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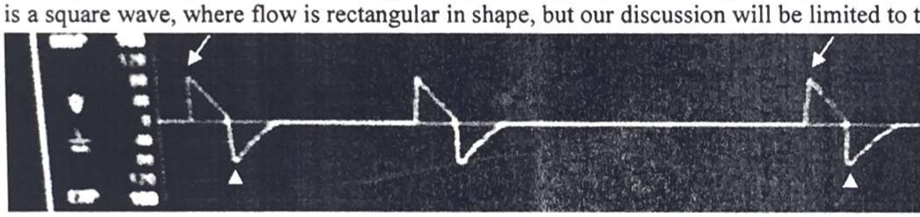
Basics of Mechanical Ventilation
D. Modes of Mechanical Ventilation

1. ***What are the basic modes of mechanical ventilation?*** The terminology used to describe ventilator settings frequently varies from institution to institution and from one type of ventilator to another. Thus, it is important to be precise when communicating ventilator settings to another health care provider. This chapter begins with a discussion of the three basic modes of ventilation: assist control (AC), synchronized intermittent mandatory ventilation (SIMV), and pressure support ventilation (PSV). The mode is intentionally distinguished from the cycling mechanism, i.e. pressure (PCV) vs. volume cycled ventilation (VCV), since either pressure or volume can be cycled with the AC and the SIMV modes. The table below summarizes the parameters that must be set by the clinician for each of the three basic modes of mechanical ventilation. The less commonly used modes include proportional assist ventilation, high frequency oscillation, and airway pressure release ventilation. This chapter includes a discussion of airway pressure release ventilation since it is available on most modern ventilators. However, the reader is referred to more advanced manuals for discussion of proportional assist ventilation and high frequency oscillation.

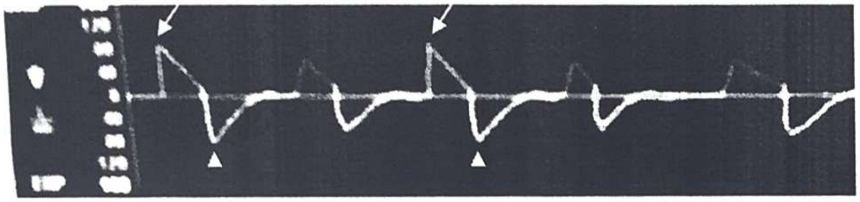
	AC	SIMV	PSV
Cycling Mechanism	Volume or Pressure	Volume or Pressure	Pressure
Universal Settings	FIO_2 PEEP	FIO_2 PEEP	FIO_2 PEEP
Major Settings	Tidal Volume or Pressure Control Respiratory Rate	Tidal Volume or Pressure Control Respiratory Rate Additional Pressure Support	Pressure Support
Other Settings	Inspiratory Time or Flow Rate Flow Pattern Sensitivity	Inspiratory Time or Flow Rate Flow Pattern Sensitivity	Sensitivity

a. Assist Control (AC) – Consider a patient who is on AC mode of ventilation as follows: 30% FIO_2 / TV 0.5 L / rate 10 / PEEP 5 / flow 90 lpm via decelerating pattern. A flow-time curve for this patient is shown below. By convention, inspiration is positive (arrows) and expiration is negative (arrowheads). Decelerating wave refers to delivery of the inspiratory breath using a triangular shaped (decelerating) flow pattern. An alternative flow pattern is a square wave, where flow is rectangular in shape, but our discussion will be limited to the decelerating pattern.

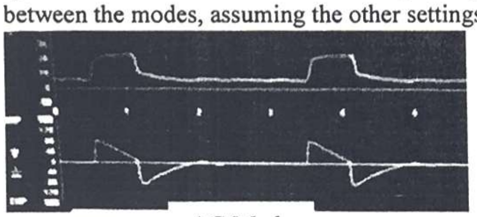


1) ***What is another name for assist control mode?*** AC is also known as CMV on some machines.
2) ***Is there a minimum number of breaths that this patient has to take?*** Since the respiratory rate is set at 10, patient must take at least 10 breaths per minute. Each mandatory breath consists of 0.5 L of 30% oxygen delivered at a decelerating flow rate of 90 lpm.
3) ***Is the patient able to take additional breaths spontaneously?*** Yes, patient may take spontaneous breaths in addition to the 10 mandatory breaths. The figure above shows one spontaneous (gray arrow) and two mandatory breaths (white arrows). Notice that in the AC mode, the spontaneous breaths are identical and indistinguishable from the mandatory breaths in that each will be 0.5 L of 30% oxygen delivered at 90 lpm via decelerating wave pattern.
4) ***What is this patient's inspiratory time?*** Recall that the area under the inspiratory flow curve is the tidal volume. For a decelerating wave pattern, the shape of the flow curve is a triangle as shown by the arrows above. Since the area of a triangle is equal to ½ of the base times the height, the TV is equal to ½ of the inspiratory time (IT) times the initial flow rate (Flow): TV = ½(IT)(Flow). Therefore, the inspiratory time for this patient is 0.67 seconds given a TV of 0.5 L and flow of 90 lpm (1.5 lps).
5) ***What will be the pressure at end of expiration?*** At the end of expiration, the ventilator maintains a positive end expiratory pressure (PEEP), which is 5 cm of H_2O in this example.
6) ***Does AC automatically mean that TV is used?*** When a clinician states that a patient is on AC mode, it is often implied that the patient is also on TV control rather than pressure control. Although this is common practice, it is incorrect since either TV or pressure can be used with the AC mode. In this example, TV is being cycled but PC could have been used just as easily. Thus, in order to minimize confusion, both the mode and the cycling mechanism should be specified (i.e. volume cycled AC or pressure cycled AC).

