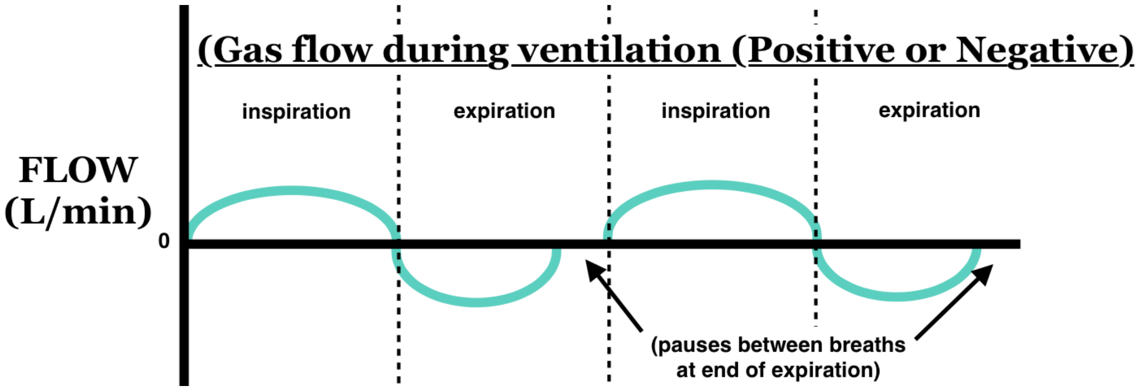
Let's start with FLOW

Imagine a healthy person breathing normally. Now give them a simple tube to breath through & place a transducer in that tube (a pinwheel of sorts, which spins in the breeze as the person inhales & exhales.) The following graph would represent what we see as we monitor FLOW:



As the person inhales gas moves towards the lungs (+ve deflection), but at the end of the inhalation the flow slows, briefly hits zero then reverses as gas moves out of the lungs (-ve deflection). Also note at the end exhalation there is a brief pause with zero flow that occurs before the next breath.

Conceptually, this graph applies no matter if the patient is breathing on their own, or mechanically ventilated. In either case when observing FLOW, it will vary from positive during inhalation (or *inspiration* with a ventilator breath) to negative during exhalation (*expiration* with the vent.)

