Patient-ventilator dyssynchrony

Dyssynchrony is the effect of the patients respiratory demands not being appropriately met by the ventilator. The patient has their own idea about how to breathe, and the machinery supporting them, instead of making breathing easier, interferes with respiration and increases the work of breathing.

Patient-ventilator dyssynchrony has occasionally appeared in the past papers. Question 11.2 from the second paper of 2017 asked for potential causes for auto-triggering during pressure support ventilation. Question 11 from the second paper of 2001 discussed the topic in a broad "what is it and what's your management" sort of way. On the other hand, Question 21 from the first paper of 2007 was weird - it discussed the reasons for apparent triggering in a brain-dead patient, which is a dyssynchrony of a sort, as it represents inappropriate auto-triggering by the ventilator.

Why is it bad?

- **The work of breathing increases:** which is what you don't want with mechanical ventilation (remember, the point is to make breathing EASIER.)
- **Thus oxygen demand increases**, tachycardia develops, and bad hearts get worse.
- **The patient becomes distressed** (the experience of being dyssynchronous with one's ventilator resembles asphyxiation)
- **The patient begins to cough and/or vomit**, which is a sub-optimal level of comfort.
- If there was an intracranial pressure problem, it will get worse with all this straining. Then, your nurse will bolus the patient with a massive amount of propofol, and their blood pressure will plummet, which does nothing to improve their cerebral perfusion.

The causes of patient-ventilator dyssynchrony

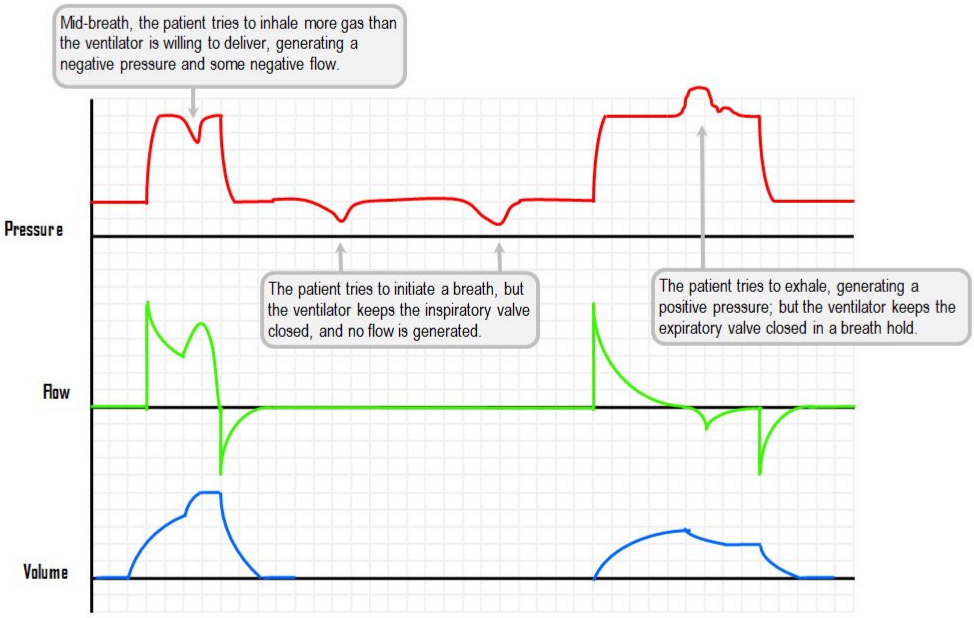
- **Wasted Effort:** work of breathing increases because...
  - The mode is mandatory but the patient is awake and fighting the ventilator;
    - Effort is wasted when the patient tries to terminate a breath (straining to exhale against a closed expiratory valve)
    - Effort is wasted when the patient tries to initiate a breath (straining to inhale against a closed inspiratory valve)
  - The trigger is too high and the ventilator fails to supply gas when the patient demands it.
  - **Inadequate level of support:** the flow rate is too low and it does not meet patient demand.
  - The auto-PEEP is too high and the patient expends a lot of effort trying to defeat it
- **Auto-triggering:** something other than the patient's respiratory effort initiates a breath, eg. cardiac oscillations
- **Double-triggering, premature breath termination:** the ventilator delivers an inappropriately short breath, and the patient wants more air.

The management of patient-ventilator dyssynchrony

- Make the mode patient-triggered
- Improve trigger sensitivity to include patient efforts and exclude cardiac auto-triggering
- Increase flow rate if it is inadequate
- Manage the auto-PEEP
- Increase flow cycle-off to a higher value, terminating a breath early if the patient wants shorter breaths
- Decrease the flow cycle-off to a lower value if the patient requires longer breaths
- Clear the airway of sputum and secretions, and ensure its patency
- Increasethe sedation
- Use neuromuscular blockade

Wasted effort: The mode of ventilation is mandatory; the patient wants to trigger but cannot.

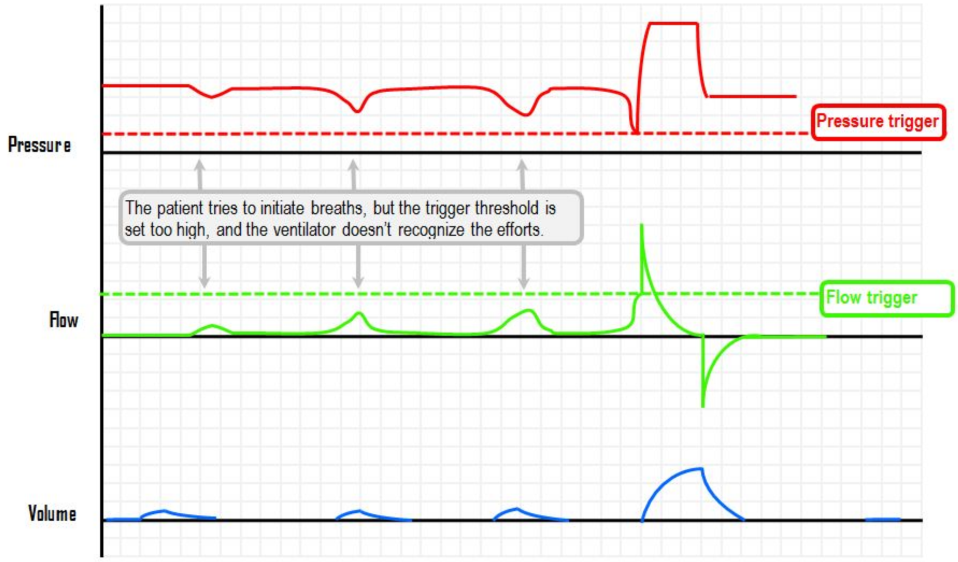
Something like this was shown to the candidates in Question 11.3 from the second paper of 2017.



The patient tries to breathe, but try as they may the cold indifferent ventilator refuses to help. Instead, it blows air at them when they don't want it, and closes the valve on them when they try to take a breath.

The solution is progress the patient to a patient-triggered mode of ventilation (eg. PSV) or to sedate them more, persisting with the same mode but abolishing their respiratory drive.

Wasted effort: the trigger is not sensitive enough; the patient wants to trigger but cannot.



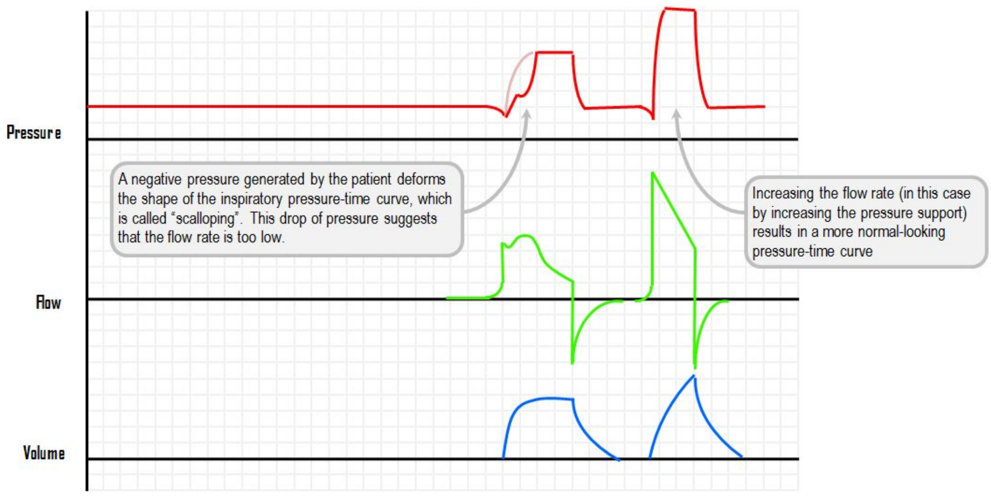
The patient tries to breathe, but owing to whatever patient factors they are unable to generate the effort required to deflect 2L/min of flow, or whatever your flow trigger setting is. These minor efforts may be generating some laughably small tidal volumes, but its nothing but dead space. However, it is exhausting to continue in this fashion.

The solution is to adjust the trigger to a lower setting, or sedate the patient and move to a mandatory mode. A decently low flow trigger is **0.8L/min.**

Flow rate is inadequate to meet inspiratory flow demand

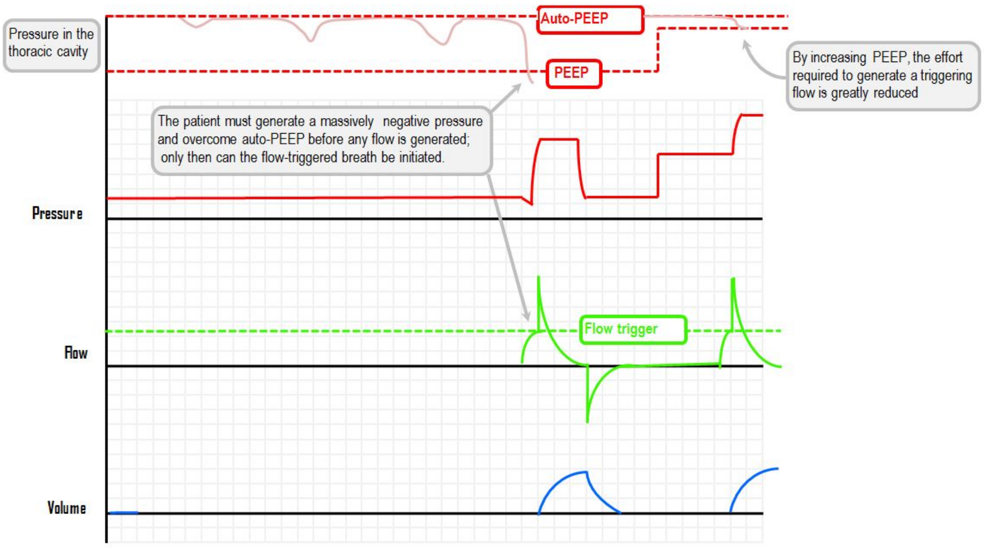
Something like this was shown to the candidates in Question 11.3 from the second paper of 2017.

In order to breathe comfortably, one needs a steady flow of gas, at a sufficiently high rate.
If the flow demand is not met, the patient makes an effort ON TOP of the ventilator effort.
This appears as a "scalloping" of the pressure-time curve, which reflects the fact that the patient is generating a negative pressure with their respiratory muscles while the ventilator turbine is generating a positive pressure.



The solution is to increase the flow rate. Typically, a pressure controlled mode (including PSV) delivers maximal flow at the beginning of a breath. In fact, most modern machines do this. In some machines it is possible to adjust the "ramp" of the flow curve, in which case one may be able to increase the steepness of the ramp and thereby increase the rate of flow.