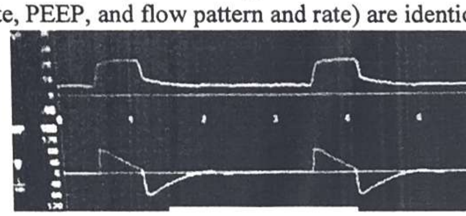
b. Synchronized Intermittent Mandatory Ventilation (SIMV) – Consider a patient who is on SIMV mode of ventilation as follows: 30% FIO_2 / TV 0.5 L / rate 10 / PEEP 5 / flow 90 lpm via decelerating pattern / PS 10 above PEEP. A flow-time curve for this patient is shown below. Inspiration and expiration are indicated by the arrows and arrowheads, respectively.



1) ***What is another name for Synchronized Intermittent Mandatory Ventilation?*** SIMV is also known as IMV on some machines.
2) ***Is there a minimum number of breaths that this patient has to take?*** Since the respiratory rate is set at 10, patient must take at least 10 breaths per minute. Each mandatory breath (white arrows) consists of 0.5 L of 30% oxygen delivered at a decelerating flow rate of 90 lpm.
3) ***Is the patient able to take additional breaths spontaneously?*** Yes, patient may take spontaneous breaths in addition to the 10 mandatory breaths. As in the AC mode, each mandatory breath will be 0.5 L of 30% oxygen delivered at 90 lpm via decelerating wave pattern. The difference between SIMV and AC modes is in how the spontaneous breaths are handled. In contrast to the AC mode where the spontaneous breaths are identical to the mandatory breaths, each spontaneous breath in the SIMV mode is determined by the patient. This is because the spontaneous breaths in SIMV are permitted and often supported (i.e. PS of 10 above PEEP in this example) but are not constrained so that the patient decides the TV, flow, and inspiratory time for the spontaneous breaths. Thus, each spontaneous breath (gray arrows) will not only differ from the mandatory breaths (white arrows) but also from any other spontaneous breath in terms of TV, flow, and inspiratory time.
4) ***What is this patient's inspiratory time?*** Recall that the area under the inspiratory flow curve is the tidal volume. For the mandatory breaths, the shape of the flow curve is a triangle whose area is defined by the equation: TV = ½(IT)(Flow). Therefore, the inspiratory time is 0.67 seconds given a TV of 0.5 L and flow of 90 lpm (1.5 lps). For the spontaneous breaths, there is no set inspiratory time and it is determined solely by the patient's effort. As shown above, the inspiratory time may vary from breath to breath.
5) ***What will be the pressure at end of expiration?*** At the end of expiration, the ventilator maintains PEEP, which is 5 cm of H_2O in this example.
6) ***Does SIMV automatically mean that TV is used?*** Similar to AC, when a clinician states that a patient is on SIMV mode, it is often implied that the patient is also on TV control rather than pressure control. Although this is common practice, it is incorrect since either TV or pressure can be used with the SIMV mode. Thus, in order to minimize confusion, both the mode and the cycling mechanism should be specified (i.e. volume cycled SIMV or pressure cycled SIMV).
7) ***Consider a patient who is on volume cycled AC mode as follows: 30% FIO_2 / TV 0.5 L / rate 20 / PEEP 5 / flow 90 lpm via decelerating pattern. Patient does not breathe spontaneously due to sedation. The settings are now changed to volume cycled SIMV mode as follows: 30% FIO_2 / TV 0.5 L / rate 20 / PEEP 5 / flow 90 lpm via decelerating pattern / PS 10 above PEEP. If the patient does not breathe spontaneously, what is the difference between AC and SIMV?*** The left graph is from this patient while on AC mode and the right graph is from the same patient while on SIMV mode. For both graphs, the top and bottom curves indicate pressure-time and flow-time curves, respectively. Recall that these two modes differ only in how the spontaneous breaths are handled. Thus, if the patient does not breathe spontaneously, there is no difference between the modes, assuming the other settings (i.e. TV, rate, PEEP, and flow pattern and rate) are identical.



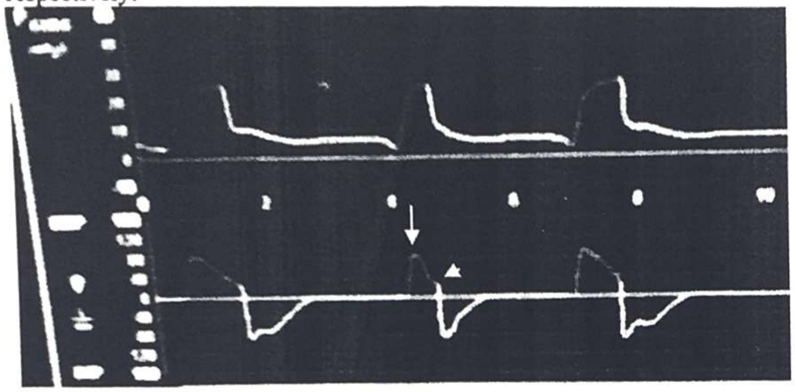
AC Mode



SIMV Mode

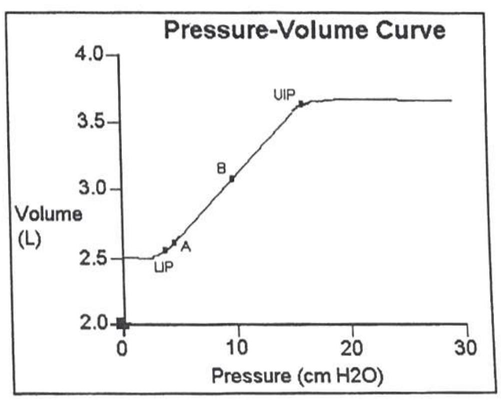
8) ***For the patient above who does not take spontaneous breaths, what is the expiratory time?*** Given a TV of 0.5 L and decelerating flow rate of 90 lpm (1.5 lps), the inspiratory time is 0.67 seconds. Since the respiratory rate is 20 per minute, the breath-to-breath time is 3 seconds. Therefore, the expiratory time is 2.33 seconds.

