period of time. The expiratory waveform is a mirror image of the inspiratory waveform. In B, note how the expiratory waveform is shorter (less flow rate) and the expiratory time is longer. This indicates there is resistance to exhalation. Also note on the volume scalar the shape of the volume scalar as compared to the first volume scalar. The time for volume emptying is longer due to expiratory resistance. Also recognize how the volume baseline is raised compared to the first volume waveform. The second pressure waveform also shows extended time for emptying of the lung. No breath-stacking is seen here in spite of prolonged exhalation due to the long exhalation time set on the ventilator.

OBSTRUCTION TO EXPIRATORY F-V AND P-V LOOPS

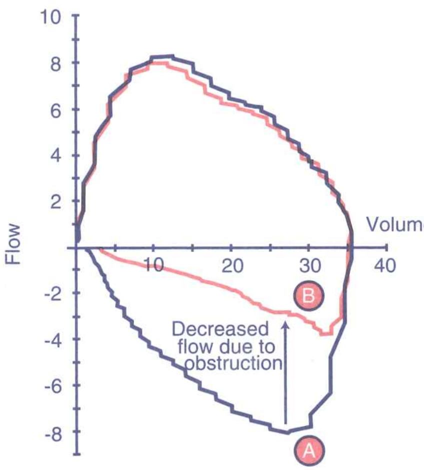

Figure 6-27. Expiratory flow rate obstruction F-V loops.

Compare points A and B in the F-V loop shown in Figure 6-27. The inspiratory flo
is normal in both A and B. A decrease in expiratory flow rate occurs during gruntin
and less volume returns at B than at A. The P-V loop in Figure 6-28 shows a widene
loop appearance from A to B, indicating a greater resistance, accompanied by exp
ratory grunting. The loop enlargement during exhalation indicates resistance durin
exhalation.

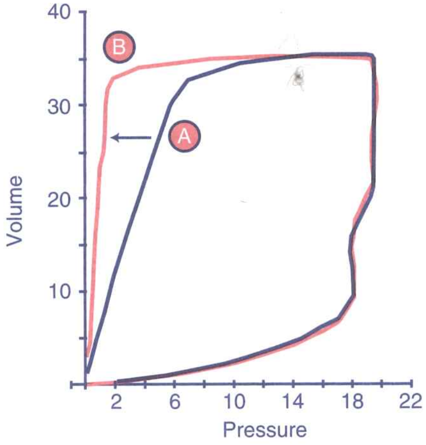

Figure 6-28. Expiratory flow rate obstruction P-V loops.

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RIGHT MAINSTEM INTUBATION SCALARS

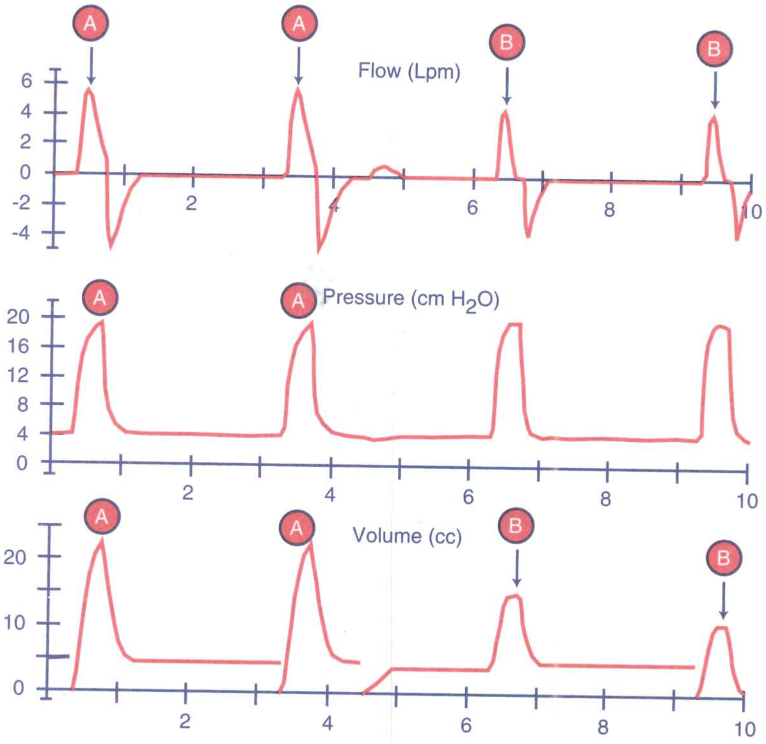

Figure 6-29. Neonatal right mainstem intubation scalars.