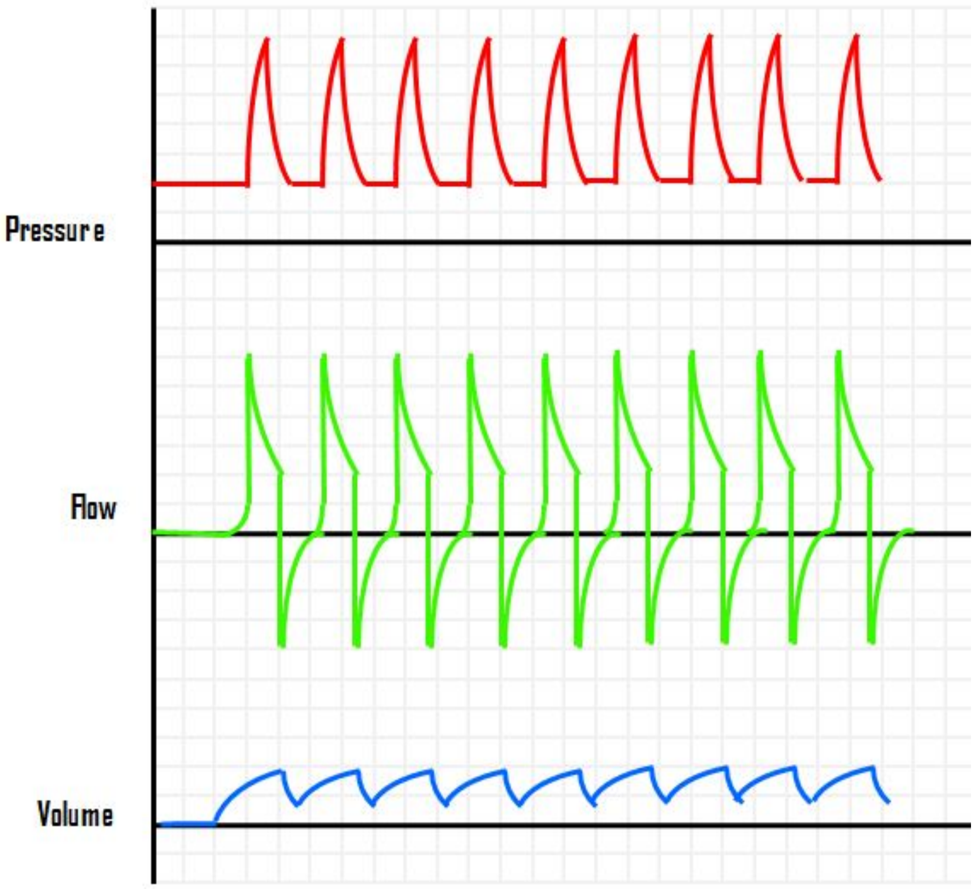
Wasted effort: there is too much Auto-PEEP and it makes it harder to trigger a breath



Let us say one has a serious airflow limitation, with tightly constricted airways and hyperinflated lungs. Let us say the intrinsic PEEP in these lungs is around 10cmH$_2$O. In order to generate a breath, one must defeat one's intrinsic PEEP. Thus, this poor chest must generate a negative pressure of 11cmH$_2$O to get any air movement happening (to activate the flow trigger). Perhaps the machine then supports this breath with additional flow, but so what? It doesn't help in terms of reducing respiratory effort, because a breath like this has taken an enormous effort to trigger.

The solution, apparently, is to adjust the PEEP to about 80%-90% of the intrinsic PEEP. The additional work of breathing is the result of a pressure difference between the patient and the circuit. Increasing the circuit pressure decreases this pressure difference and therefore decreases the work of breathing.

Auto-triggering: the trigger is too sensitive. Non-respiratory factors trigger the ventilator.



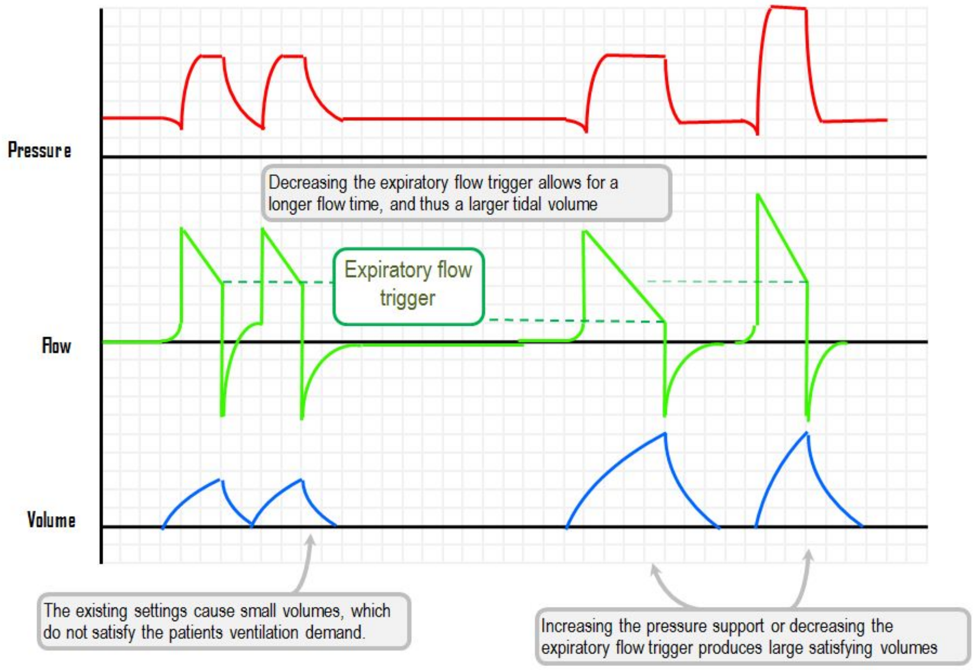
Cardiac contractions cause a small amount of air movement, and in someone with a hyperdynamic ventricle and a sufficiently sensitive flow trigger these air movements can trigger ventilator breaths. The resp rate will resemble the heart rate.

Question 11.2 asked for four possible causes of auto-triggering. Including the above, the list could potentially contain the following:

- Cardiac oscillations
- Leak from the circuit
- Leak from the chest drain (eg. a bronchopleural fistula)
- Inappropriate sensitivity settings
- Water condensation sloshing and bubbling in the circuit
- Large volume of respiratory secretions, eg. bronchiectasis
- Swallowing or vomiting
- Peristalsis in a massive hiatus hernia or intrathoracic bowel loops
- Muscle contractions due to external pacing (or misplaced leads in transvenous pacing)
- Transmitted movement from patient transport or repositioning
- IABP (Turns out, the balloon can generate enough gas displacement to fool a flow trigger. Richard Arbour (2018) published this case report in CCM. He doesn't mention how sensitive the flow trigger was.)

The solution is to adjust the trigger to a higher setting.

Double triggering and premature breath termination



Double triggering is evidence that the ventilator has not met the patients demand for tidal volume. The typical setting is pressure support ventilation in ARDS- the lung compliance is so low that the expiratory flow trigger is reached too soon. That trigger is usually 25-30%. Changing to a lower trigger tends to prolong insufflation time, and increase the tidal volume.

The solution is to adjust the expiratory flow trigger until the desired tidal volume is achieved.

There is too much leak around the NIV mask

In order to generate the specified pressure, the ventilator continues to deliver flow. With a large leak, this inspiration can be very uncomfortable (as the ventilator delivers 70-80 litres per minute of gas into the patients face). The normal human response to such an experience is to cough, splutter and claw desperately at the mask/nurse/doctor.

One can adjust the mask, to minimise the leak.

If this does not work, one can move on to decreasing the level of pressure support (it makes sense that with less pressure there should be less leak).

If it is not practical to decrease the pressure support level, one can **INCREASE the expiratory flow trigger**. This will decrease the total inspiratory time, as the machine will cycle to expiration sooner, instead of blowing ridiculously to compensate for a leak. In some ventilators, one can actually adjust the inspiratory time directly.

Previous chapter: Ventilator-associated lung injury (VALI or VILI)

Next chapter: Causes of respiratory failure

References

Most of this information comes from only two textbooks. With "Basic Assessment and Support in

Intensive Care" by Gomersall et al (was well as whatever I picked up during the BASIC course) as a foundation, I built using the humongous and canonical "Principles and Practice of Mechanical Ventilation" by Tobins et al – the 1442 page 2nd edition.

Arnaud W. Thille, MD, and Laurent Brochard, MD. Promoting Patient-Ventilator Synchrony (Clin Pulm Med 2007;14: 350 –359)

Petrof BJ, Legare M, Goldberg P et al. Continuous positive airway pressure reduces work of breathing and dyspnea during weaning form mechanical ventilation in severe chronic obstructive pulmonary disease. Am Rev Respir Dis 1990; 141: 281–9.

Arbour, Richard. "170: Ventilator Autotriggering Consequent To Intra-aortic Balloon Pump Counterpulsation." *Critical Care Medicine* 46.1 (2018): 68.

Triggering of a mechanically supported breath

The trigger phase variable determines how a mechanical breath is initiated. This variable determines whether a mode of ventilation can be described as "mandatory" or "spontaneous". Historically, this has been a purely machine-driven affair – but with advent of microprocessor-controlled ventilators, mechanical ventilation has become more user friendly (where the user is the patient). Patient-triggered modes are generally more comfortable, and can improve the work of breathing.

From an exam point of view, it is hard to fit this topic into the domain of the CICM primary, mainly because there is no room for it in their 2017 syllabus. It remains in this position because of the authors obstinate insistence on the importance of this knowledge to the junior trainee at the beginning of their training. Though the college does not appear to share this view, their mid-training WCA competency "Ventilation" includes "describes methods of triggering and cycling in spontaneous ventilation" as one of the performance criteria. Moreover, of the past paper questions regarding triggering, there have been some notable Part II questions about this variable: Question 18 from the second paper of 2015 and Question 11.1 from the second paper of 2017 both asked for some detailed information on these topics (at least as much as would be expected from a ten-minute exam answer). The author assumes that at Fellowship exam-level the trainees already have a firm grasp of these matters, and in the Part II required reading section mechanisms of ventilator breath triggering are dealt with in a very condensed and heavily redacted format, suitable for rapid revision.

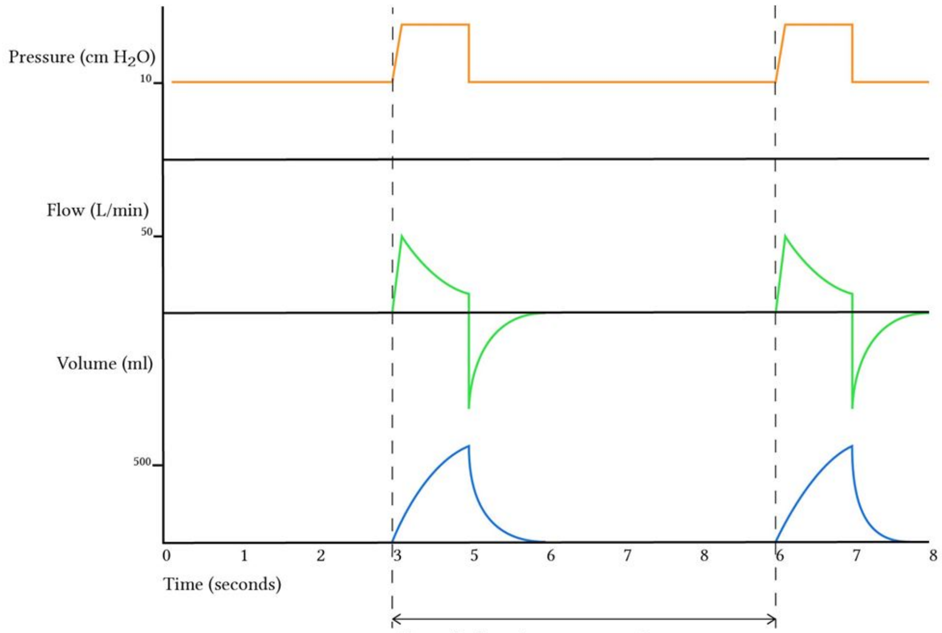
In summary:

- The trigger phase of mechanical ventilation is defined by the transition from expiration to inspiration
- The trigger variable determines when this transition occurs
- There are serval methods of triggering, each of which have advantages and disadvantages:
  - **Time triggering** which guarantees a minute volume and decreased work of breathing but which is less comfortable
  - **Pressure triggering** which gives the patient more control over the initiation of a breath, but which can also be uncomfortable
  - **Flow triggering** which is the most comfortable but which can be over-sensitive, leading to dyssynchrony
  - **Shape-signal triggering** which may decrease wasted effort by "predicting" the next respiratory effort, and which is not widely available
  - **Neural assist (NAVA) triggering** which is theoretically the most effective but which is practically difficult to maintain, and which does not have strong evidence to back it
  - **Volume-triggering**, which requires the patient to decrease the volume in the circuit – this is virtually unknown
- Of these, time pressure and flow triggers are the most common.
- Flow triggering is favoured as the best choice for spontaneously breathing patients because of some (low quality) evidence in support of its positive effect on ICU stay and duration of ventilator weaning

In terms of wider reading on this topic, there is plentiful information in the free article by Catherine Sassoon (2011). One should not need to read more broadly than that for the purposes of exam preparation. Having constructed this summary, one must reluctantly acknowledge that there is probably little merit in pursuing this topic to the level of detail presented below, and that it is perfectly possible to complete one's training in intensive care medicine and then have a fruitful career without being even vaguely aware of any of these minutiae.