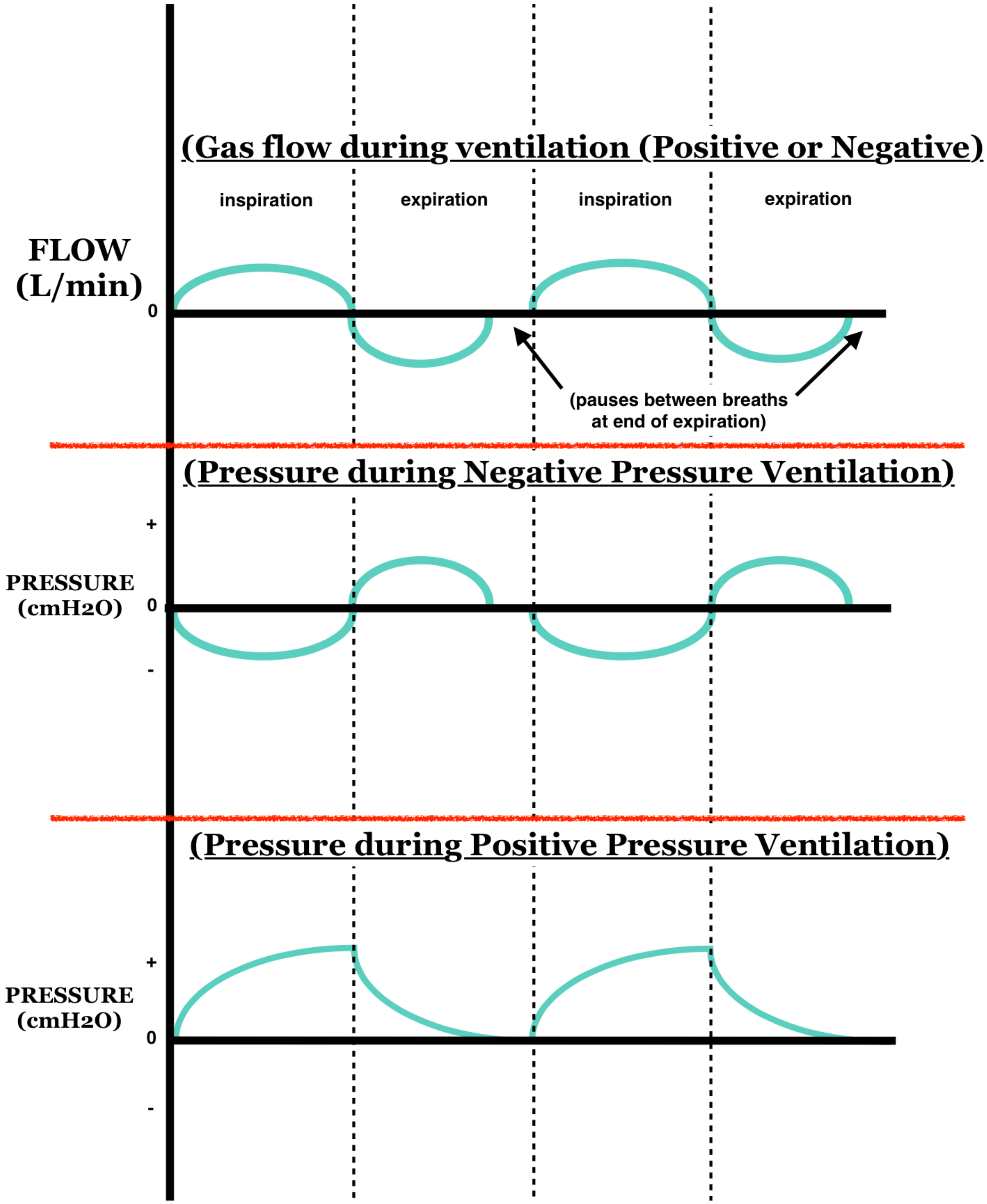
Now let's look at PRESSURE

Natural breathing is Negative Pressure Ventilation (NPV) or if we want to get technical: Intermittent Negative Pressure Ventilation (INPV). When we breathe, our diaphragm & chest wall create a vacuum inside the chest and thus air is sucked in. Then our muscles relax and the natural recoil of our chest wall ± gravity to some extent, cause the thorax to compress and we "blow" air out.

Application of pressure is fundamentally different in <u>mechanical ventilation</u>, which uses Positive Pressure Ventilation (PPV) - it essentially blows gas into the lungs during inspiration. Then at the start of expiration that positive pressure drops precipitously and the lack of positive pressure permits gas to come out under the natural recoil of the chest wall. Thus <u>Inspiration</u> is fundamentally different with Mechanical Ventilation (PPV) as compared to natural (NPV) breathing, but <u>expiration</u> is the same process.

With our sample person above, if we add a PRESSURE transducer into our circuit we are going to see two very different PRESSURE graphs depending on whether the patient is breathing spontaneously (NPV) or whether they are being mechanically ventilated (PPV).

Note, for ease of visual reference, the top graph (Flow) remains as the top graph. NPV the second, and PPV the third.



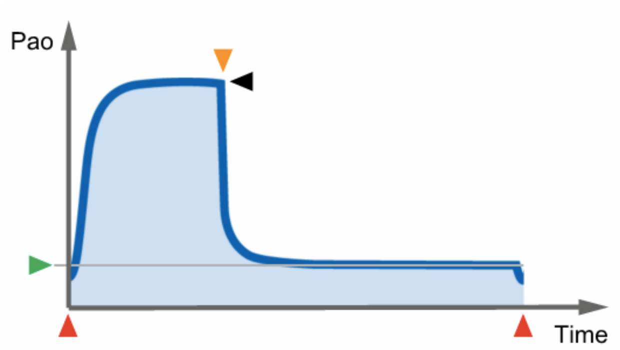
In NPV, during **inspiration** the PRESSURE drops and gas FLOW is sucked into the lungs. At the start of **expiration**, the PRESSURE reverses (becomes positive from chest wall recoil) and FLOW reverses as well.

