Review

Review of mechanical ventilation for the non-critical care trained practitioner. Part 2

Rebecca Shimabukuro RRT [1], Ehab Daoud MD [2]

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Abstract

There have been a recent shortage of both critical care physicians and respiratory therapists with training in mechanical ventilation that is accentuated by the recent COVID-19 crisis. Hospitalists find themselves more often dealing with and treating critically ill patients on mechanical ventilation without specific training.

The first part of this review attempted to explain and simplify some of the physiologic concepts and basics of mechanical ventilation. This second part of the review we will discuss some of the common modes used for support and weaning during mechanical ventilation and to address some of the adverse effects associated with mechanical ventilation.

We understand the complexity of the subject and this review would not be a substitute of seeking appropriate counselling, further training, and medical knowledge about mechanical ventilation.

Further free resources are available to help clinicians who feel uncomfortable making decisions with such technology

Keywords: COPD, ARDS, Weaning, VCV, PCV, ASV, MMV, NAVA, PSV, ATC, VSV, PRVC, APRV

Authors

1. Rebecca Shimabukuro RRT, Adventist Health Castle, Hawaii, USA
2. Ehab G Daoud, MD, FACP, FCCP. Associated professor of Medicine, John A Burns School of Medicine, Hawaii, USA and director of respiratory care program, Kapiolani Community College, Hawaii, USA

Corresponding author: rebeccashimabukuro@gmail.com

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Introduction

Over the last decade, there has been a shortage of critical care physicians [1] and respiratory therapists, [2] which has been markedly accentuated during the COVID-19 pandemic crisis. Hospitalists find themselves confronted with taking the lead of caring for such complex patients, especially the ones suffering from respiratory failure requiring mechanical ventilatory support.

The science of mechanical ventilation has evolved significantly over the last decades with new smart modes and automatic feedback Servo systems. Furthermore, the issue has been made more confusing by the different nomenclature of modes in the literature and between ventilator manufactures. [3]

The literature is cramped by so many mechanical ventilator articles, but most are difficult to understand and read. Also, there are multiple mechanical ventilation textbooks and online materials that are great resources for those dealing with mechanical ventilatory support. The problem is lack of training and time to gain expertise with such complex technology.

This article can not be used as a substitute for adequate training or expertise but tries to simplify the basics of mechanical ventilation. We advise to refer to part one of these reviews before proceeding. [4]

Modes of Mechanical ventilation:

What is a mode?

A mode is the process by which the mechanical ventilator determines, either partially or fully, when the mechanical breaths are to be provided to the patient. Thus, determining the breathing pattern of the patient during mechanical ventilation.

Classification

There have been multiple classifications of the modes of mechanical ventilations, yet the most popular is Chatburn's classification.[3] He simplifies all modes, basically down to 8 modes.

This is beyond the scope of this review. For simplicity, we will discuss some of the best known and commonly used modes. For the sake of simplicity, we will list them in no specific order.

Which mode to use?

With over two hundred available modes commercially, the question always come, which mode is better than the other? To be quite simplistic, we can achieve the same goals with pretty much any mode of mechanical ventilation. The availability of the modes on each ventilator as well as the knowledge and familiarity with the mode probably are the most important factors.

We will summarize the advantages and disadvantages of some of the modes below with some of the commercial names.

Conventional modes of ventilation

Volume Controlled Ventilation (VCV, VC-AC, CMV)

This set point (the ventilator doe does not change any of the set inputs by the clinician) controlled mandatory ventilator mode is commonly used in anesthesia and critical care settings. The ventilator will give the patients a preset tidal volume with a minimum mandatory respiratory rate and a constant preset flow. The resultant airway pressure will be the independent variable. The inspiratory time will depend on the flow rate as well, e.g. if the flow rate is 60 L/min (1L/s) and the tidal volume is set at 500 ml, the I-time would be 0.5 seconds.

However, having a constant (square) flow could cause the peak pressures to increase putting the patient at risk for barotrauma. With this mode, the patients' alveoli tend to have a hard time filling up during inspiratory time. This can cause a delay in the inspiratory time which then can lead to the lungs having less time for gas exchange to occur. The constant invariable flow can also cause flow starvation if it does not meet the patients' demands, which can cause patient-ventilator asynchrony and increased work of breathing.[5]

Most new generation ventilators offer that mode with the descending flow wave form and with a set I-time or I:E ratio.

To summarize, with a fixed flow rate, the peak inspiratory flow (PIF) will remain constant while the inspiratory time will be variable according to the flow rate (higher with lower flow and vice versa), and the peak inspiratory pressure (PIP) will vary according to the respiratory mechanics (higher with high resistance and low compliance). On the other hand, when the I:E ratio is fixed, the PIF and inspiratory time will be variable according to the RR (i.e. the PIF increases and the inspiratory time shortens with the higher RR and vice versa). The PIP will change similar to the fixed flow rate (table 1 and figures 1 and 2).

Table 1 (VCV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Set Flow: Tidal volume Respiratory rate Inspiratory flow rate Inspiratory flow wave form PEEP FiO_2	Inspiratory airway pressure Inspiratory time	Set point (ventilator does not change any input)	Easy Tidal volume controlled Minimum minute ventilation known	Tidal volume and flow rate are locked Flow starvation Lower mean airway pressure More asynchronies
Set I-time: Tidal volume Respiratory rate I-time or I:E ratio Inspiratory flow wave form PEEP FiO_2	Inspiratory airway pressure Inspiratory flow rate			