The scalars in Figure 6-29 show changes in flow rate and volume as the ET tube moves from the trachea into the right mainstem bronchus. Point A represents normal flow and volume and pressure scalars from proper placement of the ETT. Point B represents the tube having moved into the right mainstem bronchus. The volume scalar at point B shows a reduction in volume compared to point A and flow rate at point B is reduced compared to point A. Pressure remains unchanged in this pressure controlled mode of ventilation.

RIGHT MAINSTEM INTUBATION F-V AND P-V LOOPS

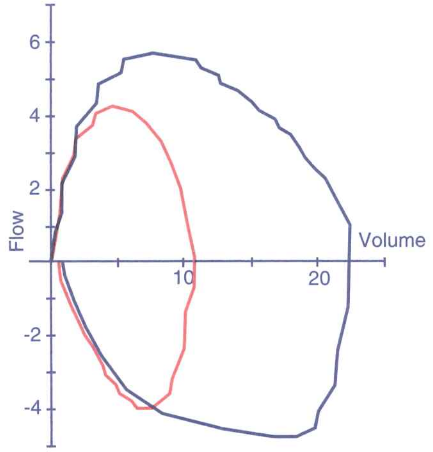

Figure 6-30. Right mainstem bronchus intubation F-V loops.

Right mainstem intubation results in decreased volume and peak flow rate a seen in Figure 6-30. The red loop take on the typical pattern for a restrictiv condition. This is due to the decrease compliance of ventilating one lung.

A change in patient compliance durin pressure-targeted ventilation cause change in both pressure and volume. Th ventilator adjusts flow rate to maintain constant pressure as seen in Figure 6-31 A change in patient respiratory syster compliance using pressure-targeted ver tilation results in a volume change.

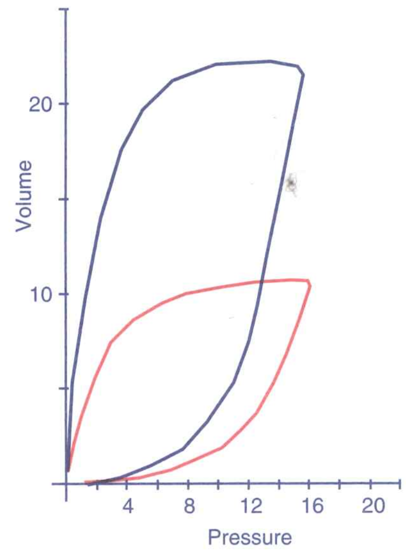

Figure 6-31. Right mainstem bronchus intubation P-V loops.