c. Pressure Support Ventilation (PSV) – Consider a patient who is on PS mode of ventilation as follows: 100% FIO_2 / PEEP 5 / PS of 20 above PEEP. The top and bottom curves indicate pressure-time and flow-time curves, respectively.



1) ***What is another name for Pressure Support Ventilation?*** PSV is same as continuous positive airway pressure (CPAP) on some machines.
2) ***Is there a minimum number of breaths that this patient has to take?*** In PSV mode, there are no mandatory breaths. It is entirely up to the patient to initiate all breaths. However, an apnea limit can be set as a safe guard so that the ventilator will alarm if no breath is taken within a specified time window, i.e. 20-60 seconds. In addition, minimum TV or minute ventilation can be set so that the ventilator will alarm if these parameters are not met.
3) ***Is the patient able to take additional breaths spontaneously?*** Since there are no mandatory breaths in this mode, every breath is spontaneous and is supported by a set pressure (i.e. PS of 20 above PEEP in this example). In contrast to the AC mode but similar to the SIMV mode, each spontaneous breath will potentially differ from any other spontaneous breath in terms of TV, flow pattern, and inspiratory time. However, all of the breaths will be similar in that they are supported by 20 cm H_2O.
4) ***What is this patient's inspiratory time?*** There is no set inspiratory time in PSV mode. Rather, the patient determines the inspiratory time for all breaths. Typically, the breath is terminated by the ventilator when the inspiratory flow falls to a preset level. In the example above, the peak inspiratory flow is indicated by the arrow and inspiration is terminated when the flow decreases to 25% of the peak inspiratory flow (arrowhead).
5) ***What will be the pressure at end of expiration?*** At the end of expiration, the ventilator maintains PEEP, which is 5 cm of H_2O in this example.
6) ***Does PSV mean that pressure is always used?*** Yes, by definition, only pressure can be used in PSV mode.

2. Cycling Mechanism
   a. As stated above, it is important to distinguish the mode of ventilation (i.e. AC, SIMV, PS) from the cycling mechanism. Cycling mechanism refers to whether pressure (PCV) or volume (VCV) is being cycled with each breath. Thus, it is possible for a patient to be on various combinations of modes and cycling mechanisms: volume cycled AC (AC VCV), pressure cycled AC (AC PCV), volume cycled SIMV (SIMV VCV), or pressure cycled SIMV (SIMV PCV). By definition only pressure can be cycled in PSV mode. Therefore, when a clinician states that a patient is on "PCV mode," it is an imprecise statement since it not a mode per se and the patient could be on either pressure cycled AC or pressure cycled SIMV.
   b. ***What is the difference between volume and pressure cycling?*** Consider a patient with the PV curve shown on the right and following settings: AC mode, FIO_2 50%, TV 0.5 L, rate 10, PEEP 5. Assume the following coordinates: point A (P=5, V=2.7), point B (P=10, V=3.2).



1) ***What is the cycling mechanism?*** Since tidal volume is being set, rather than pressure, this patient is on volume cycling. Thus, a more accurate description of this patient's ventilator mode is volume cycled AC mode (AC VCV).
2) ***Which point on the PV curve represents end expiration?*** At end expiration, the pressure will be 5 since PEEP is set at 5. Pressure of 5 is associated with a volume of 2.7 L which is represented by point A on the PV curve.