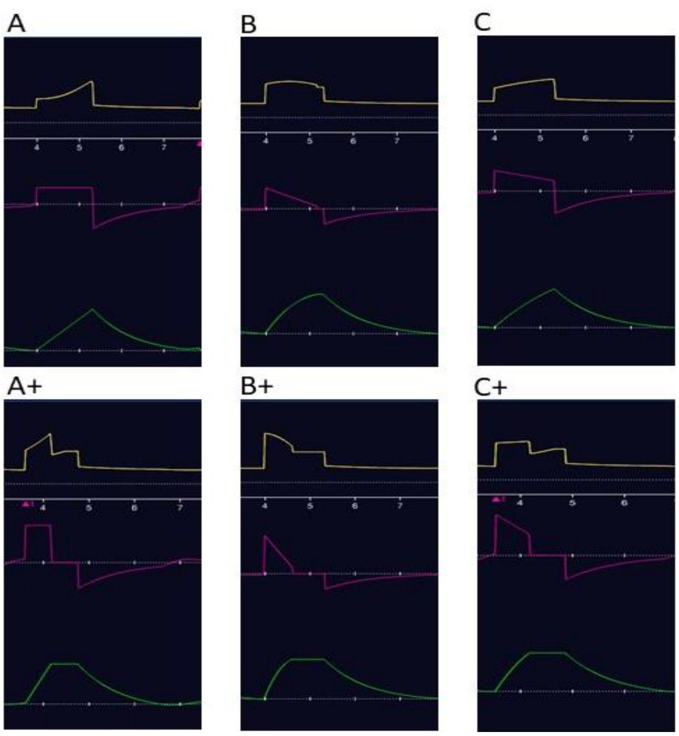


Figure 1: VCV with different flow wave forms (A, B, C) with no inspiratory pauses, and with inspiratory pauses (A+, B+, C+) and the resultant different airway pressure waveforms. Tidal volumes are the same. Yellow curve: airway pressure vs. time, Pink: flow vs. time, Green: tidal volume vs. time.

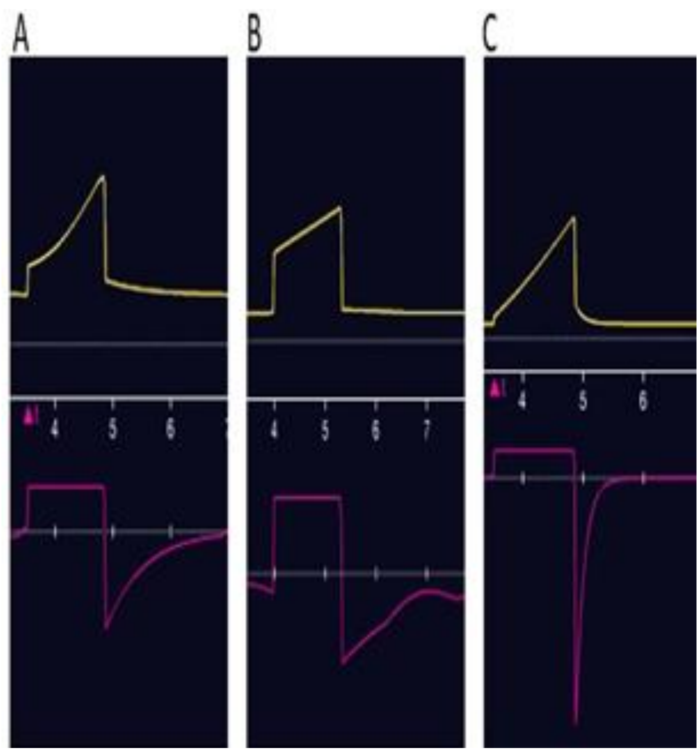


Figure 2: VCV with set insiratory time using the constant (square) flow waveform in normal lung (A), Obstructive lung disease (B) and restrictive lung disease (C).
Note the different shapes of airway pressure (yellow) and different insiratory and exiratory flow (pink curve).

Pressure Controlled Ventilation (PCV, PC-AC, P-CMV)

This mode is also a set point mandatory ventilator mode that is pressure controlled and limited. With this mode, the clinicians will set inspiratory (Driving) pressure, minimum respiratory rate, I-time or I:E ratio, FiO_2, and PEEP.

The inspiratory flow and thus the tidal volume will be the independent variable according to the patients' respiratory mechanics and effort (higher flow and tidal volume with the increased efforts and vice versa). These settings can help control the peak pressures and can help protect the lungs and airways from barotrauma.

Additionally, the inspiratory time can be controlled directly, either by setting inspiratory time or I:E ratio. This mode usually results in higher mean airway pressure (mPaw) and thus oxygenation, in addition to being more tolerable given the unrestricted variable flow [6] (table 2 and figure 3).

Table 2 (PCV)

What clinicians set	**What is variable**	**What ventilator adjusts**	**Advantages**	**Disadvantages**
Inspiratory pressure Respiratory rate Inspiratory time or I:E PEEP FiO_2	Inspiratory flow Tidal volume	Set point (ventilator does not change any input)	Easy Inspiratory pressure known Higher mPaw	Tidal volume and flow rate can change

VCV versus PCV

PCV has more advantages over VCV as outlined above, PCV is better tolerated, given the variable flow and tidal volume which improves physiologic response. The fact that the ventilator does not alter its WOB regardless of patients' effort is greatly beneficial regarding patient-ventilator asynchrony. The decelerating flow used in PCV usually leads to better, more uniform alveolar distribution of tidal volume. The higher mean airway pressure translates to better oxygenation.[7] All that said, studies have shown no difference in outcome between both modes.

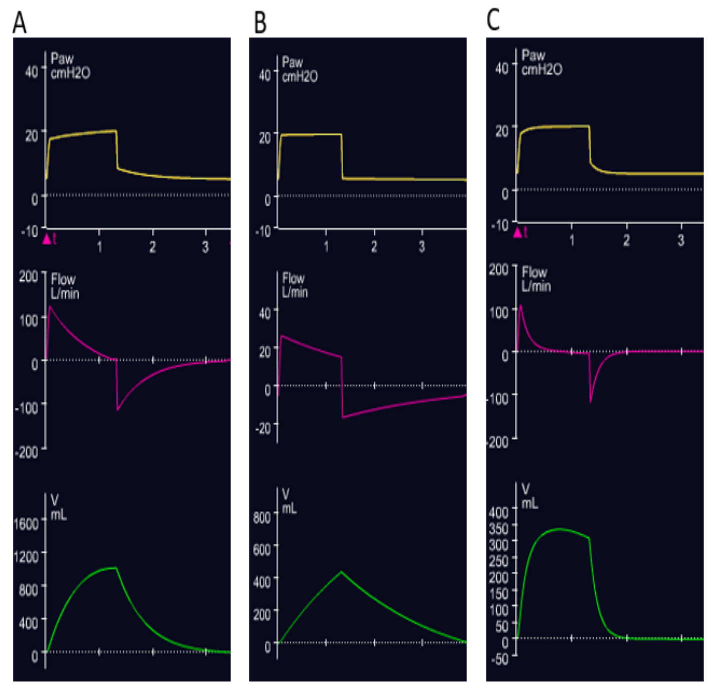


Figure 3: PCV with set inspiratory pressure of 15 cmH_2O and PEEP of 5 cmH_2O resulting in inspiratory pressure of 20 cmH_2O. A is normal lung, B is obstructive lung disease and C is restrictive lung disease. Note the difference in shape of the flow curve in pink and the resulting different tidal volumes in green.