Time-triggered ventilation

When a ventilator is set to time-triggered ventilation, it will measure a period of time since the last expiration and then deliver a breath. For instance, when a respiratory rate of 12 has been set, the ventilator will deliver inspiratory flow exactly every five seconds. Such breaths are characterised as "mandatory", implying that the patient has no choice in the matter. This is what determines whether one's mode of ventilation is mandatory or spontaneous; a time-triggered mode is always mandatory. All the other trigger mechanisms permit the patient to have some control over the timing of inspiration.



Prescribed respiratory rate = 12
Therefore, prescribed time interval between breaths: 5 sec

This was the default setting in earlier ventilator models which did not permit the patient to take breaths beyond the set rate. Most modern ventilators allow patient triggering, and take some effort to synchronise their mandatory breaths with patient effort. Synchronised intermittent mandatory ventilation or SIMV is discussed in greater detail in a later section of this learning module.

Without digressing into a discussion of the advantages and disadvantages of spontaneous and mandatory modes of ventilation, it will suffice to say that time-triggering has its merits.:

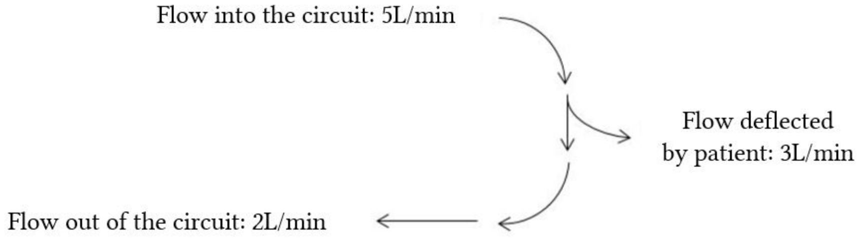
- There is a guaranteed respiratory rate for patients who are ...insufficiently interested in breathing
- The guaranteed minute volume offers predictable CO2 removal
- There is no increased patient effort wasted on triggering the ventilator

There are also some drawbacks:

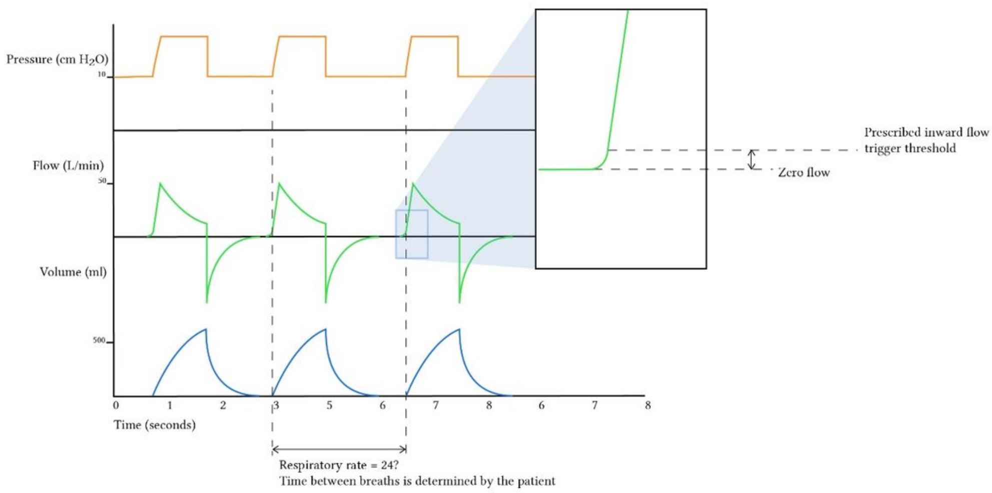
- It may be uncomfortable
- The sedation requirements are likely going to be higher
- It may lead to deconditioning

Flow-triggered ventilation

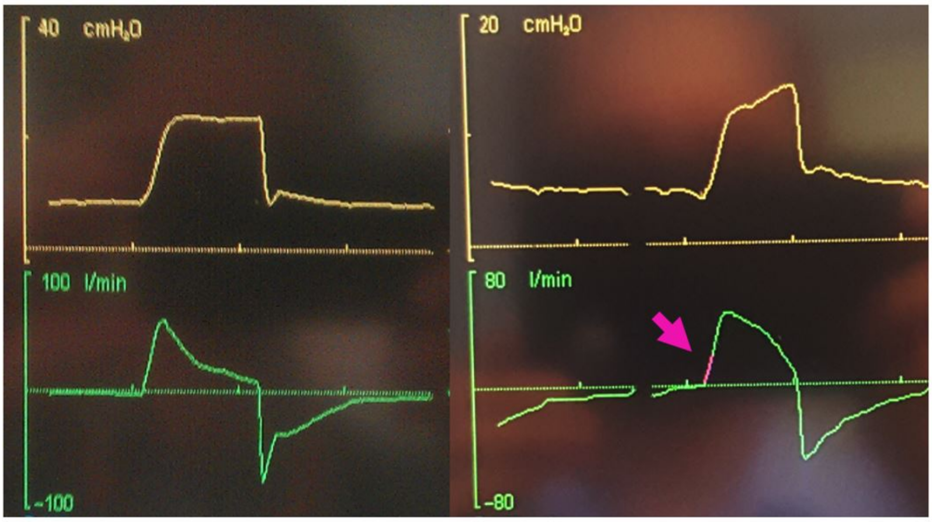
The flow trigger is the most commonly used form of triggering for spontaneous modes ventilation, as creating a small inward flow is a convenient low-effort way for the patient to notify the ventilator of the fact that they want a breath. This is possible because the ventilator circuit has a constant bias flow going through it during the expiratory phase, which is usually low enough not to be wasteful of gas. In the SERVO-i model this flow is around 2 litres per minute. In order to trigger the ventilator, the patient needs to deflect some of this bias flow, so that the expiratory flow sensor and the inspiratory flow sensors detect a difference between inspiratory (Vin) and expiratory (Vout) flow rates. In the absence of respiratory effort (or significant leak), the circuit has intact bias flow such that Vin - Vout = 0 (i.e all of the flow is "accounted for").



When a patient takes a breath, some of the flow is directed into their lungs. The expiratory flow rate in the ventilator circuit is decreased by this, such that Vin - Vout = x, where x is some "missing" flow measured in L/min. Flow triggering occurs when this missing flow reaches some prescribed threshold value, which causes the ventilator to open the inspiratory valve and deliver a breath. The exact value is susceptible to manipulation via the settings, and the default setting differs between manufacturers, but generally it's in the ballpark of 1-2 L/min. For comparison, the normal mean inspiratory flow rate at rest is probably about 15L/min, with a peak of around 30-35L/min (Tobin et al, 1983) which makes this a relatively effortless goal to achieve.

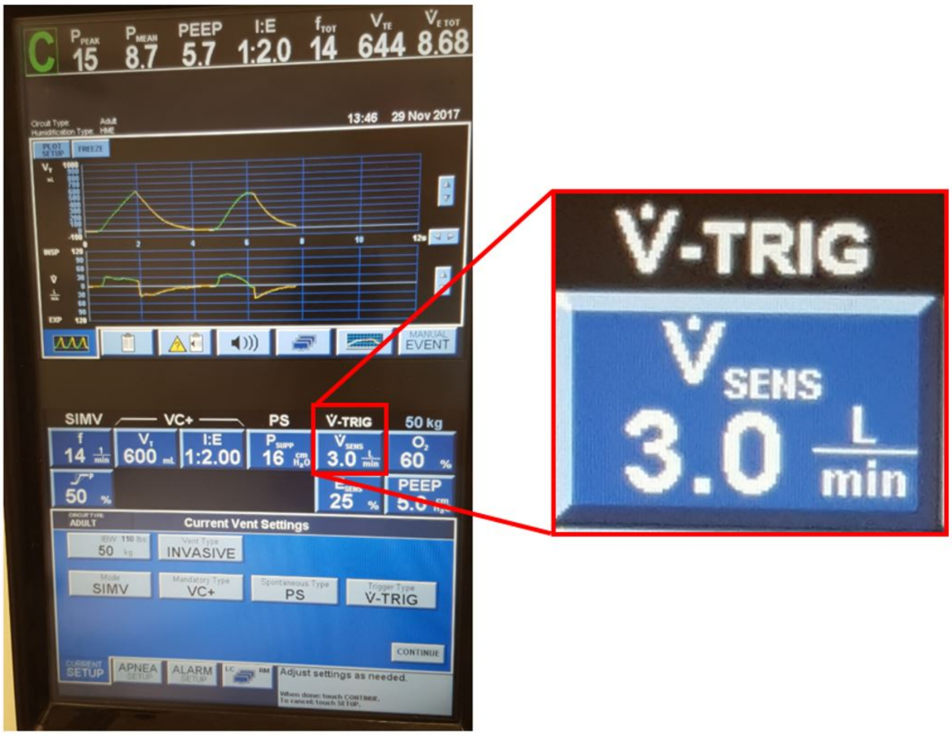


In general, the ventilator will also alert you to the fact that the patient made a spontaneous respiratory effort, eg. by colouring the waveform. For example, the SERVO-i model makes the flow waveform pink.

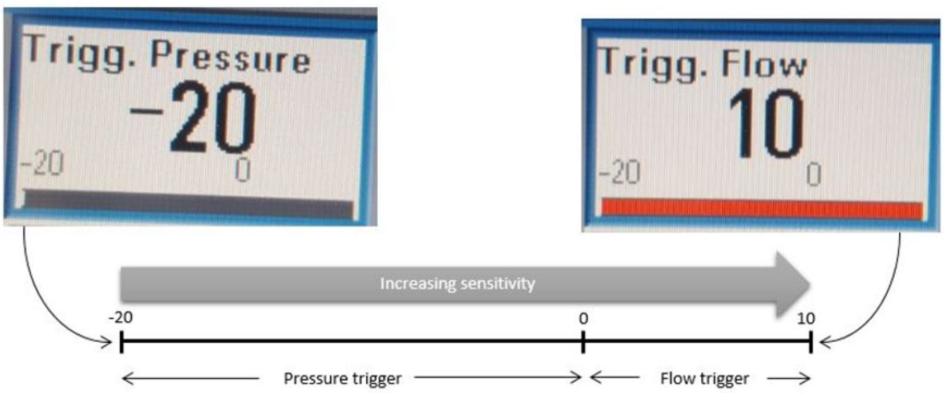


Mandatory breath Patient-triggered breath

Interestingly, the flow trigger setting should probably be in litres per minute (that, after all, is how we measure flow) but this is not viewed as mandatory by all ventilator manufacturers. For instance, the Puritan Bennett 840 allows the user to set a flow trigger directly, in L/min. In the case below the trigger is set to 3L/min.



Thus, in the Puritan Bennett models, setting a lower value of flow trigger (eg. 2L/min or 1L/min) represents an increase in sensitivity, i.e. a lower flow required to trigger a mechanical breath. In contrast, in the Maquet SERVO-i model interface, a decreasing trigger value corresponds to a *decrease* in sensitivity. Their trigger variable is controlled by the twiddly dial on the ventilator and can be tuned to a range of settings from -20 to +10. This range represents an increasing sensitivity of the trigger, from least sensitive at -20 to most sensitive at 10.



To make things more confusing, the range between -20 and 0 actually represents a pressure trigger; the values in this range correspond to a negative pressure in cm H_2O, such that a setting of -20 represents a pressure trigger of -20 cm H_2O. The range between 0 and 10 represents a flow trigger, and corresponds to a percentage of the bias flow which needs to be "deflected" by the patient in order to trigger the mechanical breath. A setting of 0 is the least sensitive flow trigger, and represents a 100% deflection (i.e. the patient must generate a flow equal to 100% of the bias flow though the circuit, or 2L/min). A trigger of 10 is the most sensitive, and represents a flow deflection close to 1% of the bias flow. The default setting of a recently reset/restarted SERVO-i ventilator is a flow trigger of 5, which corresponds to a bias flow change of 50%, or 1L/min. It would be wonderful if these things were made obvious to the user, but in fact one needs to dig through the SERVO-i service manual to find such information.