3) ***Which point on the curve represents end inspiration?*** At end inspiration, the volume will be 3.2 L since the TV is 0.5 L. Volume of 3.2 L is associated with a pressure of 10 which is represented by point B on the PV curve.
4) ***What if the ventilator settings were changed as follows: FIO_2 50%, PC 5 above PEEP, rate 10, PEEP 5 on AC mode? (Assume that the PC is maintained long enough so that Ppl = PC + PEEP.)*** Since pressure is being set, rather than tidal volume, this patient is more accurately on pressure cycled AC mode (AC PCV). Notice that at end expiration, patient will still be at point A since the PEEP is still 5. Since PC is 5 above PEEP, the end inspiratory pressure will be 10, which brings the patient to point B at end inspiration.
5) ***What is the difference between volume cycling and. pressure cycling?*** In the example above, the patient still moves from point A to B with each breath whether volume or pressure is cycled. As long as the PV curve does not change, there is no real difference between the two cycling mechanisms. However, there would be important differences if the compliance or the resistance of the respiratory system were to change. For example, if the patient develops severe pulmonary edema, the compliance of the respiratory system would decrease. If the patient is on volume cycling, the TV does not change but the plateau pressure will increase given poorer compliance. On the other hand, if the patient is on pressure cycling, the pressure control level does not change but the TV will decrease given poorer compliance.
6) ***Consider a patient whose ventilator settings are as follows: volume cycled AC mode; FIO2 50%; TV 0.5 L; rate 12; PEEP 5. Patient appears agitated and is noted to have a respiratory rate of 28, O_2Sat of 96%, and PIP of 57. The ventilator is alarming because the PIP exceeds the set pressure limit of 55. The ventilator settings are changed as follows: pressure cycled AC mode; FIO2 50%; PC 30 above PEEP; rate 20; PEEP 5. Patient still appears agitated and is noted to have a respiratory rate of 24 and PIP of 35. Approximately 30 minutes later, patient becomes hypotensive and norepinephrine drip is started. Another 15 minutes later, patient develops asystolic arrest and is unable to be revived. The ABG results which were drawn 10 minutes prior to the cardiac arrest reveal: PO_2 65; PCO_2 164; pH 6.91. What happened to this patient?*** With the initial volume cycled settings, patient had a minute ventilation of 14 lpm (TV 0.5 L and respiratory rate of 28) and a distending pressure during inspiration of 52 cm H_2O (PIP of 57 minus PEEP of 5). With the pressure cycled settings, the distending pressure during inspiration is now only 30 cm H_2O. Therefore, the tidal volume and the minute ventilation likely decreased substantially. The abrupt decrease in minute ventilation likely lead to the severe respiratory acidosis which in turn caused the cardiac arrest. As this case illustrates, neither volume cycling nor pressure cycling is necessarily better than the other. They both simply have their advantages and disadvantages. The advantage of volume cycling is that the TV and minimum minute ventilation are guaranteed. Its disadvantage is that the airways pressures may be very high in some cases which can cause hemodynamic compromise, barotrauma, or death. The advantage of pressure cycling is that the airway pressure is guaranteed. Its disadvantage is that the TV and the minute ventilation are not guaranteed which, as illustrated by this case, can cause respiratory acidosis, hemodynamic instability, and death.

c. ***What is the difference between pressure control vs. pressure support?*** Although PCV and PSV both cycle pressure rather than volume, they are otherwise very different concepts. As discussed above, PCV is not a distinct mode but rather a cycling mechanism that can be used either with AC or SIMV. In contrast, PSV is a distinct mode. Following examples compare and contrast AC PCV, SIMV PCV, and PSV.
   1) Consider a patient who is on AC PCV as follows: 40% FIO_2 / PC 20 above PEEP / rate 10 / PEEP 5 / inspiratory time 1 second.
      a) ***Is there a minimum number of breaths that this patient has to take?*** Since the respiratory rate is set at 10, patient must take at least 10 breaths per minute. Each mandatory breath consists of 40% oxygen delivered at a pressure of 20 cm H_2O above PEEP, applied for 1 second.
      b) ***Is the patient able to take additional breaths spontaneously?*** Yes, patient may take spontaneous breaths in addition to the 10 mandatory breaths. As is true for anyone on the AC mode, the spontaneous breaths are identical to the mandatory breaths. In this example, both the mandatory and spontaneous breaths will be 40% oxygen at a pressure of 20 cm H_2O above PEEP, applied for 1 second.
      c) ***What is this patient's inspiratory time?*** In pressure control, the inspiratory time is set directly by the clinician. In this example, the inspiratory time is 1.0 second for both spontaneous and mandatory breaths.
   2) Consider a second patient who is on SIMV PCV as follows: 40% FIO_2 / PC 20 above PEEP / rate 10 / PEEP 5 / inspiratory time 1 second / PS 10 above PEEP.
      a) ***Is there a minimum number of breaths that this patient has to take?*** Since the respiratory rate is set at 10, patient must take at least 10 breaths per minute. Each mandatory breath consists of 40% oxygen delivered at a pressure of 20 cm H_2O above PEEP, applied for 1 second.

b) ***Is the patient able to take additional breaths spontaneously?*** Yes, patient may take spontaneous breaths in addition to the 10 mandatory breaths. As in the AC mode, each mandatory breath in the SIMV mode will be 40% oxygen at a pressure of 20 cm H_2O above PEEP, applied for 1 second. Once again, the difference between SIMV and AC modes is in how the spontaneous breaths are handled. In contrast to the AC PCV where the spontaneous breaths are identical to the mandatory breaths, the spontaneous breaths in the SIMV PCV are determined by the patient. This is because the spontaneous breaths in SIMV are permitted and supported (i.e. PS 10 above PEEP in this example) but are not constrained in terms of TV, flow, or inspiratory time. Thus, each spontaneous breath will not only differ from the mandatory breaths but potentially also from any other spontaneous breath in terms of TV, flow, and inspiratory time.

c) ***What is this patient's inspiratory time?*** Just as in AC PCV, inspiratory time is set directly by the clinician in SIMV PCV. However, the inspiratory time of 1 second only affects the mandatory breaths. For the spontaneous breaths, there is no set inspiratory time and it is determined solely by the patient's effort, which may vary from breath to breath.

d) ***If a patient does not take any spontaneous breaths, what is the difference between AC PCV and SIMV PCV?*** Recall that these two modes differ only in how the spontaneous breaths are handled. Thus, if the patient does not take any spontaneous breaths, there is no difference between the modes, assuming the other settings (i.e. PC, respiratory rate, PEEP, inspiratory time, etc.) are identical.