Pressure Regulated Volume Controlled Ventilation
(PRVC, VC+, APV, Auto-flow)

It is an adaptive (the ventilator will adjust its output to meet a set input) continuous mandatory ventilatory pressure-controlled mode of ventilation.

The clinicians would set the minimum respiratory rate, targeted tidal volume, FiO_2, PEEP, and I-time or I:E ratio. The ventilator will adjust the inspiratory pressure up and down in a step-by-step fashion to achieve the preset target tidal volume.[8] Those are summarized in table 3 and figure 4.

This mode tries to combine the benefits of both the VCV and PCV in one mode. The disadvantage of this mode similar to VCV, is that the ventilator will decrease its work applied, when the patients' effort increase, falsely attributing that increase in tidal volume to improved respiratory mechanics (table 3 and figure 4 and 5).

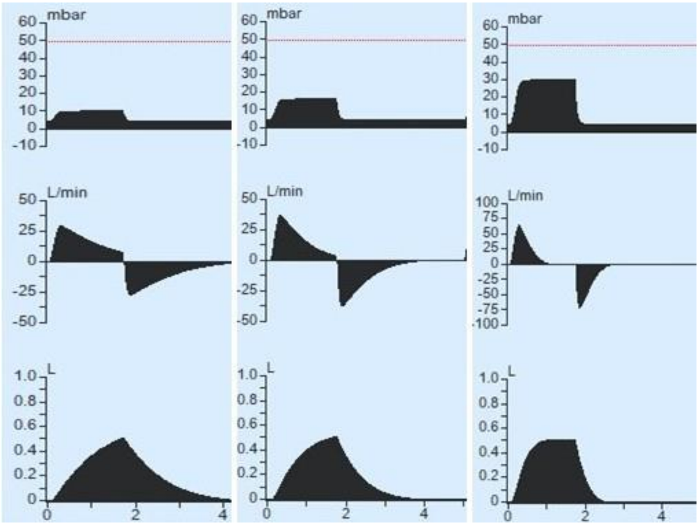


Figure 4: PRVC mode, set tidal volume at 500 ml/breath. As the respiratory mechanics declines or patient effort lessens, the tidal volume starts decreasing and thus the ventilator increases the applied pressure and flow to achieve the set tidal volume. The opposite happens when respiratory mechanics improve or patient effort increases, the applied pressure decreases.
Top: airway pressure in cmH2O, middle: flow in L/min, bottom is tidal volume in ml.

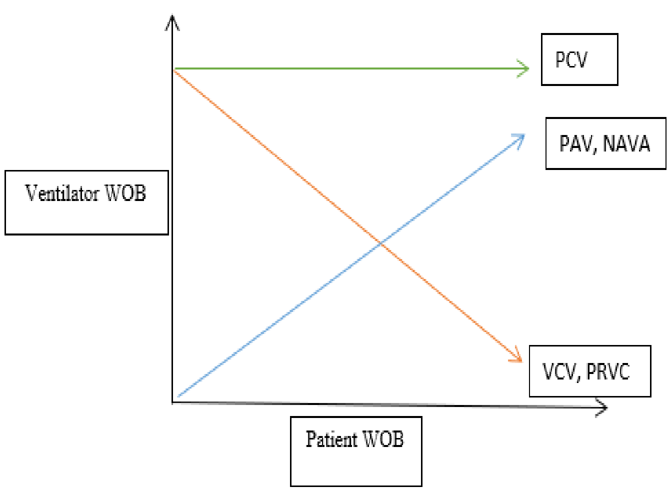


Figure 5: Relative ventilator work of breathing (WOB) in relation to patients' WOB. In PCV (green arrow) the ventilator does not change its WOB in relation to increase patients' effort, however in VCV and PRVC, the ventilator decreases its WOB when patients' efforts increase. Conversely, the ventilatory output increases in relation to patients' efforts in NAVA and PAV.
PCV: pressure-controlled ventilation, PRVC: pressure regulated volume controlled, VCV: volume-controlled ventilation, PAV: proportional assisted ventilation, NAVA: neurally adjusted ventilatory assist

Table 3 (PRVC)

What clinicians set	**What is variable**	**What ventilator adjusts**	**Advantages**	**Disadvantages**
Tidal volume Respiratory rate I-time or I:E PEEP FiO_2	Inspiratory flow Inspiratory pressure	Adaptive mode (the ventilator adjusts the inspiratory pressure to target a set tidal volume)	Tidal volume known Same benefits of a PCV mode Less manipulation by operator	Inspiratory pressure variable. Decrease support to patient if high effort or WOB

Mandatory minute ventilation (MMV)

This mode is a volume controlled intermittent mandatory ventilation mode. The clinician would set a minimum minute ventilation. If the patient does not meet that minute ventilation spontaneously, the ventilator will apply time triggered mandatory breaths that are synchronized with the breathing effort of the patient.

The patient can always breathe spontaneously at PEEP level. Pressure support can be added to patients' spontaneous breaths.[9] Those are summarized in table 4 and figure 6.

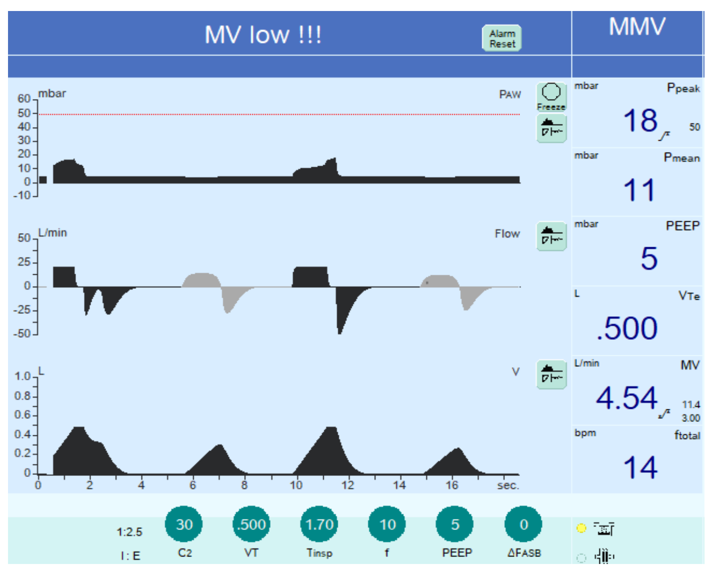


Figure 6: Screen of MMV. Top is airway pressure, middle is flow (blue is mandatory breath and grey is spontaneous breaths supported by PSV), bottom is tidal volume

Table 4 (MMV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Minute ventilation Pressure support for spontaneous breaths I-time for mandatory breaths PEEP FiO_2	Inspiratory flow Inspiratory pressure	Adaptive mode (the ventilator ads more volume-controlled breaths to achieve a set minute ventilation)	Minimum minute ventilation guaranteed	Inspiratory pressure variable. Empiric setting of minute ventilation initially

Airway Pressure Release Ventilation (APRV, BiLevel, DuoPAP, Biphasic)

This mode is inverse ratio, pressure controlled, intermittent mandatory ventilation with unrestricted spontaneous breathing. It is based on the principle of open lung approach.