In PPV, during **inspiration** the PRESSURE rises and gas FLOW is blown into the lungs. At the start of **expiration**, the PRESSURE decreases to ambient (and positive pressure from chest wall recoil) causes the FLOW to reverse.

Memorizing the graphs above is not necessary, however in PPV, understanding how artificially generated intermittent circuit pressure creates a pressure-differential (between the external circuit pressure & intrathoracic pressure) is important. Specifically, in order to generate inspiration / expiration cycles a ventilator must be set with several key variables.

Conceptual Key Variables in Mechanical Ventilation

Note: "Pao" in the graph refers to "positive airway opening pressure" — don't get hung up in the terminology; think of the Y-axis as pressure in the circuit & larger airways.



The graph above highlights what specific parameters must be defined for a ventilator to function. They are:

1. when to start of inspiration (trigger point)
2. when to start of expiration (cycle point)
3. **size of breath** (black arrow)
4. Control Type - i.e. how gas is delivered during inspiration, i.e. a set volume then stop vs. a set constant pressure throughout — depicted by the shape of the waveform
5. Baseline Pressure

In actual fact you may not directly set every one of these variables because they may be set automatically or as a result of other settings. Nevertheless, in order for the ventilator to run it must be programmed one way or another with each of these conceptual values. Let's step through and review each key concept.

Timing (Conceptual variables #1 & #2)

Key concepts & terms:

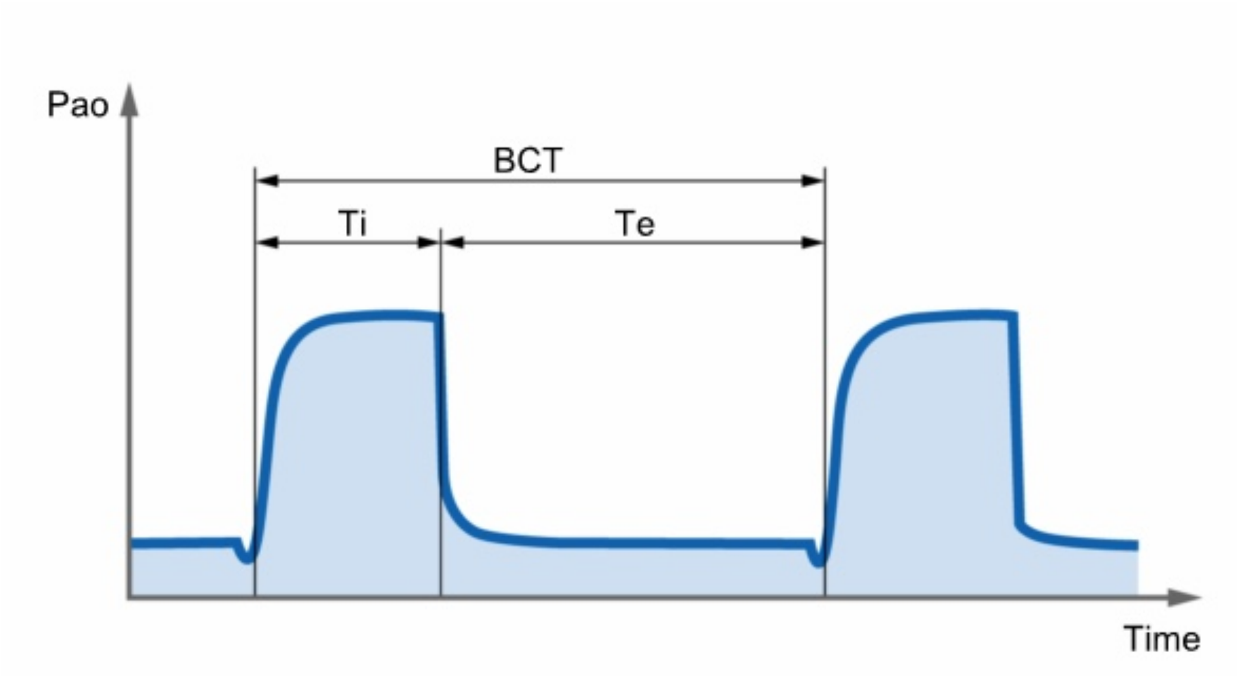
- **BCT** (breath cycle time) - is one full breath (i.e. inspiration & expiration) cycle. By definition a breath cycle always starts with inspiration. BCT is important as a concept but generally when using the ventilator you don't deal in "BCT", rather you simply set the Respiratory Rate (RR). Since mechanical breaths are generally constant in timing from one to the next, BCT & RR have an inverse relationship. For example as you increase the RR (say from 10 breaths/min to 15 breaths/minute), the BCT decreases from 6 seconds to 4 seconds[1] which should be fairly intuitive math.
- *Trigger Point & Cycle Point* - These are 2 other ventilator terms which are useful to understand. The Trigger Point is the exact instant at which a ventilator initiates a new breath