PROGRESSION TO EXTUBATION SCALARS

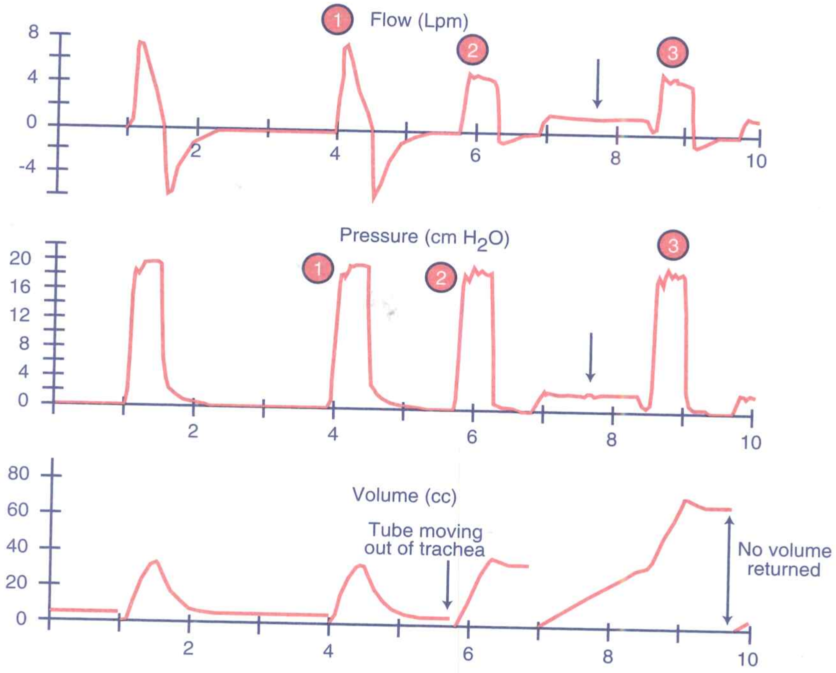

Figure 6-32. Progression to extubation scalars.

Breath 1 on the flow scalar in Figure 6-32 represents a normal condition with the ET tube positioned through the vocal cords into the trachea. Normal flow rate, pressure, and volume waveforms are seen at this point. As the tube starts to move out of the trachea, note the decrease in returned volumes. With the tube completely out of the trachea, no volume is returned. The flow and pressure curves are altered by the reduction in returned volume.

TURBULENT BASELINE FLOW RATE SCALARS

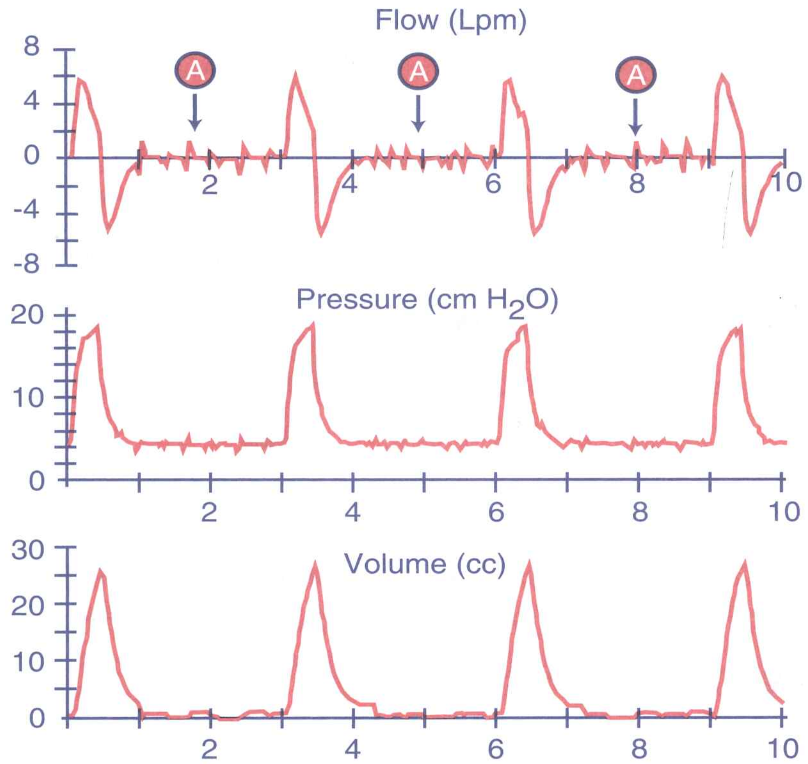

Figure 6-33. Turbulent baseline flow rate scalars.

Water from condensation in the inspiratory limb of the ventilator circuit creates nonuniform waveform appearance in each of the scalars between each positive pressure breath. This may also be caused by secretions in the endotracheal tube and airways or water within the inspiratory limb of the patient's circuit.

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HIGH FREQUENCY VENTILATION

High frequency ventilation (HFV) is a mode of mechanical ventilation in which lung recruitment is accomplished without exposing the lungs to high peak pressures. Tidal volumes are utilized that are near dead space and the breaths are delivered at very high frequencies. The goals of HFV are to maintain a nearly constant alveolar volume and alveolar pressure to prevent lung stretch injuries. The main characteristics of high frequency ventilation are small tidal volumes, short inspiratory times, and optimally inflated alveoli. There are several different types of high frequency ventilators utilized in the United States and around the world. They all differ slightly in how the breaths are delivered, but the basic theory of operation is the same for all and the basic terms utilized to discuss their settings are closely related.