Described initially as two levels of CPAP, the mode uses extremely high inspiratory time (T High) and extremely low expiratory time in milliseconds (T Low) to intentionally create auto-PEEP. The driving pressure is named P High while the P Low is usually set at zero cmH_2O, however, because of the short T Low, the alveolar pressure never reaches zero (table 5 and figure 7).

There has been much of controversy about this mode, perhaps more than any other mode regarding its safety, efficacy, and its settings. It is important that the patient has spontaneous breathing effort and participates 20-30% of MV.
It has been proven to improve oxygenation, hemodynamics, less sedation, and recently mortality in ARDS. [10]

Adaptive Support Ventilation (ASV)

ASV was developed in 1994. This mode is a closed loop system that adjusts tidal volume and respiratory rate to reduce the work of breathing (WOB) by using the Otis equation.

ASV is a mode is many modes within one mode of ventilation. When the patient is breathing spontaneously the patient is using a PSV mode. When the patient is not breathing spontaneously then the patient is using a PCV mode. Lastly, when the patient is breathing more at a lower respiratory rate then the patient is breathing in a PCV-IMV mode of ventilation (Table 6 and Figure 8).

The clinician will set the percent minute ventilation between 25%-350% (100% is 100 ml/kg/min) based on the Ideal body weight (IBW), and the ventilator will decide on the best (target) tidal volume, respiratory rate, I-time according to respiratory mechanics measured by expiratory time constant (TC = resistance x compliance). PEEP and FiO_2 have to be set separately.

A newer "version" of ASV called Intellivent-ASV where the ventilator adjusts the PEEP and FiO_2 according to the SpO_2 and the percent MV per the end-tidal CO_2 ($EtCO_2$). This mode can be used as a full support mode or weaning mode. [11]

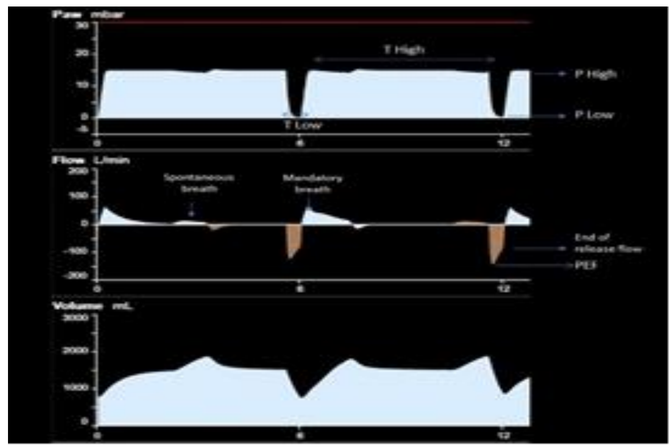


Figure 7: Screenshot of APRV. Top is airway pressure, middle is the flow showing the combined mandatory breath alternating with the spontaneous breaths, bottom curve is the tidal volume during the mandatory and spontaneous breaths.

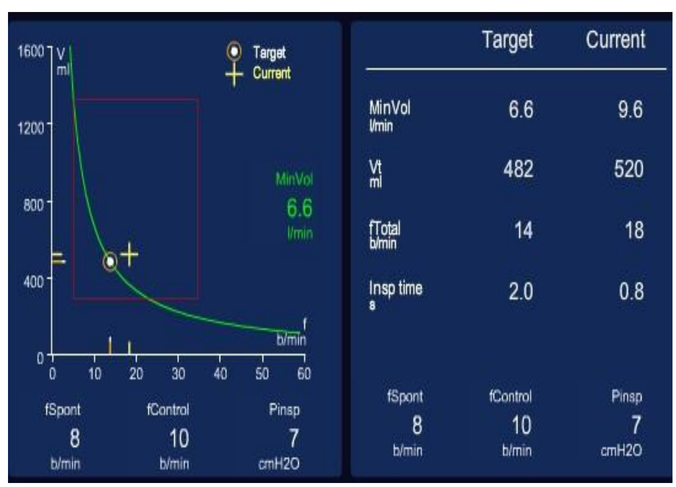


Figure 8: ASV graph and table showing the target respiratory rate and tidal volume versus patients' status.

Table 5 (APRV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
P High (Inspiratory pressure) P Low (expiratory or release pressure) T High (inspiratory time) T Low (expiratory or release time) Pressure support for spontaneous breaths FiO_2	Inspiratory flow Release tidal volume Spontaneous breaths tidal volume	Set point mode (the ventilator does not adjust any input) The ventilator allows spontaneous patient breathing during the whole mandatory cycle	Improved oxygenation in the difficult to oxygenate patients. Allow unrestricted spontaneous breathing so less sedation and synchrony Improved hemodynamics New evidence of improved mortality Can be used for weaning patients	Release volume can get too high

Table 6 (ASV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Ideal body weight (height and gender) Percent minute ventilation PEEP FiO_2	With change of respiratory mechanics: Airway pressure Respiratory rate Inspiratory time	Optimal mode (the ventilator adjusts the respiratory rate, and tidal volume)	Minimum minute ventilation guaranteed Minimum WOB Full support or weaning	Only available on one ventilator manufacturer
Intellivent-ASV IBW		Intellivent-ASV Ventilator adjusts PEEP, FiO_2, percent minute ventilation		

High-Frequency Oscillatory Ventilation (HFOV)

HFOV is a mode used in refractory cases of severe ARDS, still commonly used in pediatrics and infants, but its use in adults have waned significantly in recent years after reports of worsening survival in adults. [12]

The tidal volume is known as amplitude. The power is controlled, which is determined by the forward and backward movement of the piston which is creating distance. The number of excursions will determine the frequency in hertz (3-15) also known as respiratory rate (60 per hertz). The mode uses much higher mean airway pressure than conventional ventilation. Patients must be heavily sedated or paralyzed to tolerate such a mode. In addition, hemodynamics can gets inversely affected by this mode. [13]

Neurally Adjusted Ventilatory Assist (NAVA)

This is a novel continuous spontaneous mode using a servo targeting schema (the ventilator converts the signal from the patient and translates it in form of airway pressure, tidal volume) that allows the patient to have full neurological control of their respiratory rate and tidal volume even if there are changes in respiratory drive and muscle function.