3) Consider a third patient who is on PSV as follows: 40% FIO_2 / PS 20 above PEEP / PEEP 5.

a) ***Is there a minimum number of breaths that this patient has to take?*** Recall that there are no mandatory breaths in PSV mode. It is entirely up to the patient to initiate all breaths.

b) ***Is the patient able to take additional breaths spontaneously?*** Since there are no mandatory breaths in this mode, every breath is spontaneous and is supported by a set pressure (i.e. PS 10 above PEEP in this example). In contrast to the AC PCV but similar to SIMV PCV, each spontaneous breath will potentially differ from any other spontaneous breath in terms of TV, flow, and inspiratory time.

c) ***What is this patient's inspiratory time?*** There is no set inspiratory time in the PSV mode. In contrast, recall that in AC PCV, the clinician sets the inspiratory time directly which regulates both the mandatory and the spontaneous breaths. In SIMV PCV, the clinician sets the inspiratory time directly but this regulates only the mandatory breaths and the patient determines the inspiratory time for the spontaneous breaths. In PSV mode, the patient determines the inspiratory time for all breaths. Typically, the PSV breath is terminated by the ventilator when the inspiratory flow falls to a preset level (i.e. 25% of peak flow depending on the ventilator).

4) The table below summarizes the settings for AC PCV, SIMV PCV, and PSV.

	AC PCV	SIMV PCV	PSV
Cycling Mechanism	Pressure	Pressure	Pressure
Universal Settings	FIO_2 PEEP	FIO_2 PEEP	FIO_2 PEEP
Major Settings	Pressure Control Respiratory Rate	Pressure Control Respiratory Rate Additional Pressure Support	Pressure Support
Other Settings	Inspiratory Time Sensitivity	Inspiratory Time Sensitivity	Sensitivity

d. ***What is volume targeted ventilation?*** Volume targeted ventilation is a mixed cycling method where volume is targeted using pressure cycling. Thus, it is not a distinct mode but along with volume cycling and pressure cycling, it is a third cycling mechanism. Consider a patient who is on AC mode of ventilation as follows: 30% FIO_2 / volume target 0.5 L / rate 10 / PEEP 5 / inspiratory time 1 second.

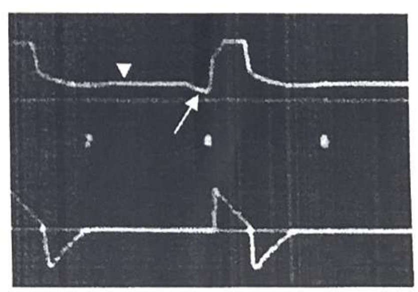
1) ***What are other names for volume targeted ventilation?*** Some of the other names for volume targeted ventilation include VC+, autoflow, and pressure regulated volume control.

2) ***How does volume targeting differ from the other cycling methods?*** In volume cycling, the ventilator delivers a set TV using a specified flow pattern. For the given TV, flow, and PEEP, the airway pressure will vary according to the resistance and the compliance of the respiratory system. In pressure cycling, the ventilator delivers a set pressure for a specified time. For the given pressure, inspiratory time, and PEEP, the tidal volume will vary according to the resistance and the compliance of the respiratory system. Recall that the advantage of volume cycling is that it guarantees the TV but its disadvantage is that the pressures generated to deliver the volume may be excessively high. For pressure cycling, its advantage is that it guarantees the pressure level but its disadvantage is that the tidal volume may be insufficient. Volume targeting is a mix of these two cycling mechanism where it uses the lowest pressure possible to deliver the

targeted tidal volume. Thus, it cycles pressure but the level of pressure is not specified. The ventilator simply tries to use enough pressure to generate the targeted tidal volume.

3) ***Consider a mechanically ventilated patient who is sequentially placed on three different cycling mechanisms. Setting A is pressure cycled AC mode with the following settings: 30% FIO_2 / PC 20 above PEEP / rate 10 / PEEP 5 / inspiratory time 1 second. The resulting tidal volume is 0.5 L. Setting B is volume cycled AC mode with the following settings: 30% FIO_2 / TV 0.5 L / rate 10 / PEEP 5 / flow 60 lpm decelerating wave pattern. The resulting inspiratory time is 1 second. Setting C is volume targeted AC mode with the following settings: 30% FIO_2 / volume target 0.5 L / rate 10 / PEEP 5 / inspiratory time 1 second. What will happen under these settings if the compliance of the respiratory system were to decrease?*** For setting A, the ventilator applies a total pressure of 25 (20 + PEEP) for 1 second which results in 0.5 L of tidal volume. For setting B, when the ventilator delivers 0.5 L of tidal volume, the end inspiratory pressure will be 25 since the resistance and compliance have not changed. For setting C, the ventilator applies total pressure of 25 to achieve the target volume of 0.5 L. When the compliance decreases under setting A, the ventilator will continue to apply a total pressure of 25 and the tidal volume will decrease. For setting B, the ventilator will continue to deliver 0.5 L of tidal volume and the airway pressure will rise. For setting C, the ventilator will initially apply a total pressure of 25 as before but the target volume of 0.5 L will not be achieved. Therefore, the ventilator will then increase the pressure in a step wise fashion until the target volume is achieved again.
4) ***Consider the same patient under three different cycling mechanisms described above. What will happen under these settings if the patient wants to consistently take bigger tidal volumes?*** For setting A, the ventilator will continue to apply a total pressure of 25 but the tidal volume is not regulated. Therefore, patient is able to take larger volumes as desired. For setting B, ventilator will continue to deliver a fixed tidal volume of 0.5 L. Therefore, patient will be unable to do so and may become agitated. For setting C, the ventilator will initially apply a total pressure of 25 as before but the resulting volume will exceed the target volume of 0.5 L. Therefore, the ventilator will then decrease the pressure in a step wise fashion until the target volume is restored.
5) ***Consider a mechanically ventilated ARDS patient with the following settings: volume targeted AC mode / 50% / volume target 0.29 L (6 ml/kg) / rate 18 / PEEP 5 / inspiratory time 0.95 seconds. What is the potential problem of volume targeting for ARDS patients?*** With volume targeting, the tidal volume is targeted but not fixed. Usually the difference between the targeted and the actual tidal volume is not large and is of little consequence. However, occasionally the difference may be large and it could be clinically significant in the setting of ARDS. For this patient, although 6 ml/kg was targeted, the actual tidal volume was more than 12 ml/kg (see circle on the right).