FACTORS AFFECTING GAS EXCHANGE

The following are the three main factors affecting gas exchange during HFV:

a. Frequency
b. Amplitude
c. Mean airway pressure

The measurement of the respiratory rate is called the frequency. Frequency is expressed in Hertz (Hz) or cycles per minute: one Hz = 60 cycles per minute.

For example, 10 Hz (10 x 60) = 600 cycles per minute.

Depending on the type of high frequency ventilator chosen, increasing the Hz, otherwise known as the frequency or respiratory rate, does not necessarily improve minute ventilation and gas exchange as in traditional modes of mechanical ventilation. In fact, the reverse actually occurs. In the most common form of HFV, a piston is used to push pulses of gas through a continuous flow circuit. Increasing the Hz or frequency in HFV can decrease the amount of time this piston spends in the inspiratory position (decreasing inspiratory time) which can decrease tidal volume delivered to the patient. To increase gas exchange in patients on HFV, often the Hz or frequency will be decreased not increased.

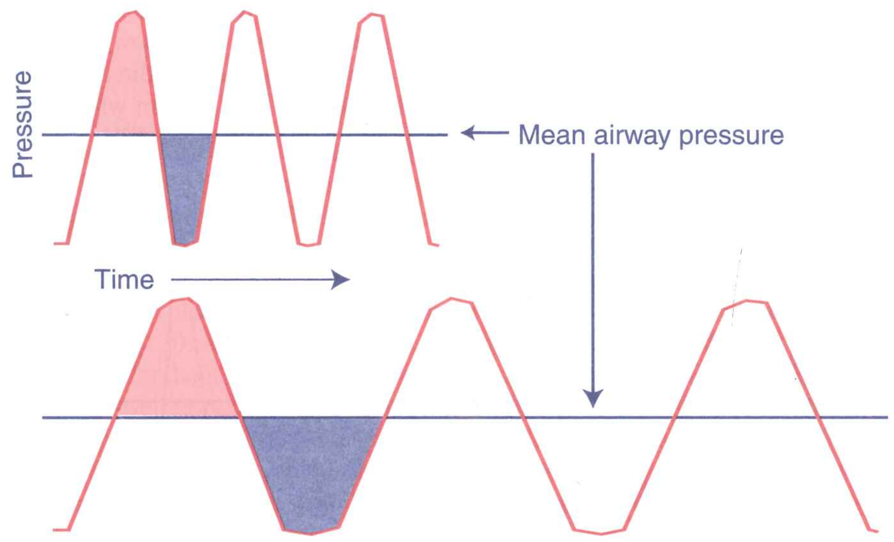

Figure 6-34. Frequency's affect on tidal volume displaced.

Frequency controls the time allowed (distance) for the piston to move. Therefore, th lower the frequency, the greater the volume displaced; the higher the frequency, th smaller the volume displaced. Increasing frequency in HFV with a piston driven ver tilator will decrease tidal volume and minute ventilation and increase the patient $PaCO_2$.

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The amplitude adjustment affects the pulse volume or the amount of gas pushed back and forth through the circuit. The amplitude is not measured from baseline as PIP is above PEEP. Amplitude is a measurement of change above and below baseline. Increases in amplitude can increase tidal volume displacement and will directly affect ventilation. Amplitude adjustments are the first choice for the clinician who would like to increase or decrease carbon dioxide clearance in the patient on HFV.