In order to use this mode, you must insert a catheter into the stomach that measures the electrical activity of the diaphragm (EAdi). The degree of pressure support applied varies with the amplitude of the detected EAdi and the preset gain set by the clinician called NAVA level. The higher the NAVA level the more pressure support applied to the airways. NAVA level is measured from 0 to 15 micro volts. Thus, the Airway pressure = Paw (cmH2O) = EAdi (µV) X *NAVA level* (cmH2O/µV).

NAVA is particularly useful for patients who have a lot of gas trapping and auto-PEEP and may decrease patient-ventilator asynchrony [14] (table 7 and figure 9).

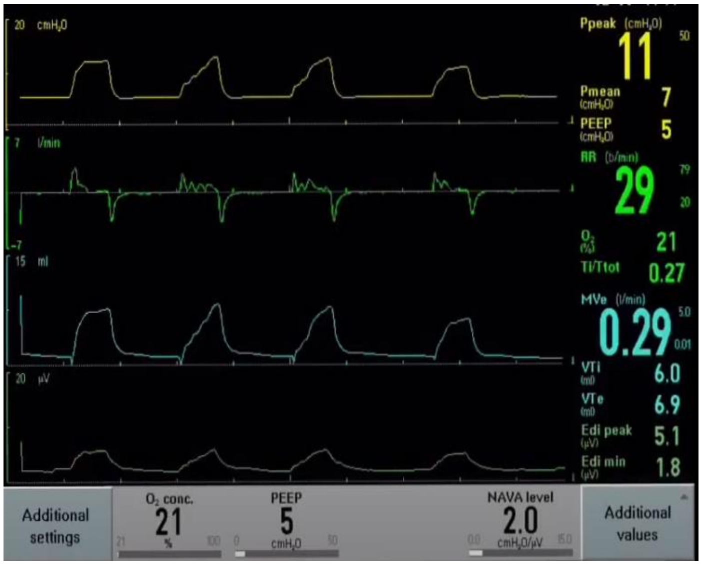


Figure 9: NAVA screenshot. Top curve in yellow is airway pressure in cmH_2O, second curve in green is flow in l/min, third curve is tidal volume in ml, bottom curve is EAdi in µV. Note that the airway pressure, flow, and tidal volumes are all variable and mirror the curve of the EAdi.

Proportional Assist Ventilation (PAV)

Similar to NAVA, this mode is a continuous spontaneous mode using a servo scheme. The ventilator measures the respiratory mechanics and patients' WOB and delivers pressure support breaths in proportion to the patients' effort to maintain the same patient WOB.

When the WOB increased, the ventilator will give the patient more pressure support to help decrease the patient's WOB and vice versa.

However, when the patient is not working at all the ventilator will not give any ventilatory support. The clinician sets the level of support from the ventilator (5%-95%), Fio_2 and PEEP.

Proportional Assist Ventilation helps the patient and the ventilator remain synchronized and can be used as a full support mode or a weaning mode [14] (table 8 and figure 10

Table 7 (NAVA)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
NAVA level PEEP FiO_2	Pressure support applied Flow Tidal volume	Servo mode (the ventilator adjusts the pressure support applied according to the electric signal from the diaphragm)	Totally spontaneous mode Minimum WOB Improved synchrony Can be used as full support or weaning	Need specific catheter to measure Eadi Only available on one ventilator manufacturer

Table 8 (PAV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Percentage support PEEP FiO_2 Airway type and diameter	Pressure support applied Flow Tidal volume	Servo mode (the ventilator adjusts the pressure support applied according to the WOB of the patient)	Totally spontaneous mode Minimum WOB Improved synchrony Can be used as full support or weaning	Only available on one ventilator manufacturer

Figure 10: Screen shot of PAV. The top graph shows the airway pressure supported by pressure support breaths (note the variable airway pressure). The bottom bar shows the calculated WOB being partitioned to patient (WOB_{PT}) and total (WOB_{TOT}) in J/L.

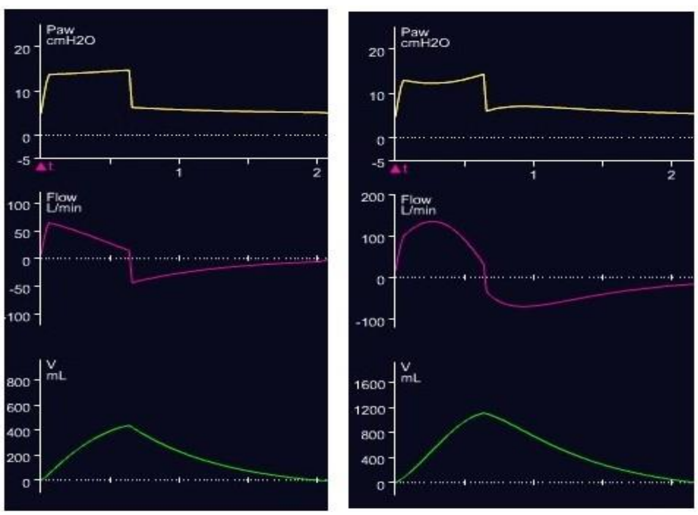


Figure 11: PSV on same patient. Left side: normal respiratory effort, note the perfect square shape of the airway pressure (top), straight descending flow waveform (middle) and TV (bottom) about 450 ml. Right side: same patient on same settings with excess respiratory effort, note the convexity of the airway pressure (top), the increased concave flow (middle) and increased TV (bottom) about 1200 ml.

Pressure Support Ventilation (PSV)

A continuous spontaneous pressure-controlled mode, and perhaps the most common and successful modes used for spontaneous breathing trials and weaning off mechanical ventilation. The patient triggers the breaths and control the respiratory rate (RR). The I-time is dictated by the flow decay to a certain percent of peak inspiratory flow (expiratory sensitivity) usually set at 25% but can be increased or decreased to match the patients' own effort.