As already mentioned, flow triggering is used on most modern ventilators as the default trigger variable for all spontaneous modes of ventilation. Again, without digressing extensively on the merits and demerits of spontaneous ventilation, it will suffice to summarise its advantages:

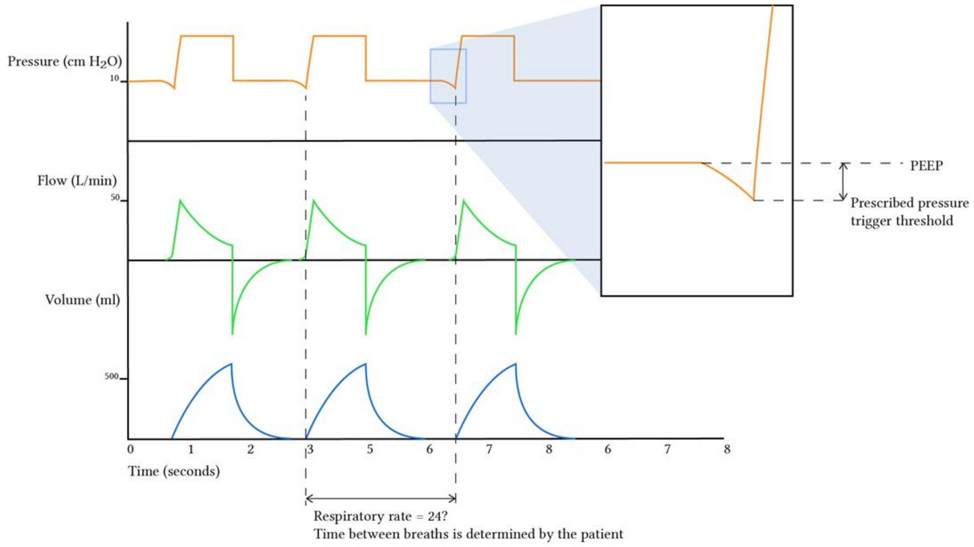
- It is quite sensitive; i.e. little patient effort is required to trigger a mechanical breath, and therefore the patient's work of breathing is not "wasted" on triggering the ventilator.
- It allows the patient to have control over their minute volume, which prevents dyssynchrony due to unsatisfied respiratory drive
- Work of breathing may be decreased.
- It is more comfortable because of a decreased work of breathing in triggering, increased control over ventilation and also because the triggering occurs with less delay, so that the initiation of a breath by the patient is rapidly translated into a mechanical breath.
- It permits a lower level of sedation because it is more comfortable.
- It may reduce patient-ventilator dyssynchrony particularly when the dyssynchrony is due to wasted effort (eg. an insufficiently sensitive trigger)
- As the result of all these benefits, flow triggering permits earlier extubation according to a study by Khalil et al (2015). Less sedation probably plays a major role in this.

There are also some problems with flow triggering:

- It may be too sensitive, giving rise to auto-triggering (a form of dyssynchrony where non-respiratory influences on circuit flow trigger mechanical breaths; for example, the cardiac pulsation, fluid in the circuit, secretions in the airway, etc). In these cases, a pressure trigger may be better (that's probably one of the only uses of a pressure trigger).
- It does not guarantee a minute volume, which means it is unsuitable for patients with a diminished or unreliable respiratory drive. Fortunately, most ventilators come with a backup mode which automatically starts a mandatory breath rate if the patient decided to be apnoeic for some sustained period of time.

Pressure triggering

Pressure triggering describes a method whereby a decrease in circuit pressure is detected by the ventilator pressure sensors and interpreted as patient effort. The patient inhales against a close inspiratory valve, producing a pressure drop by this effort, and in response, the ventilator delivers a mechanical breath by opening the inspiratory valve. Conventionally, where a pressure trigger is used for a prolonged period, a typical setting would be 1 cm H_2O.



This is very old-school. In the 21st century pressure triggering is seldom used in routine mechanical ventilation, but back in the day it was the only method of giving patients any control over their respiratory rate, and the main reason for this was technological.

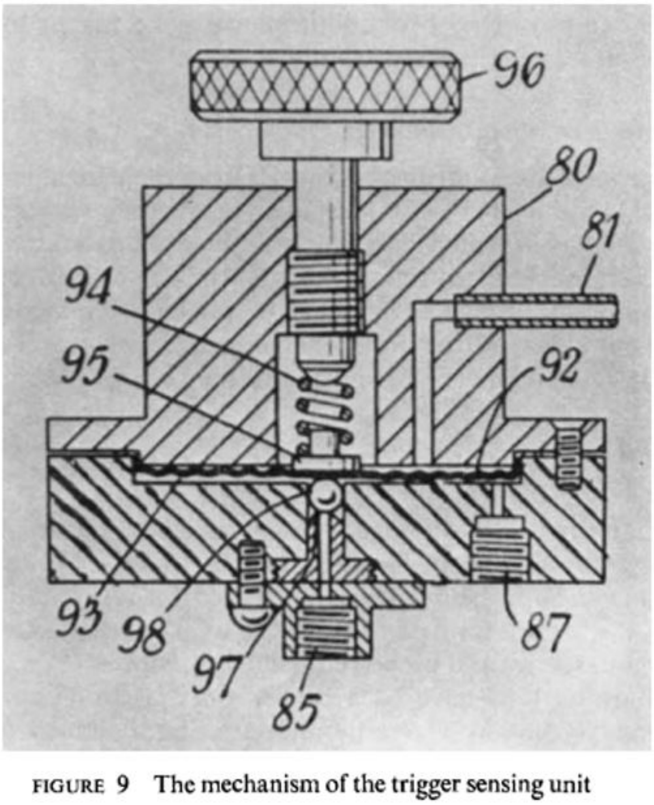


FIGURE 9 The mechanism of the trigger sensing unit

Miniaturised aneroid manometers were expensive, drifted from calibration and required servicing. Instead, pressure sensors were coupled into the actual inspiratory valve mechanism in various ingenious ways. An excellent example of an early application of this positive pressure triggering is described by Geoffrey Burchell (1965), and the image to the left is also misappropriated from his excellent paper. The schematic describes the mechanism of the pressure trigger sensing unit, which was a purely mechanical device. In essence, it is a valve where a slight negative pressure in the circuit snaps open the compressed gas supply regulator, thereby delivering the mechanical breath. The knob on the top (96) can be twisted to adjust the tension on the spring, thereby increasing or decreasing the sensitivity of this trigger.

Though the exact mechanism doubtlessly became more sophisticated with the years, the combination of instrument cost and corporate inertia produced an environment in which these technologies persisted until relatively recently. Writing in 1997, Nava et al complained that of the commercially available models of non-invasive ventilators, only 28% were equipped with flow-triggering capabilities. The rest were set to trigger at 1.0 cmH_2O.

Why that pressure? Among the desirable characteristics for a ventilator, Burchell listed a pressure trigger capable of sensing negative pressure in the range of around 1 cm H2O, and ideally below. It was felt that this represented some sort of sensible compromise between patient comfort and synchrony-wrecking oversensitivity. However, though it is relatively small, a 1cm H2O pressure trigger still represents a non-trivial workload. Banner et al (1993) demonstrated a significantly increased respiratory workload with pressure triggering, as compared to flow triggering. Where intrathoracic pressure is already high (eg. where there is auto-PEEP) this effect is probably exaggerated. Nava et al had mainly COPD patients in their study and found that the work of breathing was increased by about 20% with pressure triggering. This makes sense, as no inspiratory flow is generated while the patient is inhaling against a closed inspiratory valve; this wasted effort could be viewed as counterproductive wherever the main objective of mechanical ventilation is to reduce the work of breathing.

These problems have implications for patient comfort. Apart from the increased work of breathing, it is felt that the experience of pressure-triggered mechanical ventilation is rendered much more frustrating by a delay between trigger effort and breath initiation. In that scenario, there is a period of time between the initiation of respiratory effort and the opening of the inspiratory valve during which the patient is essentially choking (inhaling against an obstructed respiratory circuit).

In summary, the disadvantages of pressure triggering are:

- It requires more effort to trigger the ventilator, as a change in pressure of even -1cm H2O requires more patient effort than a change in flow
- It represents a wasted respiratory effort, as no inspiratory flow is generated while the patient is inhaling against a closed inspiratory valve; this wasted effort may be counterproductive when the main objective of mechanical ventilation is to reduce the work of breathing
- It is less comfortable for the patient
- It may result in increased sedation requirements because of the above factors, which may be counterproductive in the course of ventilator weaning

So, in a modern ventilator, what's the use of this option? Surely if flow triggering is so good you would just use that as a default? Well. There are some scenarios which make a good case for the use of a pressure trigger.

- It can be used to decrease auto-triggering, for instance by a circuit leak, bronchopleural fistula or a hyperdynamic circulation. Decreasing the trigger sensitivity could prevent the inappropriate triggering of breaths by these non-respiratory stimuli. In this case, the inappropriately triggered breaths lead to *more* wasted respiratory effort, because the patient does not want them and will actively resist them (sedation requirements also tend to increase). Paradoxically, a more "stiff" trigger setting will actually improve patient-ventilator synchrony in this scenario.
- It can be used to test the power of respiratory musculature, in the context of an assessment of readiness for extubation. A patient who is able to trigger the ventilator by generating a negative intrathoracic pressure of -20 cm H2O is unlikely to fail extubation due to the weakness of their respiratory muscles.

Comparison of pressure triggering and flow triggering

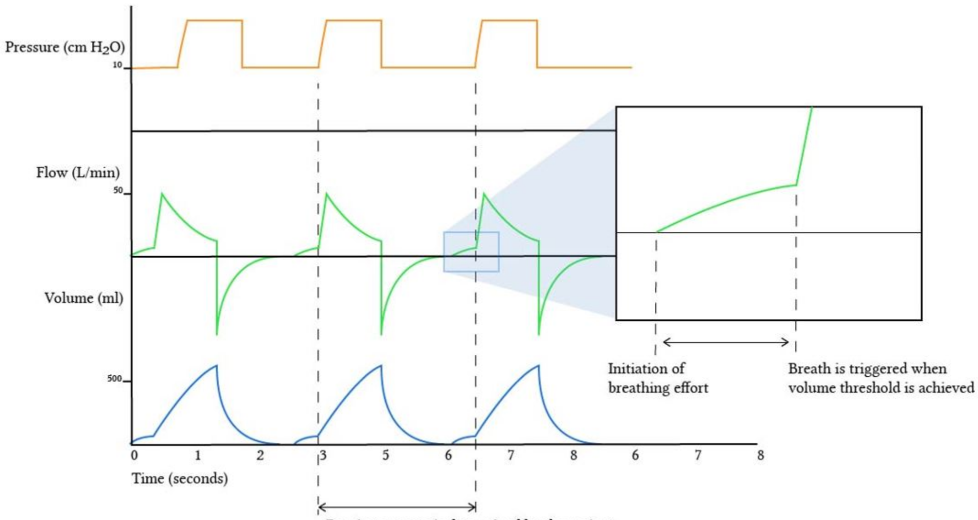
You have the option of both. Is one really better, all other things being equal? Outside of special use cases, one probably has the choice of either, and which one chooses does not seem to matter in the short term. A representative study is this trial by Tutuncu et al (1997), where sixteen ventilated patients underwent several changes to triggering conditions (pressure trigger of 1.0 cm H_2O, flow triggers ranging from 0.7 to 2.0 L/min) and found absolutely no difference in short-term gas exchange respiratory mechanics or inspiratory workload.

Over the duration of the patient's stay in the IUC, flow triggering appears to have some advantage. The trials of mechanical ventilation weaning which focused on important patient-centered outcomes (mortality, days off the ventilator) instead of the abstract surrogates (work of breathing, asynchrony) have found some benefit. Khalil et al (2015) compared flow (2 L/min) pressure (2.0 cm H_2O) in a group of 100 ventilated patients; the flow trigger group appeared to get off the ventilator much faster. Admittedly, something is funny about the data - the difference in ventilator days was massive, 4.72 vs 8.18 days, and the pressure trigger group had a much higher mortality (44% vs 36%) which causes one to question whether bias was present, but the overall signal appeared to favour flow triggering.