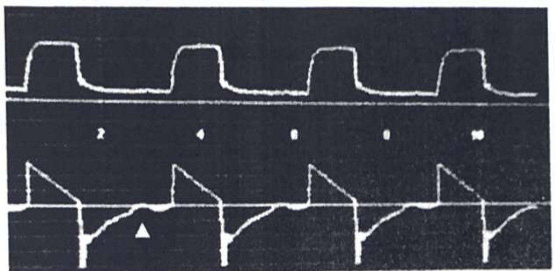
3. Sensitivity
   a. ***How does the ventilator know that a patient is trying to take a breath?*** The ventilator recognizes a patient's inspiratory effort when the effort exceeds the sensitivity threshold of the ventilator. There are two major types of sensitivity settings: pressure vs. flow triggering.
   b. ***How does pressure triggering work?*** Consider a patient who is on AC mode of ventilation as follows: 30% FIO_2 / TV 0.5 L / rate 10 / PEEP 5 / flow 90 lpm via decelerating pattern / pressure triggering threshold of 2 cm H_2O. This patient's pressure-time (top) and flow-time (bottom) curves are shown on the right. During exhalation, the pressure in the ventilator circuit is PEEP (arrowhead). When the patient tries to breathe, the inspiratory effort (arrow) will lower this pressure. If the pressure in the ventilator circuit decreases from 5 to 3 cm H_2O as in this example (i.e. 2 cm H_2O pressure sensitivity), the ventilator will be triggered and TV of 0.5 L will be delivered.



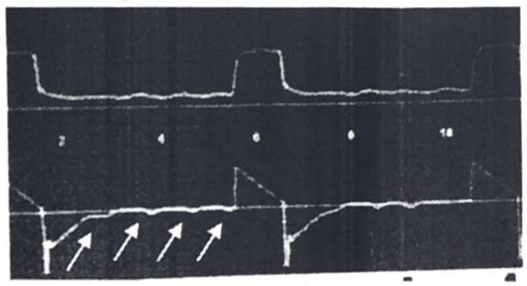
   c. ***How does flow triggering work?*** Consider a patient who is on AC mode of ventilation as follows: 30% FIO_2 / TV 0.5 L / rate 10 / PEEP 5 / flow 90 lpm via decelerating pattern / flow triggering. With flow triggering, ventilator is configured with a continuous flow of air in the range of 3-6 lpm in the circuit. When the patient tries to breathe, the inspiratory effort will alter this base flow rate. If the flow rate is altered sufficiently by the patient's effort, the ventilator will be triggered and TV of 0.5 L will be delivered.

d. ***Why is sensitivity important?*** A triggering threshold that is set too high (i.e. overly insensitive) will cause unnecessary work of breathing and patient discomfort. For patients with marginal respiratory reserve, this additional work of breathing imposed by the high threshold may be enough to keep the patient in persistent respiratory failure. On the other hand, a triggering threshold that is set too low (i.e. overly sensitive) may cause the ventilator to be triggered by artifact (i.e. tremor, heartbeat, vibration in the tubing, etc.) which could cause unwanted breaths and patient-ventilator dyssynchrony. In the ranges of flow (2-5 lpm) and pressure (1–3 cm H_2O) thresholds that are typically used, flow triggering is more sensitive (i.e. easier to trigger the ventilator) compared to pressure triggering. However, pressure sensitivity of 0.5 cm H_2O is at least as sensitive as flow triggering. (Goulet. Chest 1997; 111: 1649-53.)

e. ***Consider a patient with massive intracerebral hemorrhage who is on AC mode of ventilation as follows: 30% FIO_2 / TV 0.5 L/ rate 12 / PEEP 5 / flow 55 lpm decelerating pattern / flow triggering 2 lpm. Patient is breathing at a rate of 20 breaths per minute but is otherwise unresponsive to noxious stimuli and exhibits no brainstem reflexes. When the sensitivity setting is switched from flow to pressure triggering (sensitivity of 2 cm H_2O), patient no longer breathes above the ventilator. The pressure-time (top) and flow-time (bottom) curves for flow and pressure triggered settings are shown below. Why does the patient's respiratory rate decrease with pressure triggering?*** Recall that flow triggering is generally more sensitive than pressure triggering. This patient was actually brain dead and made no respiratory effort but the ventilator was actually being triggered by the patient's heartbeat (arrowhead). When the ventilator is switched to a less sensitive but still reasonable pressure trigger threshold of 2 cm H_2O, the ventilator is no longer falsely triggered by the heartbeats (arrows). Therefore, flow triggering was overly sensitive for this situation and was in fact masking brain death.

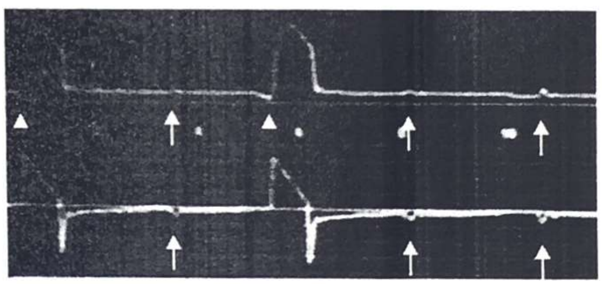


Flow Triggering



Pressure Triggering

f. ***Consider a patient with the following ventilator settings: AC VCV mode / 30% / TV 0.65 L / rate 8 / PEEP 5 / flow 95 lpm decelerating wave pattern / pressure triggering 2 cm H_2O. The pressure-time (top) and flow-time (bottom) curves are shown on the right. The ventilator triggers once for every two or three inspiratory efforts made by the patient. What causes ineffective triggering?*** Ineffective triggering may occur in the setting of profound neuromuscular weakness or insensitive trigger thresholds, but by far, the most common cause is autopeep. (Leung. AJRCCM 1997; 155: 1940-8.)