The clinician adds a minimum amount of pressure support on top of PEEP that overcome the resistance of artificial airway (5-7 cmH_2O), the tidal volume is variable and would depend on the amount of pressure applied, respiratory mechanics, and patient effort [15] (table 9 and figure 11).

Of note, PSV can be a stand-alone mode or can be incorporated within other modes e.g. APRV, ASV, MMV, SIMV, Smart Care.

Synchronized Intermittent Mandatory Ventilation (IMV, SIMV)

As the name implies, this mode is intermittent between controlled breaths either volume or pressure alternating and synchronized with the patients' spontaneous breaths either supported by PSV or not. [16]

That mode was developed in 1970 and was commonly used to wean patients off mechanical ventilation till shown to be inferior to PSV or T-piece alone in success of liberation and time to liberate [17] (table 10 and figure 12).

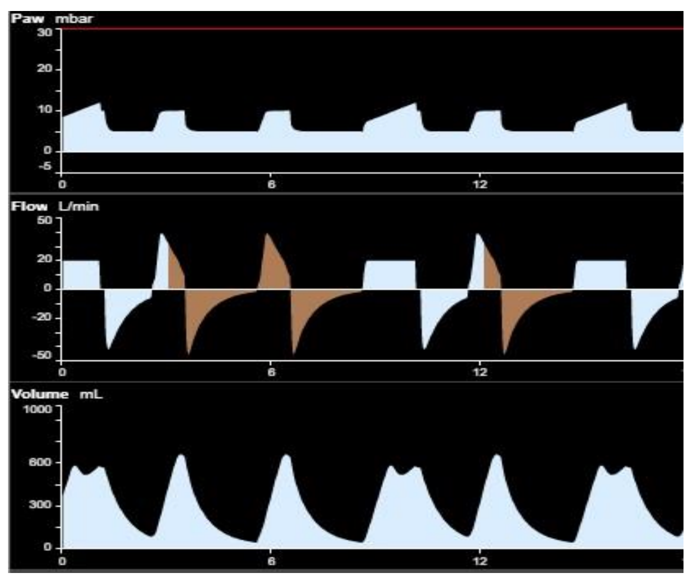


Figure 12: SIMV mode using VCV for the mandatory breath and PSV for the spontaneous breaths. Top graph is the airway pressure (note the difference between the controlled breaths semitriangular waves while the spontaneous with square waves). The middle graph is the flow with the brown ones indicate the spontanous PSV descending waveform while the mandatory breath are in constant square waveforms. The bottom curve is the tidal volume (note the difference in tidal volume between the mandatory and spontaneous breaths.

Continuous Airway Pressure (CPAP)

Is also a continuous spontaneous positive pressure ventilation mostly used as non-invasive mode. CPAP mode is practically only PEEP and the patient breath unassisted above that level of PEEP.

CPAP can aid in helping prevent atelectasis, increase V/Q matching, and improve oxygenation in the lungs. It is rarely used alone in intubated patients.

Volume support (VS, VAPS)

Despite its name, volume support is an adaptive pressure-controlled continuous spontaneous mode. Similar to PRVC described above.

It is a totally spontaneous mode. The clinician sets a target tidal volume, and the ventilator adjusts its output pressure to target the desired volume. The benefits over PSV hasn't been fully examined [18] (Table 11).

Tube Compensation (TC, ATC)

This mode is a closed loop mode that measures the airway respiratory resistance imposed by the artificial airway and supplies sufficient pressure support to overcome this resistance instead of a set pressure applied in PSV.

It can be a standalone mode or can be added to most other modes of ventilation. [19] The clinician selects the type of the artificial airway (endotracheal tube or tracheostomy tube), the internal diameter, and the amount of support (usually 100%)

Proportional Pressure Support (PPS)

This is a continuous spontaneous ventilatory mode using servo scheme that applies pressure support breaths in proportion to patients' inspiratory effort.

The level of support can be set separately for restrictive or obstructive work of breathing. The pressure support amount will vary according to patients' inspiratory effort and the amount of support set by the clinician. [20]

Two parameters have to be set. The "volume assist" which helps to overcome the WOB imposed by the compliance, and the "flow assist" helps to overcome the WOB imposed by resistance (table 12 and figure 14).

T-Piece

Not particularly a mode but commonly used in weaning or the spontaneous weaning trial. The patient is disconnected from the ventilator and oxygen flows through s single chamber tube with no support whatsoever.

Its advantage is the patient is back to the physiologic negative pressure breathing. Tidal volumes, respiratory rate cannot be measured via the ventilator. Most studies showed compared efficacy to PSV.

Table 9 (PSV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Set pressure support for the spontaneous breaths PEEP FiO_2 Expiratory sensitivity for pressure support breaths	Respiratory rate Tidal volume Inspiratory time	Set point, the ventilator does not change any inputs	Most commonly used for weaning or spontaneous breathing trial Can be used for full support Less asynchronies than controlled modes Available in every commercial ventilator	Asynchronies still can occur especially with high levels of support Amount of pressure support set empirically

Table 10 (SIMV)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Set pressure or volume for the mandatory breaths Set pressure support for the spontaneous breaths PEEP FiO_2 Expiratory sensitivity for pressure support breaths	Respiratory rate Tidal volume during the pressure controlled mandatory breaths or the spontaneous pressure support breaths Inspiratory time of the pressure support breaths	Set point, the ventilator does not change any inputs	Synchronizes the mandatory and spontaneous breath Assures a minimum minute ventilation Available in every commercial ventilator	Asynchronies still can occur especially with high levels of support Might increase the patient work of breathing Delayed weaning off mechanical ventilation compared to other modes

Table 11 (VS)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
Set tidal volume for the spontaneous breaths PEEP FiO_2 Expiratory sensitivity for pressure support breaths	Respiratory rate Inspiratory pressure Inspiratory time	Adaptive mode, the ventilator changes the inspiratory pressure to maintain a set tidal volume	Assures stable tidal volume	Superiority compared to pressure support is not convincing

Smart Care

This mode is a form of continuous spontaneous intelligent mode. In this automatic mode closed loop system, the ventilator monitors the patients' tidal volume, respiratory rate and end tidal CO_2 ($ETCO_2$) and changes the amount of pressure support to keep the patient in a comfortable zone of normal ventilation.