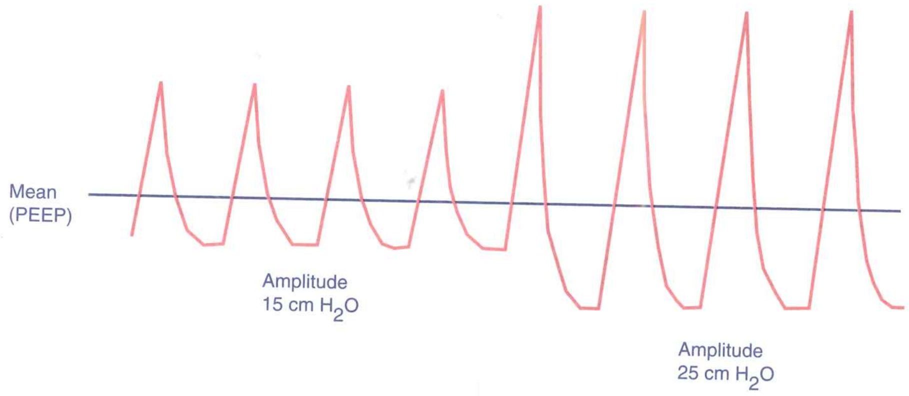

Figure 6-35. Amplitude is measured as the distance peak to trough from above and below the mean airway pressure.

The mean airway pressure adjustment is used to inflate the lung and to improve gas exchange, primarily oxygenation. The goal is to keep the alveoli above critical opening pressure and maintain them in the open position. With optimal lung expansion the alveoli may stabilize and be protected against overdistension and sheer stretch injuries.

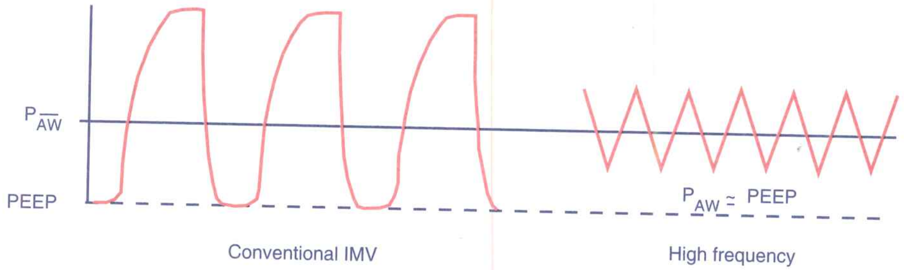

Figure 6-36. Mean airway pressure and PEEP are completely different measurements during conventional ventilation but the same during HFV.

APPENDIX
CASE STUDIES

NEONATAL CASE STUDY 1

A 20-year-old gave birth to Rodney, a 27-week, 785-gram baby born by vaginal deliv ery. The mother had no prenatal care, and she had premature rupture of membrane for three days prior to delivery. Apgar scores were 5 and 9 at 1 minute and 5 minutes respectively, following bag-mask ventilation. Rodney was intubated with a 2.5 mr ID oral endotracheal tube and given one dose of surfactant. Rodney was transferre to NICU and placed on pressure limited, time cycled ventilation with the followin settings: PIP 20 cm H_2O, rate 40/min, inspiratory time 0.3 seconds, PEEP 5 cm H_2 F_IO_2 1.0. Ten hours after the initial dose of surfactant was given, Rodney exhibite signs of respiratory distress with intercostal and suprasternal retractions, spontaneou respiratory rate increased from 48 to 88/min, pulse increase from 138 to 178/min, an increased periods of desaturation below 90%. Exhaled tidal volume decreased from mL/kg to 2.5 mL/kg. The F_IO_2, which had been weaned to 0.30, has been increase to 0.70 to maintain saturation above 90%. The following P-V curve B was obtaine and compared to the P-V curve A taken after administration of the initial dose surfactant.

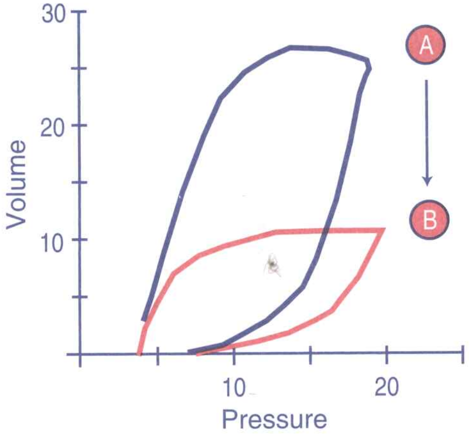

Figure A-1.

Questions

1. What has caused the change in the P-V loop between A and B?

2. Based on P-V loop B, what would you recommend at this time?