Volume triggering

If one has pressure triggering and flow triggering, and the ventilator has pressure flow and volume waveforms, then surely there must also be volume triggering, one would logically say to oneself shortly before realising that such a thing would probably be completely pointless on philosophical grounds. Indeed, volume triggering is virtually unknown. It needs to be mentioned in a footnote here to satisfy the authors' need for completeness, but it plays minimal role in the operation of modern adult ventilators, and one would probably not be penalised for not mentioning it in the exam.

Consider this. Volume triggering is described by Chatburn (2012) as *"the starting of inspiratory flow due to a patient inspiratory effort that generates an inspiratory volume signal larger than a preset threshold".* One must be reminded that under most circumstances a modern ventilator never measures volume directly, but rather calculates it from flow over time. In other words, with the inspiratory valve still giving some insufficient amount of bias flow, the patient must generate enough flow for the ventilator to detect this as a change in volume. So, if you have your ventilator measuring flow and then converting it into volume, then surely it would be easier (and more comfortable for the patient) to just omit that step and trigger breaths according to flow instead. By the same logic, any flow triggering is also technically volume triggering because some volume *must* change as the result of a change in flow. In summary, volume triggering would represent a sort of pointless duplication of flow triggering.



That conclusion wouldn't be completely accurate, but it appears to have been the conclusion of virtually all the ventilator manufacturers. Of the existing machines, the Drager Babylog appears to be the only ventilator which offers volume triggering as an option. According to this ancient operators' manual, the device offers ten trigger volume settings, ranging from about 0.02ml to 3ml.

Why? The main advantage seems to be the expectation that autotriggering should be reduced. When flow is divided by time to convert it into volume, much of the noise in the signal ends up being obliterated by the maths. Therefore, all the circuit condensation and cardiac oscillations are going to go unnoticed. This probably has implications in neonatology, where one might be ventilating somebody weighing 800g, with a tidal volume of 5 ml. With a flow trigger of 0.2 L/min, even the tiniest disturbance in the circuit could produce autotriggering. The Drager manual acknowledges that the ventilator measures flow and is nominally flow-triggered, but that "in order to reliably detect inspiration, and to avoid triggering a ventilation stroke as the result of interference signals, the patient must first breathe in a certain volume".

Searching the literature, one struggles to find any reference to the successful application of a volume-triggered mode of ventilation to adults, or a review of its physiological effects in infants. The term appears only in narrative review articles, the authors of which (like Chatburn, 2012, and Sassoon, 2011) were writing with the intent of being inclusive of every possible permutation of trigger mechanisms, for example for the purpose of classifying ventilator modes.

Neurally Adjusted Ventilatory Assist (NAVA)

Trainees of the modern era will likely never encounter this in their practice because of the decrease in its popularity. The NAVA method depends on a mechanical breath being triggered by a change in diaphragmatic EMG, detected by a properly positioned electrode array on a specially designed nasogastric tube. The tube must be positioned in precisely the right position, and when it is, the diaphragmatic EMG can be used not only to trigger breaths but also to proportionally assist the patient, adjusting the pressure volume and flow characteristics to better match the patient's inspiratory effort. Thus, a forceful diaphragmatic contraction produces a large EMG signal, which then recommends a deep breath with a fast inspiratory flow rate. The intensivist can then gradually decrease the proportion of the support, thereby weaning the patient off the ventilator.

This sounds wonderful and has several advantages which are widely deployed by the Getinge Group as propaganda to support the sale of their devices. An excellent example is this article by Skoro et al (2013) where the many merits of NAVA are listed:

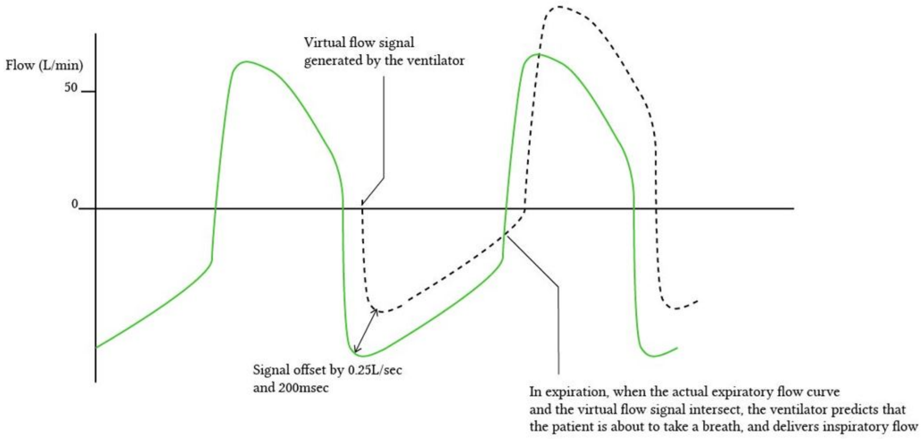
- **Synchrony should improve,** as the NAVA catheter should only detect diaphragmatic EMG. Most forms of trigger dyssynchrony are related to the pneumatic events in the ventilator, i.e. somewhere somebody is either not generating enough of pressure or flow, or too much, or at the wrong time. NAVA is completely divorced from such crude gaseous phenomena, and should therefore be sensitive only to genuine respiratory efforts. It should also be faster (reducing the delay between effort and breath delivery), given that muscle contraction is sensed by the EMG electrodes long before any air is actually moved by the patient's diaphragm.
- **The ventilator becomes more informative** - Diaphragmatic EMG can be continuously monitored for diagnostic purposes using the catheter, even when not NAVA-ing. This has implications for such pathologies as Guillain-Barre and myasthenia gravis; one may be able to observe the gradual recovery of neurological function without ever actually examining the patient, or coming anywhere near them.
- **The support is more proportional:** as intensivists, we think we know what ventilator settings the patient wants and needs on the basis of their clinical performance, blood gas biochemistry, chest Xray findings, the cleaner's comments, and so forth. NAVA proposes that we are wrong and that the patient should have more control over the amount of support they receive. With NAVA, the pressure and flow are adjusted every moment (16 ms to be precise) to better suit patient demand. This results in greater breath-to-breath heterogeneity but is much better tolerated.
- **The pressure level ends up being lower.** Because of the proportionality of support, you are not committed to using boring old square waveforms. As the result, the mean airway pressure is greatly reduced, as NAVA pressure waveforms are generally not square. This is promoted as a good thing (i.e. protective against ventilator-induced lung injury), and certainly it appears to be supported by some rabbit data (Brander et al, 2009)
- **It might be cheaper** because you wean them faster. A group of Maquet employees in a study paid for by Maquet published an economic analysis trying to convince the public of the cost savings (Hjelmgen et al, 2016). According to this literature, the 1.7 fewer days of mechanical ventilation would have cost $US 7886.

There are a few disadvantages to NAVA, which are worth being aware of.

- **Respiratory drive mechanisms need to be relatively intact.** NAVA makes assumptions about the way your brain commands ventilation and communicates with your diaphragm. If you have bilateral phrenic nerve paralysis, this method of triggering will not work for you. If your medulla is disabled and your respiratory drive is somehow affected (eg. by sedation), this spontaneous trigger is also ineffective (though in its defence so are all the other spontaneous trigger methods). If the neuromuscular junction is somehow diseased or disabled by drugs, again NAVA will not work. Conversely, if something is irritating the respiratory drive centres (eg. salicylate toxicity) the NAVA-triggered mechanical ventilator will dutifully help the patient hyperventilate.
- **The accuracy of the support relies on the nasogastric sensor position.** Obviously, that's not the most reliable feature of this process. The oesophagus is squishy, mobile, peristaltic, and potentially affected by some sort of disfiguring anomaly (like a hiatus hernia). These aspects make it difficult to prevent tube migration, to say nothing of the possibility that the patient may just pull it out in a fit of rage.
- **Obviously, nasogastric access cannot be contraindicated,** for example by trauma, rupture, surgery or something else in the mediastinum that would normally prevent you from inserting an NG tube.
- **There is no evidence that it improves outcomes.** Demoulle et al (2016) performed a multicentre RCT where they compared NAVA to PSV over the first 48 hours after coming off complete mandatory support. The primary outcome was likelihood of having to return to full mandatory support, and that was no different. Nor were the secondary outcomes (mortality, ventilator-free days, etc). NAVAed patients had a slightly lower chance of needing NIV following extubation, which was the only statistically significant finding. In spite of the fact that Maquet paid for the trial and sponsored the investigators, the group were forced to conclude that their device made no major difference in adults. Nor does it work any better in neonates (Rossor et al, 2017), though it must be said that there is no evidence of harm, and that the data at the moment is fairly sparse (only one trial made it into the Rossor meta-analysis).

Shape-signal triggering

Though this is another manufacturer-specific peculiarity, this needs to be mentioned as an alternative to all the other trigger modes, if only because is it sufficiently distinct from them by mechanism. If one wanted to read more about it, one would find the best explanation in Shape-signal triggering is essentially a method of predicting the next patient inspiratory effort by observing their expiratory flow waveform. When the patient's effort distorts this flow waveform, the ventilator assumes that a breath is being asked for. The precise level of "distortion" required for triggering is determined by superimposing the patient's own flow waveform on top of itself, with an offset value (in the Respironics Vision system, it is 0.25L/min and 200-300 msec). Given that inspiratory flows are often measured in tens of litres, 0.25L/min and 0.2 seconds are miniscule offsets; in the diagram below they have been greatly exaggerated for illustration purposes. In short, when the offset "virtual signal" is crossed by the patients' actual flow signal, the ventilator triggers a breath.



So, what would be the point of this? Well, it's apparently easier to trigger the ventilator in this manner. Priniakis et al (2002) demonstrated that 50% less effort was required to trigger the ventilator when compared to standard flow triggering (they compared it to a Drager Evita 4, flow-triggering at 2.0L/min). Predictably, "The flow waveform method of triggering was more sensitive to patient effort than the flow triggering, resulting in less ineffective effort but a greater number of auto-triggerings". One can envision an application for this system in situations where the patient would have some genuine trouble generating sufficient inward flow to trigger conventionally, but where their effort would be obvious from the ventilator waveform (eg. in significant bronchospasm). Vasconcelos et al (2013) used a similar proprietary method (Auto-Trak, by Phillips – because everything is cooler when it is misspelt). The comparison was in healthy volunteers and for some reason the control group were on a pressure trigger of 1.0 cm H_2O. Discomfort scores were statistically similar, as were many of the other variables. On the balance of evidence, one would have to conclude that these systems do not offer much advantage over conventional systems in terms of patient-ventilator synchrony or breathing effort.

Previous chapter: Control variables: volume and pressure

Next chapter: Limit (target) variables in mechanical ventilation

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Cycling from inspiration to expiration

Just as the ventilator needs to know when to start a breath, so it needs to know when to end it, and this is defined by the cycling variable. This setting determines which parameter is used to open the expiratory valve. Strictly speaking, multiple cycling variables may be active at any given time, but usually some of them (for example, pressure) take the form of alarm limits. The cycling variable is an important determinant of how comfortable your patient is going to be with their mechanical breaths, as it represents another point at which they can exercise control over their tidal volume.

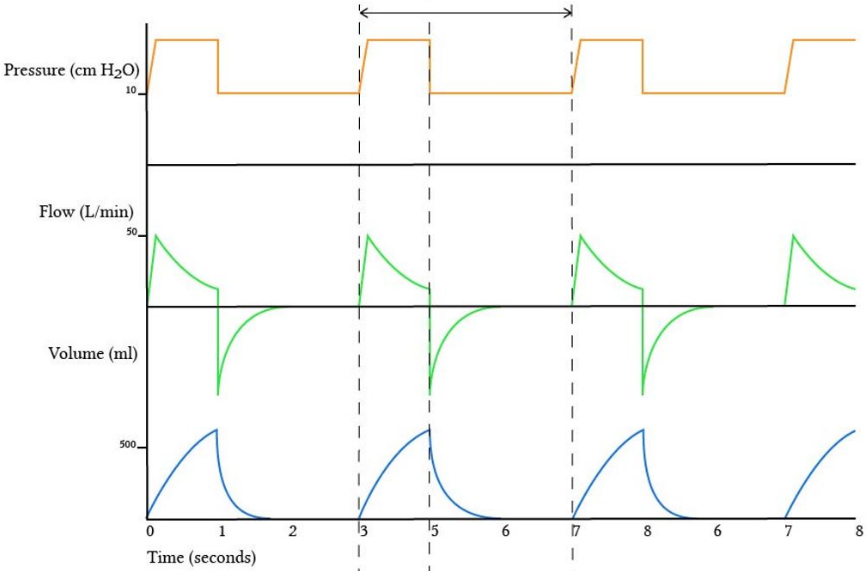
In summary:

- Cycling refers to the variable a ventilator uses to end inspiration.
- The ventilator measures this variable during the inspiratory phase.
- When the set parameter for this variable is achieved, the ventilator opens the expiratory valve, and expiration may begin.
- Typical methods of ventilator breath cycling include:
    - Time-cycled ventilation
    - Flow-cycled ventilation
    - Pressure-cycled ventilation
    - Volume-cycled ventilation
- Time-cycled ventilation is mainly used for sedated or paralysed patients, and is typical of mandatory modes
- Flow-cycled ventilation is mainly used for spontaneously breathing patients and is typical of spontaneous modes.
- Pressure cycling and volume cycling are largely historical, and were used in early ventilators.