The mode is considered an automated SBT. Some studies have suggested that it cuts the weaning time compared the usual weaning process [21] (table 13 and figure 13).

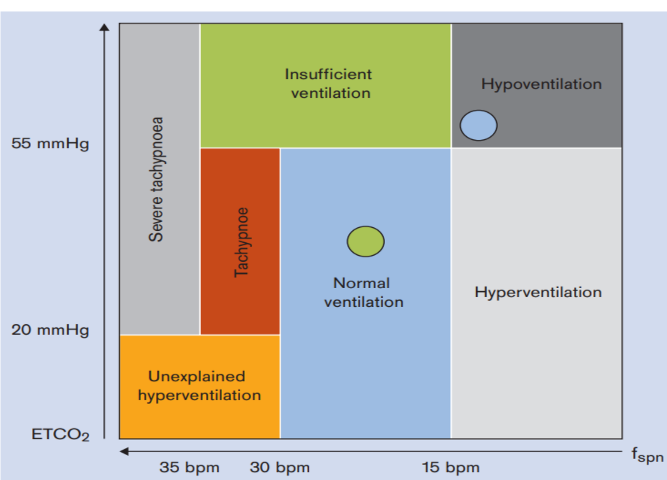


Figure 13: Smart care diagnostic diagram. Vertical axis is ETCO2 and horizontal axis id the respiratory rate. Green circle is the "comfort zone", the blue circle is an example of hypoventilation were the ventilator will increase the pressure support applied.

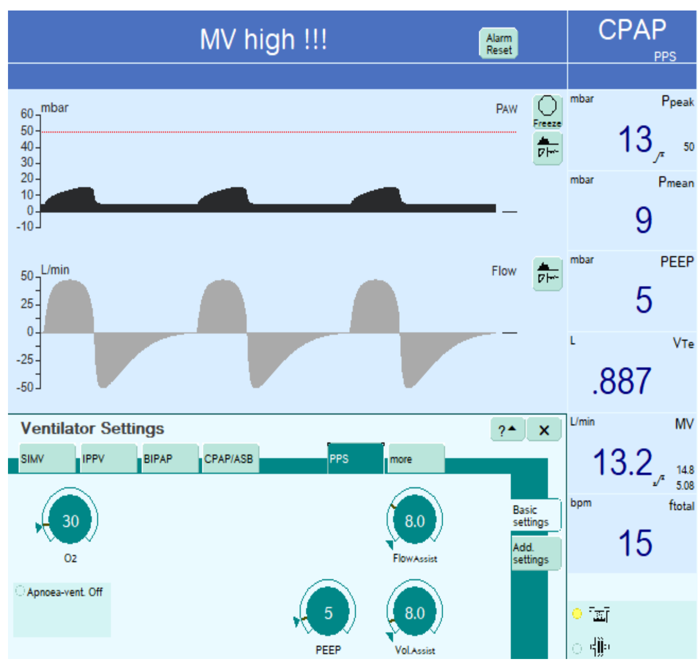


Figure 14: Proportional pressure support. Settings are flow and volume assist. FiO2 and PEEP. Top is airway pressure vs. time in black, bottom is Flow vs. time in grey

Table 12 (PPS)

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
PEEP FiO_2 Volume assist Flow assist	Respiratory rate Inspiratory pressure Inspiratory time	Servo mode, the ventilator changes the inspiratory pressure to keep the patient within a targeted WOB according to the set assistance	Assures stable for WOB May improve weaning process? More comfort	Only available on one ventilator manufacturer

Table 13 Smart Care

What clinicians set	What is variable	What ventilator adjusts	Advantages	Disadvantages
PEEP FiO_2	Respiratory rate Inspiratory pressure Inspiratory time	Intelligent mode, the ventilator changes the inspiratory pressure to keep the patient within a normal tidal volume, respiratory rate and EtCO2	Assures stable minute ventilation May improve weaning time through automated weaning	Only available on one ventilator manufacturer

Ventilator adverse effects

Ventilator Associated Events (VAE)

Is a newer term coined by the CDC that includes all the conditions that result in deterioration in oxygenation. This deterioration is defined when there is a greater than 20% increase in daily minimum of FiO_2 or increase of at least 3 cmH_2O in daily PEEP to maintain oxygenation. The causes of VAE are mainly pneumonia, fluid overload, ARDS and ventilator induced lung injury. There are several risk factors for VAE and they include sedation, high tidal volume, high inspiratory drive pressures, oral care with chlorhexidine, and blood transfusions. Strategies clinicians can use to help prevent ventilator associated events include limiting sedation, daily spontaneous breathing trials, early mobility, fluid management, and low tidal-volume ventilation.[22]

Ventilator Associated Pneumonia (VAP)

One of the most common diseases clinicians encounter, that their patients on a ventilator may develop. VAP is pneumonia that happens 48 hours after a patient is placed on a ventilator. Usually is caused by a bacterial infection, however, sometimes it can be caused by a fungal or a viral infection. VAP that occurs within 48 - 72 hours is considered early-onset pneumonia and when VAP develops after 72 hours it is considered late-onset pneumonia.

The incidence of VAP is linked to micro-aspiration of secretions and esophageal/gastric contents. VAP can also be linked to endotracheal intubation, infected aerosols, biofilm on the ET tubes, penetration from the pleural space, and other interventions that spread the infection into the lungs.

Early diagnosis and treatment of VAP with empiric antibiotic therapy is crucial.[23] The majority of VAP infections have been caused by aerobic gram-negative bacilli. There are many risk factors for patients to develop VAP including the elderly, trauma and burn patients, those with multiple organ failure and those with impaired level of consciousness. There are three main methods used to reduce VAP. They include 1: nonpharmacologic interventions, 2: pharmacologic methods which include avoiding central nervous system depressants, 3: methods to improve the patient's immunity including good nutrition, limiting invasive procedures if possible and treating other diseases that affect the patient's ability to fight off disease.

Ventilator induced lung injury (VILI) /Traumas

Our knowledge of this topic has greatly improved over the last couple decades. The lung is under continuous stress and strain during both inspiration and expiration. Multiple forces act on the alveolar units, mainly the volume, airway pressure but most importantly the trans-pulmonary pressure explained above.[24] VILI is difficult to diagnose clinically and is usually mistaken as VAP as no gold standard test is available, though some markers have shown promise. Those have been classified as:

- Volutrauma: is damage to the lungs caused by lung overdistension due to high volumes. This can cause the collagen fibers to become damaged. This can happen via too much energy applied to the lungs causing them to distend too much. The total lung compliance can become strained and causes microfractures in the extracellular matrix.