[1] Technically: BCT(sec) = 60(sec/min) ÷ Respiratory Rate (breath/min)

cycle and thus inspiration. The Cycle Point is the exact instant the ventilator initiates expiration.

- **Ti** - (That's capital T, subscript i), stands for *Time of Inspiration*, and refers to the DURATION of inspiration (in seconds). Thus Ti is the first of two parts of the BCT and starts at a Trigger Point and ends at the Cycle Point.
- **Te** - stands for Time of Expiration and is also a DURATION (in seconds.) It starts at the Cycle Point and ends at the next breath's Trigger Point.

This graph demonstrates how BCT is divided into Ti & Te. Notice the dramatic change in pressure which occurs at the Trigger Point and Cycle Point.



One final timing concept we must take away, is the concept of the **I:E Ratio**. "I:E" is just a different way to express Ti & Te. In the graph above, let's say the RR is 10 and the Ti is 2 seconds. With those variables we can calculate that the BCT is 6 seconds and thus Te is 4 seconds. (Ti + Te = BCT and BCT x RR = 60). In this example the I:E Ratio is 1:2 (Ti : Te).

Generally a ventilator will not give you a choice, its timing is set via only one method (i.e. set the RR + Ti manually which means Te & I:E are automatically calculated, vs set the RR + I:E ratio manually which means the Ti & Te are automatically calculated.) Depending on which system your vent uses, there are specific consequences to keep in mind. We'll discuss this in more detail later.

Triggering

At this point, we'll introduce the concept of triggering a breath. A ventilator can be programmed to trigger a breath in three ways:

1. Time - time triggering is <u>automatic</u> and is simply based on the internal timing of the ventilator. For example at a set respiration rate (RR) of 10, a breath will be triggered every six seconds.

2. Pressure - pressure triggering is a patient triggered breath which occurs when a patient makes a spontaneous breath effort large enough to induce a pressure change greater than the ventilator's pressure-trigger sensitivity threshold. (e.g. As a patient inhales to get a breath they induce a negative pressure in their lungs and throughout the circuit. Thus the ventilator will note a slight pressure drop and if that drop exceeds the value set as *pressure-trigger sensitivity*, a breath will be triggered. For example if the machine's sensitivity is set to (-)2 cmH_2O , then any drop in pressure detected in excess of 2 cmH_2O will trigger the next breath.
3. Flow - flow triggering is a patient triggered breath which occurs when an intubated patient makes a spontaneous breath effort significant enough to induce a flow change greater than the ventilator's flow-trigger limit. For example if the machine trigger limit is set to 2 L/min then any pressure variation equivalent to a 2L/min flow or greater, detected would trigger a breath.