In terms of peer-reviewed reading materials for this topic, probably the best reference is the 2011 article by Michael Gentile. That single reference would probably be enough to prepare the CICM primary or fellowship exam candidate for whatever the college throws at them. The next step up in sophistication would be to explore Dean Hess' article from 2005, which explores the bottomless depths of troubleshooting a spontaneous mode of ventilation (for which flow cycling is a representative phase variable)

Time-cycled ventilation

A breath is considered time cycled if the inspiratory phase ends when a predetermined time has elapsed. This is usually a feature of "mandatory" modes of ventilation. For instance, when one has set a respiratory rate of 20 and an I:E ratio of 1:2, it is understood that the inspiratory phase will last 1 second in a total 3-second breath cycle. Ergo, after 1 second the ventilator will terminate inspiratory flow and cycle to expiration.

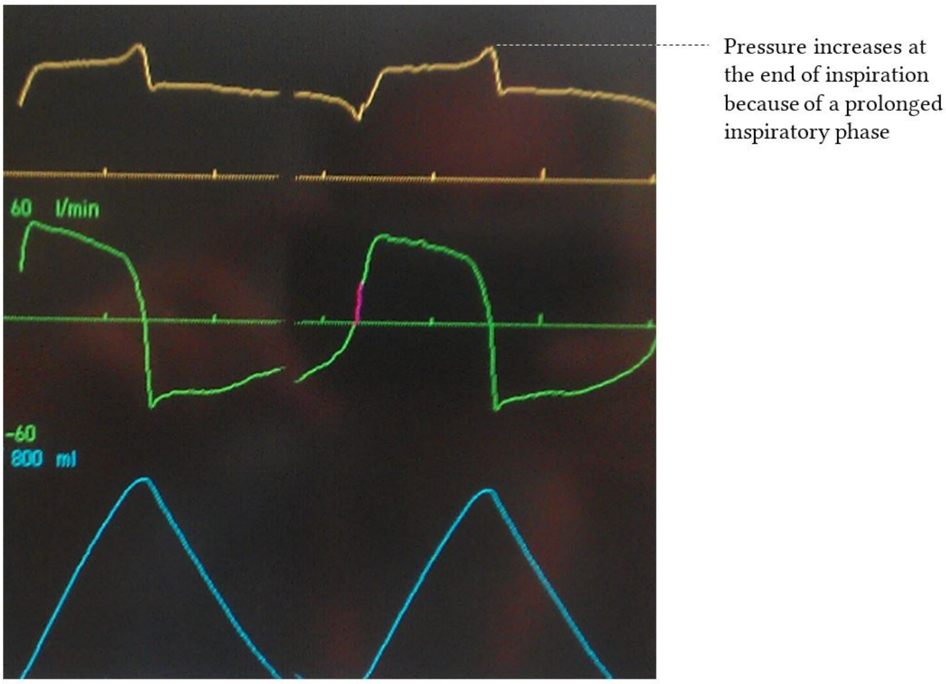


The advantages of this method of breath cycling are:

- **A careful control of minute volume can be achieved**, with obvious advantages for scenarios where tight PaCO2 control is desirable (eg. traumatic brain injury)
- **Ventilation is unaffected by changes in lung compliance or airway resistance** because the timing of the breath is unrelated to any of the respiratory system parameters, instead being controlled by a timer
- **Minute ventilation is not affected by an unreliable respiratory drive**, making this method suitable for paralysed or deeply unconscious patients.

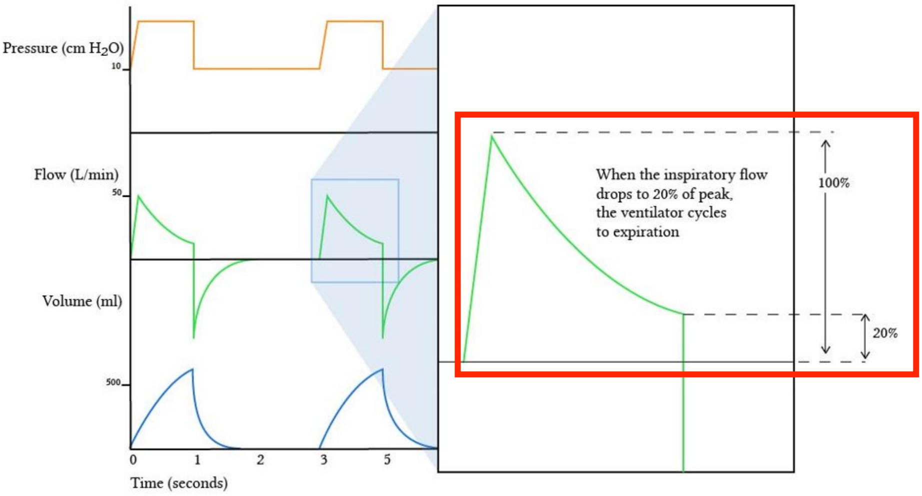
It also has disadvantages, which – if one were to list them , for example because somebody asked this in a written exam paper – would be basically the same as the disadvantages of a mandatory mode of ventilation.

- **It is unsuitable for lightly sedated and awake patients,** because such patients may become uncomfortable with a fixed and demand-independent inspiratory phase – perhaps some breaths they would like to go on for longer, whereas others they would prefer to terminate shorter.
- **It may result in patient-ventilator dyssynchrony** particularly if the patient tries to exhale before the cycle timer runs out, as discussed above. This could give rise to a phenomenon where pressure rises at the end of inspiration, either because the lung compliance has reached a point of overdistension, or (as in the example below) the spontaneously-breathing patient has decided that they want to exhale before the breath is over.

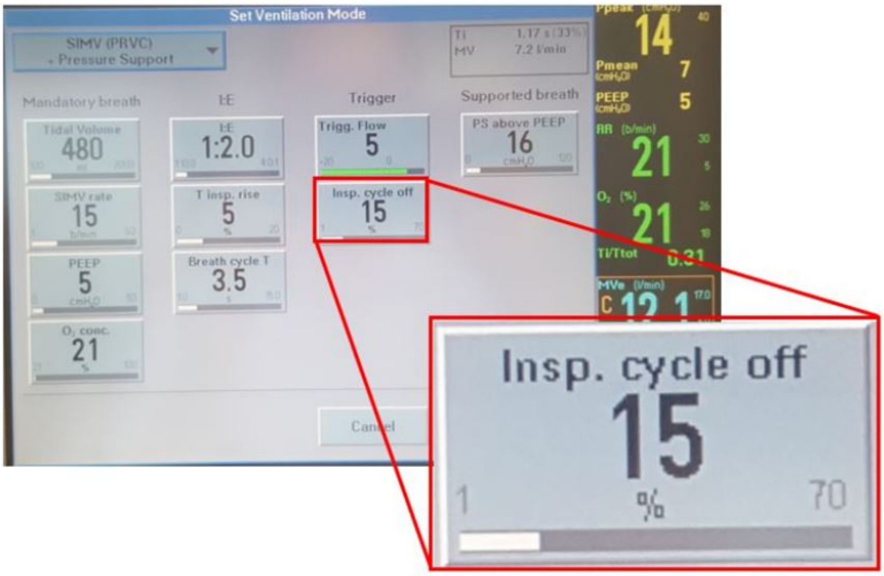


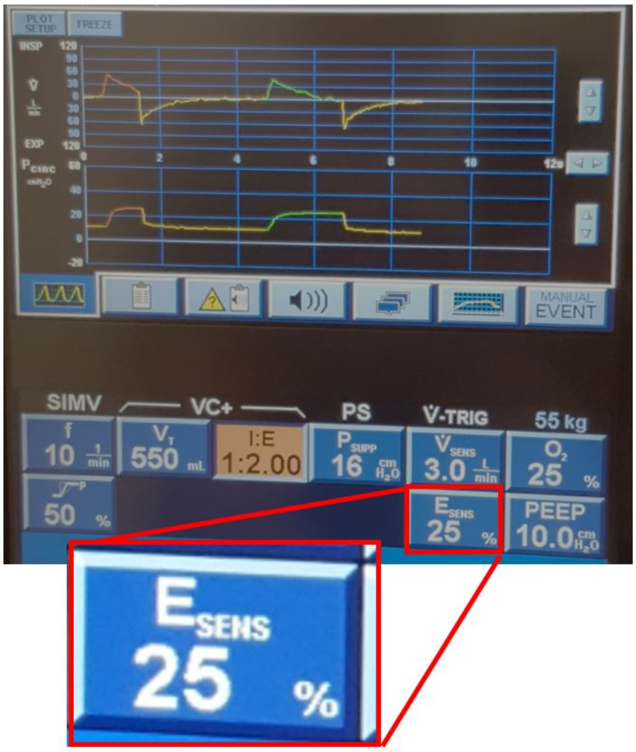
Flow-cycled ventilation

With flow-cycled ventilation, the ventilator cycles into the expiratory phase once the flow has decreased to a predetermined value during inspiration.



The flow cycling variable can be a fixed flow value in L/min or a percentage fraction of the peak flow rate achieved during inspiration. In some models it is probably something that can be pre-set at an absolute value, eg 5L/min. The Maquet SERVO-i expresses the flow cycling variable as a percentage of peak inspiratory flow and allows a range of settings (between 1% and 70%.), whereas the Puritan Bennett 840 only goes up to 45%.





A flow cycle setting of 1% would result in a breath which cycles to expiration only after the flow has essentially stopped, i.e. at a point of significant lung distension. Conversely, a flow cycle setting of 70% would terminate a breath very early in the inspiratory phase, and achieve an insufficiently low tidal volume. The default setting on the SERVO-i ventilator is 15% which corresponds to an inspiratory flow rate of 4.5L/min for a calmly breathing adult.

This has interesting implications, depending on what sort of calmly breathing adult you are ventilating. Let's take some standard setting. The patients with restrictive lung disease will have poor respiratory compliance and their flow rate will drop rather quickly; as the result their tidal volumes will be lower. In contrast, the patient with emphysematous lung disease may have a very high lung compliance and will get larger tidal volumes with the same settings on the ventilator. Exposure to pressure will be different as well: the higher inspiratory pressure will be more sustained and the waveform will be more "square" with a lower flow cycling setting. The graphics below were stolen shamelessly from the Gentile paper (2011).

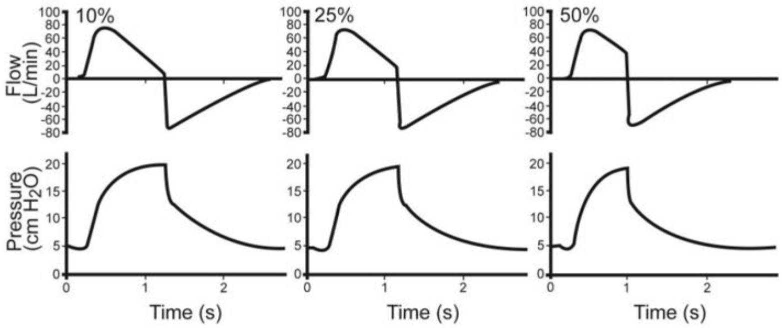


Fig. 3. Lung model waveforms with flow cycling at 10%, 25%, and 50%, with a Puritan Bennett 840 ventilator set on pressure support 15 cm H_2O and PEEP of 5 cm H_2O. The lung model settings were resistance 5 cm H_2O/L/s, compliance 0.05 L/cm H_2O. (Adapted from Reference 19.)

Gentile, Michael A. "Cycling of the mechanical ventilator breath." Respiratory care 56.1 (2011): 52-60.