1) ***Why is the patient unable to trigger the ventilator consistently?*** It turns out that this patient has a history of severe COPD and autopeep is measured to be 12 cm H_2O above PEEP. The effective and ineffective triggering efforts are indicated by the arrowheads and arrows, respectively. Given PEEP of 5 cm H_2O and pressure triggering sensitivity of 2 cm H_2O, the ventilator should deliver the TV when patient effort causes the airway pressure to fall to 3 cm H_2O. However, if autopeep is 12 cm H_2O above the set PEEP of 5 cm H_2O, the patient has to lower the pressure from 17 (autopeep + set PEEP) to 3 cm H_2O. If the inspiratory efforts are not consistently greater than 14 cm H_2O (17 minus 3), patient's trigger attempts may go unrecognized by the ventilator, causing ineffective triggering.

2) ***What interventions might improve patient-ventilator synchrony in this case?*** The patient-ventilator dyssynchrony in this example is due to autopeep. Thus, attention should be directed at lowering the autopeep. The ways to decrease autopeep include reducing the respiratory rate (to allow more time to exhale), sedating the patient (to minimize anxiety and tachypnea), and treating the underlying bronchospasm (i.e. steroids, bronchodilators, etc). In addition, increasing the inspiratory flow rate or shortening the inspiratory time will lengthen the time available for expiration and thereby reduce autopeep. However, unless the patient is

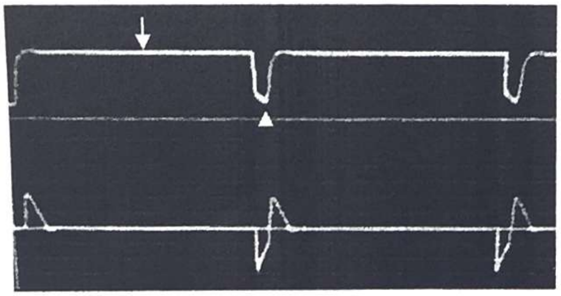
sedated, these strategies may not affect the patient's respiratory rate and there may be little improvement in autopeep. Furthermore, reducing the TV can also theoretically reduce autopeep since there will be less air to exhale. Unfortunately, the effects are generally modest. In some cases, patient may increase the spontaneous respiratory rate in order to preserve the minute ventilation. If so, the autopeep may fail to improve or may even paradoxically worsen. (Tobin. AJRCCM 2001; 163: 1059-63). In select patients, increasing the set PEEP may also improve patient ventilator synchrony. For example, if the set PEEP is increased to 14 cm H_2O and the sensitivity remains at 2 cm H_2O, this same patient would have to bring the pressure from 17 to 12 rather than from 17 to 3 cm H_2O. (Nava. Intensive Care Medicine 1995; 21: 871-9.)

3) ***Why is ineffective triggering important to detect?*** Detection of ineffective triggering is important for several reasons. First, if frequent, it may cause significant discomfort, frustration, and suffering for the patient. In some cases, ineffective triggering may cause severe agitation which may lead to overuse of sedatives or paralytic agents. Furthermore, since autopeep is the most common cause of ineffective triggering, the clinician needs to make sure that patient is being treated with appropriate measures to decrease the airway resistance (i.e. bronchodilators, etc.) and maximize the time for exhalation (i.e. decrease the respiratory rate, etc.). (Leung. AJRCCM 1997; 155: 1940-8.) Finally, a recent study indicates that ineffective triggering is associated with increased duration of mechanical ventilation. (De Wit. CCM 2009; 37: 2740-45.) A prospective cohort study of 60 adult mechanically ventilated patients compared those with frequent vs. infrequent ineffective triggering, as determined within the first 24 hours of intubation. Frequent ineffective triggering was defined as more than 10% of the inspiratory attempts resulting in failure to trigger the ventilator. As shown in the table below, patients with frequent ineffective triggering had significantly longer duration of mechanical ventilation. There was significant difference in mortality between the two groups.

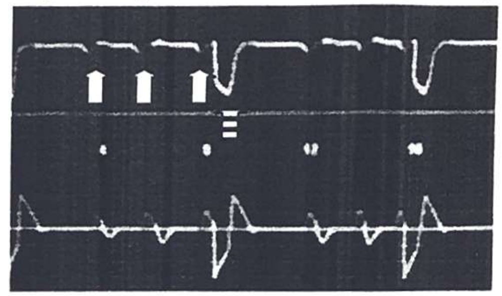
	Frequent Ineffective Triggering, N = 16	Infrequent Ineffective Triggering, N =44	P
Median Days of Mechanical Ventilation	6	2	0.007
In Hospital Mortality	31%	20%	NS