- Barotrauma: is damage to the lungs caused by high pressures and subsequent alveolar rupture which then results in air being forced into the interstitium of the perivascular sheath. This can result in a tension pneumothorax which is a life-threatening emergency and needs immediate treatment. Patients with COPD and asthma are at higher risk of dynamic hyperinflation.

- Atelectrauma: is a strain on the alveolar elasticity junctions. Atelectrauma can cause shearing stress in the lungs by the act of repeated opening and closing of the alveoli at lower lung volumes. Atelctrauma can happen when treating ARDS because low tidal volumes are needed with frequently inadequate PEEP is used resulting in the alveoli open with inspiration and collapse with expiration, this keeps happening each breath.

-Biotrauma: mechanical lung injury triggers an extensive biological response, including activation of a pro-inflammatory and pro-injurious cytokine cascade that causes damage to other lung units and even distributive shock and multi system organ failure.

-Ergotrauma: is a new term of lung injury caused by the energy and mechanical power applied to the lung that causes disruption of the lung matrix.

Ventilator induced diaphragmatic dysfunction (VIDD)

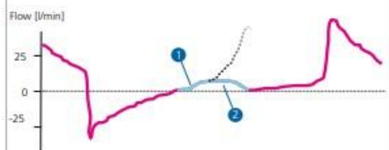
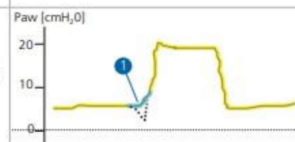
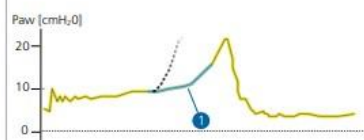
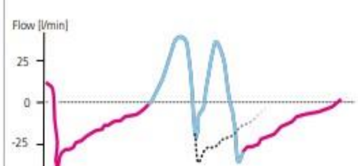
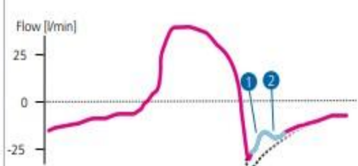
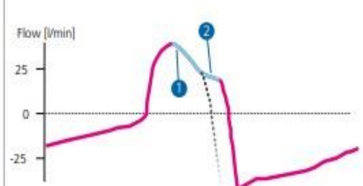
The diaphragm is the major muscle for respiration that accounts for more than 75% of the respiratory work during rest. Normally, it is exposed to a negative pressure environment that potentially serves as a stretch-like hypertrophic stimulus; applying PEEP may actually remove this stimulus effect and result in rapid diaphragmatic atrophy. Patients on heavy sedation, paralytics, and controlled mechanical ventilation are at high risk. The recognition tends to be delayed but can lead to failure of weaning and prolonged mechanical ventilation.[25]

Patient-Ventilator asynchronies

There are numerous types of patient-ventilator asynchronies and most go undetected but result in VIDD, VILI, prolonged mechanical ventilation and even mortality. [26]

Discussion of this topic is beyond the scope of this review.

The below figures summarize some of the most common asynchronies (printed with permission of Hamilton Medical at www.hamilton-medical.com/)

Asynchrony	Description	On the waveform	Waveform example	Common possible causes
Trigger asynchronies - during the beginning of inspiration				
Delayed triggering	The time interval between the patient's inspiratory effort and the delivery of a mechanical breath is increased	**Flow** waveform: look for a longer-than-normal time interval between the positive deflection in flow ❶ and the delivery of ventilatory support ❷		Trigger threshold set too high Ventilator pneumatics Presence of AutoPEEP Low respiratory drive Weak inspiratory effort
Ineffective effort	The patient's inspiratory effort fails to trigger the delivery of a mechanical breath	**Flow** waveform: look for an abrupt change in the steepness of the waveform ❶ (decrease in expiratory flow or increase in inspiratory flow) that is not followed by ventilatory support ❷		Trigger threshold set too high Pressure support too high Set frequency and/or inspiratory time too high (in controlled modes) Tidal volume set too high Presence of AutoPEEP Low respiratory drive Weak inspiratory effort Sedation
Auto triggering	A mechanical breath delivered without an inspiratory effort	**Pressure** waveform: look for a delivered mechanical breath showing no drop in airway pressure ❶ at the beginning of the inspiratory phase		Inspiratory trigger sensitivity set too high Air leaks in the endotracheal tube cuff, ventilator circuit or chest tube Flow oscillations (water or secretion in the circuit, cardiac oscillations)
Flow asynchronies - during the gas delivery				
Flow asynchrony	The delivered flow does not meet the patient's inspiratory flow demands	**Pressure** waveform: look for an upward concavity ❶ preceding the end of the mechanical breath		Inappropriate selection of ventilation mode (more frequent in volume-controlled modes) High inspiratory effort In volume-controlled modes: Inappropriate flow settings In pressure-controlled modes: Inappropriate P-ramp settings
Termination asynchronies - during the end of inspiration				
Double triggering	Two (or more) mechanical breaths are delivered during one single inspiratory effort	**Flow** waveform: look for two assisted breaths without expiration between them or with an expiration interval of less than half of the mean inspiratory time (often visually displayed as a waveform with two inspiratory peaks)		Cycling criteria (ETS) set too high Pressure support too low P-ramp too short Flow starvation High respiratory drive Time constant too short Double triggering can be an effect of and/or promoted by reverse triggering or early cycling
Early cycling	The duration of the mechanical breath is shorter than the duration of the patient's inspiratory effort	**Flow** waveform: look for a small bump ❶ at the beginning of expiration (after peak expiratory flow) followed by an abrupt initial reversal in the expiratory flow ❷		In pressure support ventilation: Cycling criteria (ETS) set too high Low levels of ventilator pressure support Time constant too short In time-cycled ventilation: Short inspiratory time setting
Delayed cycling	The duration of the mechanical breath is longer than the duration of the patient's inspiratory effort	**Flow** waveform: look for a change in the slope of the inspiratory flow: a fast decrease ❶ followed by an exponential (less steep) decline ❷		In pressure support ventilation: Cycling criteria (ETS) set too low Pressure support too high P-ramp too long In pressure control ventilation: Cycling criteria (ETS) set too low Inspiratory time too long In volume control ventilation: Low flow High inspiratory time High tidal volume

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