This is not an advantage or a disadvantage of flow cycling; merely on observation. This phase variable is an instrument, and like any instrument it has the potential for being used in some profoundly stupid fashion. For instance, in the mindless pursuit of somebody's idea of perfect tidal volumes one might be tempted to drop this setting to zero for patients with poorly compliant lungs, thereby producing good volumes together with overdistension discomfort and increased work of breathing.

Flow-cycled ventilation has many advantages:

- **It is more comfortable** for the patient by preventing frustrated expiratory efforts; if the patient needs to terminate a breath and exhale the inspiratory flow ceases and the ventilator cycles to expiration rapidly. With conventional settings, the inspiratory time is rarely uncomfortably prolonged. This is the main advantage of this method.
- **It is limited by changes in lung compliance and airway resistance**, which could theoretically prevent inadvertent ventilator-induced lung injury (i.e. with poorly compliant lungs, the ventilator will cycle to expiration rather than continue to apply distending pressure).

There are also some disadvantages:

- **Tidal volumes may be poor** in patients with poor lung compliance, resulting in inadequate minute volume
- **Patient comfort depends on intelligent settings;** inappropriately low and inappropriately high settings could result in uncomfortably deep and prolonged inspiration or "double triggering" due to insufficient inspiratory time and tidal volume.

Pressure-cycled ventilation

During pressure-cycled ventilation, inspiration ends when a certain user-prescribed pressure value is achieved. This is old-school – to the extent that no modern ventilator pressure-cycles, and most articles about this are from the 1960s. Pressure cycling is a feature of historical ventilator models (eg. the Bird Mark 8) and has become largely obsolete in the modern era of microprocessor-controlled solenoid valves.

In honour of this rich history, instead of the conventional vector diagram, here is a drawing of a pressure-cycled ventilator waveform generated by the Bird Mark 8, from a 1965 paper by H. Herzog

Herzog: Pressure-Cycled Ventilators 753

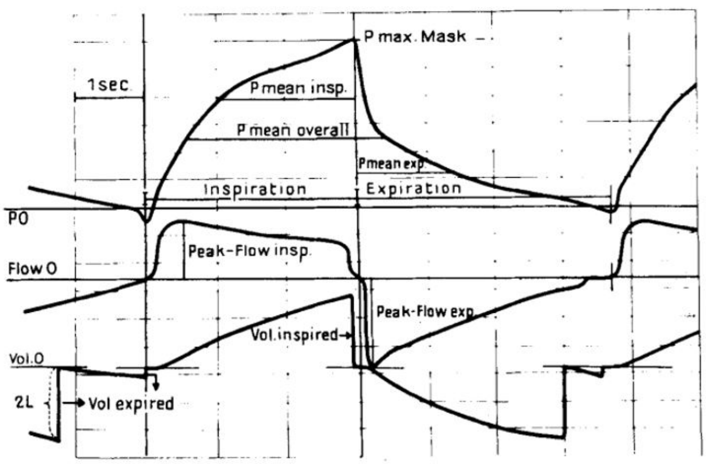


FIGURE 1. Drawing of an original curve representing one respiratory cycle, showing the mask pressure change according to an ideal type III curve (*above*); the flow rate (*middle*), and the integrated volume (inspiratory part above and expiratory part below the zero line) (*below*).

Advantages of this method are few; they include:

- **Minimal mechanical requirements.** One requires nothing more than a spring-loaded diaphragm valve to act as the pressure cycling mechanism – when the prescribed pressure is reached, the valve opens and triggers expiration.
- **Safety from pressure-related lung injury.** Because you've set a pressure as the parameter which open the expiratory valve, the circuit can never over-pressurise to damage the patient's lung (eg. if the patient decides to cough mid-inspiration, instead of blowing a pneumothorax the ventilator will just let them exhale).
- **Decelerating ramp pattern for the flow waveform,** which supposedly results in a more even distribution of gas in lung units with different time constants (more on this in the chapter on the interpretation of the flow waveform, and on the pressure and volume controlled modes of ventilation). One would probably temper this with the statement that lots of other mechanisms of cycling also co-exist a decelerating flow waveform pattern.
- **Compliance determines cycling**, which can be viewed as a patient-centred spontaneous feature. If the patient's respiratory compliance has changed, whether through pathological processes or because they are trying to exhale, the pressure in the circuit at the end of inspiration will increase, which will open the expiratory valve. In short, expiratory effort triggers expiration, which is very spontaneous-sounding.

Which is a nice segue to the disadvantages:

- **Volume is determined by compliance:** if the patient has poor lung compliance, the volume will be low. This is common to all mechanical ventilation models where the pressure is a fixed variable in some way.
- **Respiratory rate may fluctuate**. Because airway pressure is determined by airway resistance and lung compliance, this method of cycling can give rise to variable tidal volumes and respiratory rates, particularly in patients who have wildly fluctuating respiratory physiology (eg. asthmatics).
- **It may increase the respiratory effort.** The task of exhaling forcefully against the pressure valve in order to trigger expiration is not likely to be well tolerated, and the whole process may give rise to an increased work of breathing.
- **Pressure cannot be a control variable.** One is basically committed to a ramp-like pressure waveform, which will decrease the mean airway pressure. It would not be possible to have a pressure-cycled mode with a square pressure waveform by using pressure as a control variable or a limit (target) variable, because it would never reach the cycling threshold.

Volume-cycled ventilation

The inspiratory phase of a volume-cycled breath ends when the specified volume has been delivered. The volume will therefore remain constant, even though the characteristics of the patient's respiratory system may change. As a result, the pressure in the system and the flow will vary depending on lung compliance and airway resistance. As with pressure cycling, this method of terminating a breath is largely historical. Older models of piston ventilators were volume cycled, i.e. the ventilator would cycle to expiration when the piston delivered a pre-determined volume. Most modern ventilators do not make use of this method.

Its major disadvantages are related to safety. The risk of pneumothorax was probably the biggest thing. This cycling mode has the propensity to generate high peak airway pressures when the lung compliance deteriorates. The problem was at its worst in the bad old days. Steier et al (1974) reported on a scenario where the ICU started using volume-cycled ventilators and developed a shocking 43% increase in the rate of pneumothorax, where specifically the patients ventilated with on volume-cycled modes were *28 times* more likely to develop complications.

Previous chapter: Limit (target) variables in mechanical ventilation

Next chapter: Selecting and adjusting PEEP

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Control variables: volume and pressure

Control variables in mechanical ventilation are independent parameters which are targeted by the ventilator mechanism, and upon which all other variables are dependent. Along with phase variables, these are among the most important characteristics of a mode of ventilation. In terms of exam relevance, CICM have never asked about this topic directly, perhaps because it is so foundational that all trainees are assumed to have an intuitive grasp of it.

In short:

- The control variable is the parameter which the variable which the ventilator uses as the feedback signal for controlling inspiration
- Pressure flow and volume are all possible control variables, but conventionally only pressure and volume are used.
- The ventilator can only control one variable at a time, but the control variable can change during mechanical ventilation, and even in the course of a single breath.
- Using pressure as the control variable limits the risk of barotrauma and can improve oxygenation (with a square pressure waveform)
- Using volume as the control variable Promotes a stable minute volume, and therefore a stable $PaCO_2$ level
- In either case, the control variable is chosen on the basis of the most clinically important parameter (oxygenation or ventilation)

Definition of the "control" variable

The word "control" here implies that the person setting the ventilator is most interested in that specific variable, and wants to control that variable exclusively (i.e. without letting the respiratory system make any decisions about it). *Pilbeams' Mechanical Ventilation* defines the control variable as "the primary variable the ventilator adjusts to achieve inspiration". A better way to define it practically is probably the way it is done by Garnero et al (2013):

> *"the variable which the ventilator uses as feedback signal for controlling inspiration"*

This definition has a certain pragmatic appeal. Consider that the ventilator is usually a flow and pressure regulator. The flow and pressure are measured continuously, at millisecond increments. The valves which control this pressure are constantly receiving feedback from the sensors, and in this fashion, the desired variable (pressure or volume) can be achieved and maintained as prescribed.

From a scientific and theoretical standpoint, the most accurate definition is probably the one offered in the Chatburn chapter from Tobins (3rd ed), which defines the control variable in terms of the equation of motion:

$$P_{vent} + P_{muscles} = elastance \times volume + resistance \times flow$$

Thus, if one of these variables is pre-determined, it becomes the independent variable in the equation, making all the other variables dependent upon it. Volume and pressure are the only variables which can be pre-determined in this way. Flow cannot be a control variable because flow is volume over time, and thus when volume is controlled, flow is controlled indirectly.

Extending the metaphor for control brings with it the question, why would one choose one specific control variable over another? Under which circumstances would one want to ventilate the patient with a pressure controlled mode, instead of volume, and vice versa? This is actually a fundamentally important question which often determines the choice of ventilator mode. Modes of ventilation are usually defined primarily by how they handle the control variable.

Advantages and disadvantages of pressure and volume control strategies

In brief, the main differences between these control variables are seen in the following domains:

- Reliability of minute volume achieved
- Mean airway pressure achieved
- Recruitment achieved
- Patient comfort and synchrony

It is important to make sure one is clear about the separate discussion of pressure as the control variable from the discussion of the pressure control move of ventilation (usually abbreviated as PCV) which also has several other characteristics. PCV tends to be created with a square pressure waveform in mind, which has several advantages. For example, the mean airway pressure is higher, the inspiratory flow rate is higher, and the risk of barotrauma due to inadvertent overdistension is also higher. However, it also can be challenging to achieve the desired minute volume, particularly if the respiratory system characteristics change erratically. In any case, all of these are actually advantages and disadvantages of PCV, not of the pressure control variable. As such, advantages and disadvantages of each mode of ventilation will be discussed elsewhere. Here it will suffice to say that controlling the pressure variable is beneficial because it maintains a stable pressure in the face of fluctuating respiratory performance, which prevents lung injury from excess pressure. Similarly, using volume as the control variable gives one a more stable minute volume, which keeps the $PaCO_2$ at the desired level, but which may play havoc with respiratory system pressures.

Previous chapter: Phase variables: triggering, limits, cycling and PEEP

Next chapter: Triggering of a mechanically supported breath

References

Chatburn, Robert L. "Classification of mechanical ventilators and modes of ventilation." Principles and practice of mechanical ventilation. 3rd ed. New York: McGraw-Hill (2012).

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Phase variables: triggering, limits, cycling and PEEP

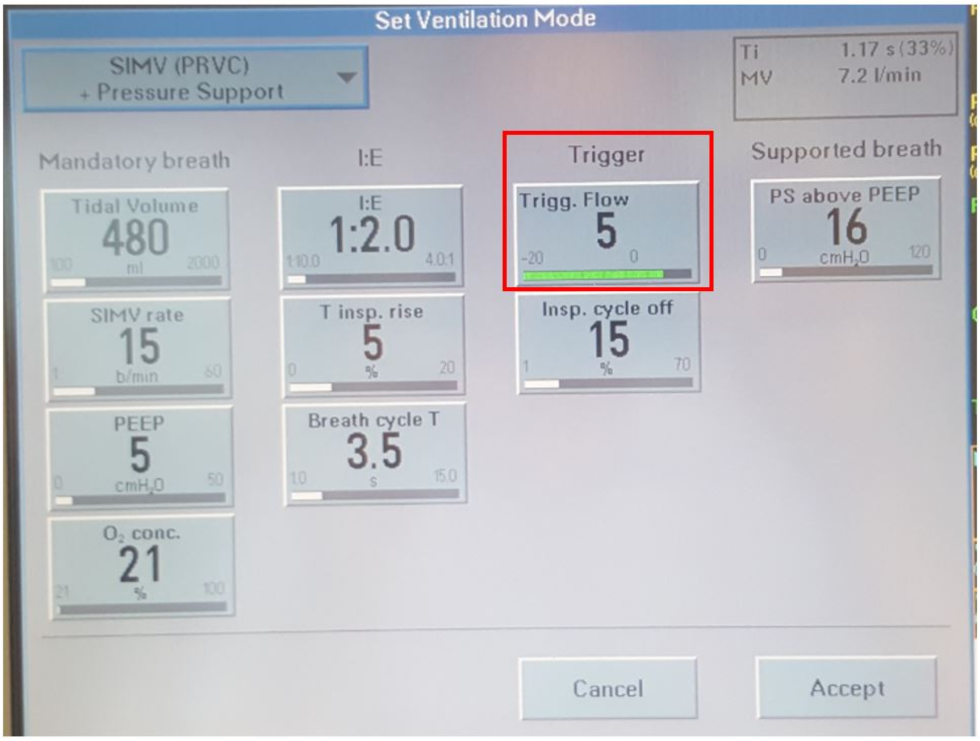
Phase variables in mechanical ventilation are parameters which control the phases of a mechanical breath. Triggering controls the initiation of inspiration, cycling controls the initiation of expiration, and limits are set to maintain control over the three main parameters while inspiration is taking place. PEEP is also viewed as a phase variable, for lack of a better classification, and is the variable which reigns over the otherwise very boring expiratory phase. CICM have shown some interest in these matters over the years, and the Fellowship Exam papers have occasionally included questions about triggering and cycling (for example Question 11.1 from the second paper of 2017 and in Question 18 from the second paper of 2015). However, each variable is treated with sufficient attention in a dedicated chapter of its own. This chapter is something of an overview to lend some structure to this topic. Depending on time pressure, an exam candidate may find it easier to skim through the point-form summary.