4. Airway Pressure Release Ventilation – Among the less commonly used modes of ventilation, only airway pressure release ventilation will be discussed here. High frequency oscillation and proportional assist ventilation are beyond the scope of this basic manual.
   a. ***What is airway pressure release ventilation (APRV)?*** APRV is a form of pressure-cycled ventilation where a prolonged duration (T_{HIGH}) of high pressure (P_{HIGH}) alternates with a relatively brief duration (T_{LOW}) of low pressure (P_{LOW}). It has similarities with pressure control with inverse ratio ventilation (inspiratory time > expiratory time). However, it differs from pressure control in that APRV allows spontaneous breathing during any part of the respiratory cycle. The spontaneous breaths are typically unsupported but additional pressure support is possible with some ventilators. The rationale for APRV is based on the "open lung" approach where P_{HIGH} is set for maximal recruitment. This high pressure is maintained for a long T_{HIGH}, which increases the mean airway pressure, maintains recruitment, and promotes oxygenation. The long T_{HIGH} may allow recruitment to occur at lower pressures. The high airway pressure is intermittently released (hence the name APRV) to a lower pressure (P_{LOW}), allowing CO_2 removal. Ideally, the P_{LOW} and T_{LOW} are set to avoid derecruitment. In addition, spontaneous breathing is maintained throughout the respiratory cycle which decreases the need for sedation or paralysis, lowers the airway pressure, and may mitigate the effect of positive pressure ventilation on venous return.
   b. ***What are the typical settings for APRV?*** Due to paucity of scientific data, there are no universally accepted settings to start a patient on APRV. The following is just one of many possible settings. In general, the goal is to use high pressures to maximize lung recruitment while minimizing derecruitment during the low pressure phase.
      1) FIO_2 - Start FIO_2 at 100%, but bring it down to 60% or less if possible.
      2) P_{HIGH} - Set P_{HIGH} at previous mean airway pressure, but it should not exceed 30 cm H_2O. A typical range for P_{HIGH} is 15-30 cm H_2O.
      3) P_{LOW} - There is no agreement for $P_{LOW,}$ but the typical range is 0-10 cm H_2O. One possibility is to set P_{LOW} at zero but use a short T_{LOW} so that air trapping (autopeep) prevents derecruitment. The pressure difference (P_{HIGH} - P_{LOW}) should be set to achieve 6 ml/kg of tidal volume and pH >7.20.
      4) T_{HIGH} - Start at 5.5 seconds but the typical range is 4-7 seconds.
      5) T_{LOW} - Start at 0.5 seconds but the typical range is 0.5-1.5 seconds. T_{LOW} is typically kept brief to avoid complete exhalation and derecruitment.
   c. Consider a patient on APRV with the following settings: 100% FIO2 / P_{HIGH} 28 / T_{HIGH} 5.5 seconds / P_{LOW} 5 / T_{LOW} 0.5 seconds. The pressure-time and flow-time curves are shown below. The curve on the left is when the patient makes takes no spontaneous breaths. The P_{HIGH} and P_{LOW} are indicated by the arrow and the arrowhead,

respectively. The curve on the right is when the patient takes spontaneous breaths throughout the cycle. The mandatory release breaths and the spontaneous breaths are indicated by the striped and solid arrows, respectively.



No Spontaneous Breaths



Spontaneous Breaths

d. ***What settings on APRV can be changed to increase the PO_2?*** In addition to increasing the FIO_2, the changes that maximize recruitment and minimize derecruitment will improve oxygenation. These changes include increasing the P_{HIGH}, T_{HIGH} and P_{LOW} or decreasing the T_{LOW}.

e. ***What settings on APRV can be changed to decrease the PCO_2?*** The changes that increase the volume or the frequency of the mandatory release breaths will lower the PCO_2. These changes include widening the pressure difference (P_{HIGH} - P_{LOW}), decreasing the T_{HIGH}, and increasing the T_{LOW}. Furthermore, the patient's spontaneous breaths also contribute to CO_2 removal.

f. ***Does airway pressure release ventilation improve clinical outcome?*** As described above, there is a paucity of scientific data comparing APRV with more basic modes of mechanical ventilation. There have been some randomized controlled trials but they have included fewer than 60 patients and have had major design flaws. (Putensen. AJRCCM 2001; 164: 43-9. Varpula. Acta Anesthesiology Scandinavia 2004; 48: 722-31.) More recently, a prospective observational study compared 234 patients on APRV vs. 234 patients on volume cycled AC mode who were matched for demographic characteristics, reason for mechanical ventilation, other complicating conditions, and SAPS II score among others. (Gonzalez. Intensive Care Medicine 2010; 36: 817-27.) Compared to volume cycled AC mode, APRV was associated with improved oxygenation but there was no difference in mortality or the duration of mechanical ventilation. For unclear reasons, the rate of tracheostomy was significantly higher with APRV. In summary, although APRV improves oxygenation, there is still no evidence that it improves any clinically important outcome. Better designed randomized controlled trials are clearly needed.

	APRV, N = 234	AC VCV, N =234	P
Peak Pressure, Day 1	25	31	< 0.001
Peak Pressure, Day 7	25	31	< 0.001
PaO_2 / FIO_2, Day 1	263	232	< 0.001
PaO_2 / FIO_2, Day 7	250	208	< 0.001
In Hospital Mortality	35%	38%	NS
Median Days of Mechanical Ventilation	3	3	NS
Tracheostomy	20%	11%	0.007

SUGGESTED READING

Book Chapters & Review Articles

Marino. The ICU Book. Williams & Wilkins 2007, Third Edition. Ch. 25. Modes of Assisted Ventilation pp. 473-489.

Key Original Articles

De Wit. Ineffective triggering predicts increased duration of mechanical ventilation. Critical Care Medicine 2009; 37: 2740-45.

Gonzalez. Airway pressure release ventilation versus assist-control ventilation: a comparative propensity score and international cohort study. Intensive Care Medicine 2010; 36: 817-27.