In short:

- The trigger variable determines how and when the ventilator ends exhalation and commenced inhalation.
  - The trigger setting can be time, flow, pressure or volume
  - This variable determines whether a mode of ventilation is "mandatory" (machine triggered) or "spontaneous" (patient-triggered)
- The limit variable restrict the maximum value which the parameters can achieve during inspiration.
  - Reaching the limit variable during inspiration does not abort the inspiratory phase
  - This is distinct from the alarm variables, which are activated whenever their values are breached, and which abort inspiratory flow or open the expiratory valve
  - Several limit variables can be selected simultaneously.
- The cycling variable is measured during the inspiratory phase; it is the mechanism used to end inspiration and commence expiration
  - Time and flow are the most common settings for this varible, though volume-cycled and pressure-cycled ventilation is also possible
  - Only one cycling variable can be set at any given time
- The PEEP variable is the pressure setting which determines the pressure maintained by the circuit bias flow during expiration.

Trigger variable

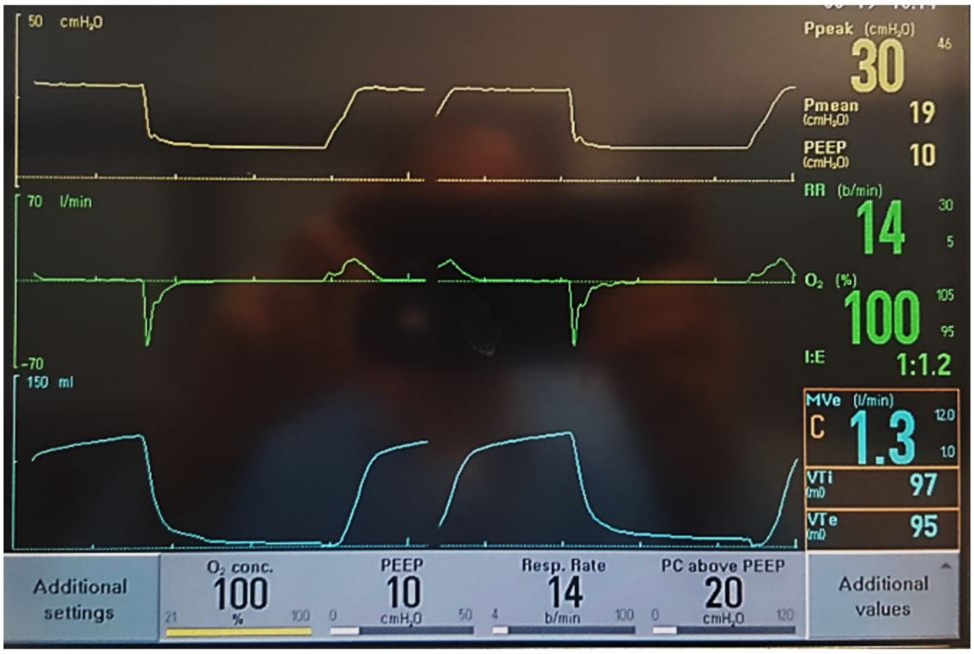
The trigger variable determines when a breath is delivered. This variable distinguishes "mandatory" from "spontaneous" modes of ventilation; where "mandatory" refers to the fact that the ventilator decides when you take a breath, usually according to a timer. In the dark ages of critical care, this was the only sort of ventilation available to the slightly comatose patient.



Limit, or "target" variables

The limit variable is the unimaginative name given to the limits of the mechanical breath. One usually has only minimal control over these, as they are integral parts of the selected mode of ventilation. In short, a limit variable is the maximum value a variable can attain during inspiration; and this is something distinct from the alarm settings, which can also be viewed as "limits". Alarm settings tend to terminate the inspiration by opening the expiratory valve, whereas the main characteristic of the limit variable is that the inspiratory phase continues even after the limit has been reached.

Specifically, the term "limit variable" refers to the inspiratory phase: during inspiration, the ventilator won't let that parameter (flow, volume, pressure, etc) get beyond its limit value. That is not to say that those parameters are completely ignored during the other phases: there are still limits in place but they fall into the territory of safety parameters. For example, let us take this pressure control mode of ventilation as depicted below.



The PEEP is set as 10 cm H_2O, and the pressure control variable is 20 cm H_2O. Thus, the pressure limit during inspiration is 30 cm H_2O. The pressure will get no higher than this during inspiration. In addition to this limit, there is also as safety limit which is set as one of the ventilator alarms, which is (conventionally) set as 40 cm H_2O. This is not unique to the inspiratory phase- breaching this limit during any phase of ventilation will abort the delivery of flow to prevent injury. This is clearly a confusing distinction: both values can be referred to as "limits". Because of this, the ISO has moved away from referring to this phase variable as "limit" – they would prefer us to call it a "target" variable, whereas the term "limit" should be restricted to the abovementioned safety alarms.
Limit variables can include flow, volume and pressure. Time is obviously not a limit variable because it would defy logic. All limit variables can be active simultaneously, i.e. one can have a mechanical breath which is pressure-limited flow-limited and volume-limited.

Cycling variable

The cycling variable determines how and when the ventilator transitions from inspiration to expiration. The ventilator measures this variable during the inspiration phase. The cycling variable is distinct from the limit variable, in that it ends the inspiratory phase when it is reached. When the set parameter for this variable is achieved, the ventilator opens the expiratory valve, and expiration may begin. Typical methods of ventilator breath cycling include:

- Time-cycled ventilation (mandatory modes)
- Flow-cycled ventilation (spontaneous modes, eg. pressure support)
- Volume-cycled ventilation
- Pressure-cycled ventilation

Unlike the limit variable (of which several can be active simultaneously), there can only be one cycling variable. In general, time and flow are the most popular settings. Volume and pressure cycled ventilation is something of a historical footnote.

PEEP – the expiratory phase variable

The expiratory phase in modern ventilators is generally a fairly passive and unexciting time, where the only thing happening is a slow bias gas flow seeping out of the circuit via the expiratory solenoid valve. This phase generally only has one variable applied to it, which is PEEP. In the absence of any pressure, one should probably refer to it as ZEEP (zero end-expiratory pressure). Historically, during the Dark Age of critical care many physicians held heretical beliefs regarding the need to actively assist patients with expiration, and so NEEP (negative end-expiratory pressure) was used as a means of promoting expiratory airflow. A representative example from that era is this article by Hill et al (1965), instructing people on the correct use of a -4 cm H2O NEEP for post-operative cardiac surgery patients via the Engstrom respirator. Around the 1960s-1970s people finally realised that this practice was insane, and ventilator manufacturers stopped incorporating sub-ambient pressure into their equipment.

Control variables, or "target" variables

The control variables are the independent limit variables in a mode of ventilation. In essence, the control variable is the constant to which all other variables are enslaved. There are only two possible control variables: pressure and flow. These are discussed in another chapter because they seemed like something fundamentally important and therefore deserving of a separate page.

Previous chapter: Phases of the mechanical breath

Next chapter: Control variables: volume and pressure

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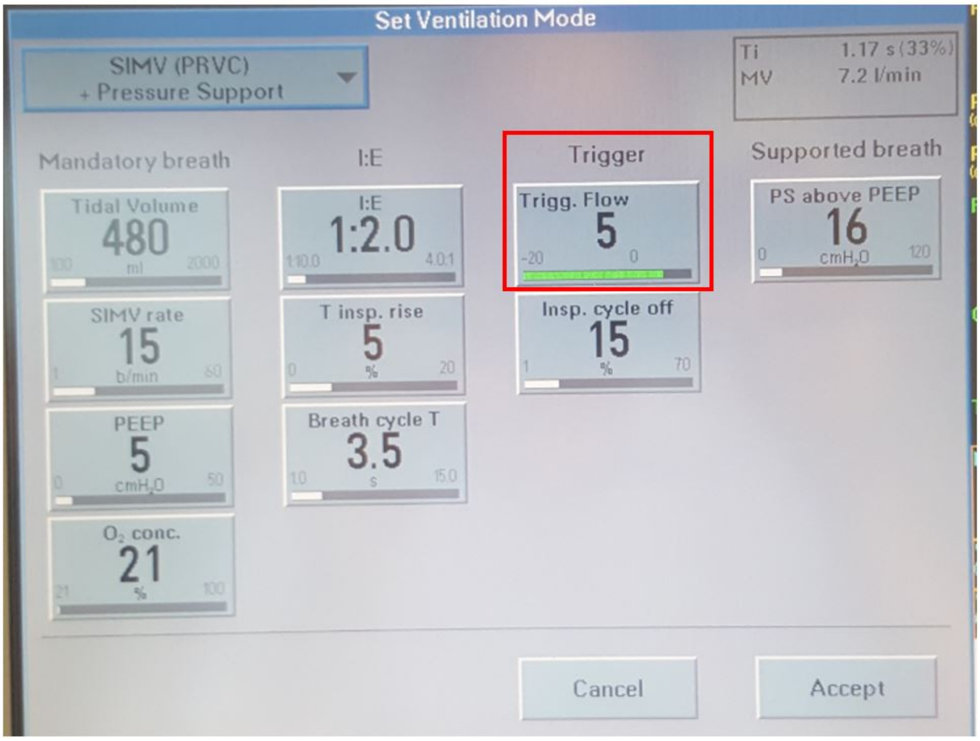

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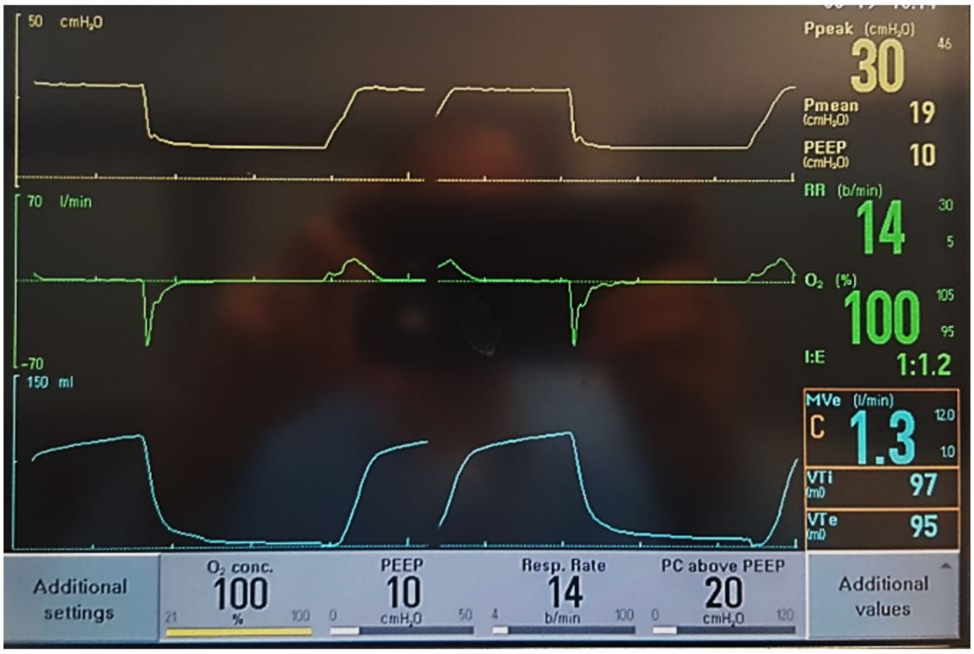

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Next chapter: Control variables: volume and pressure

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