Note:

- You can see 2 patient-triggered breaths in the pressure graph above. Note the slight drop (u-deflection) in the pressure baseline immediately before the start of inspiration. It is impossible to tell just from the graph whether these are Pressure or Flow triggered but they are definitely patient triggered. (A time triggered tracing in comparison would simply display a constant pressure baseline immediately before the trigger point.)
- all else being equal, flow triggering is generally most comfortable for a patient wishing to trigger an additional breath.
- Patient-Triggered breaths are only possible during the expiratory phase of respiration. (Think about this: if you are on a ventilator, you wouldn't want an additional breath initiated during inspiration (a "double inspiration" isn't a comfortable concept.) If you needed an extra breath you would want it early in the expiratory phase. Vents ignore patient efforts during inspiration if indeed they are sensitive enough to detect them.

As to which triggers are active and how they will override each other, depends on what mode the ventilator is set to. We'll discuss modes in detail shortly. For the remainder of this conceptual review section however let's assume our vent is just using the (automatic) Time-triggering only, and any effort a patient makes will be ignored.

Pressures

At this point it is important to define and understand some important terminology surrounding various pressure levels throughout the respiratory cycle. Please refer to the graph on the next page.

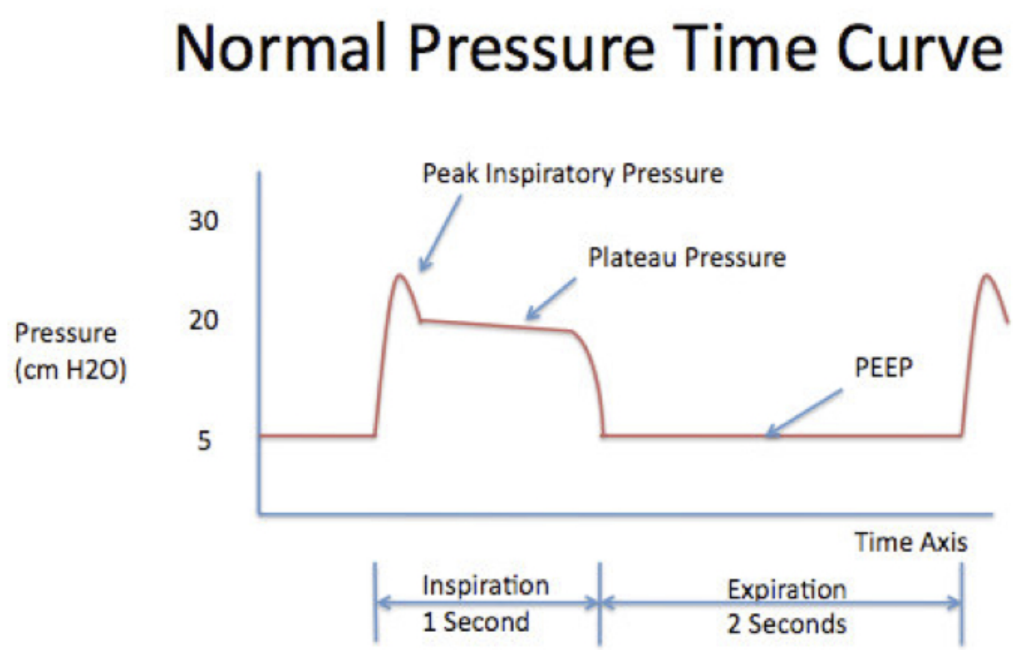
Baseline

When we naturally exhale our final resting airway pressure becomes that of the atmosphere around us. Since Mechanical Ventilation relies on the same physiologic mechanism and process for expiration (i.e. turn off the extra pressure and let the body equilibrate) the natural resting airway pressure post exhalation is also atmospheric pressure. (Let's call this atmospheric baseline zero cmH_2O)

Positive End Expiratory Pressure (PEEP)

PEEP is an augmentation of baseline pressure. It has important physiologic consequences and generally protects the lungs and the oxygenation / ventilation process. (We'll discuss those aspects in detail elsewhere.) PEEP is generally added (**set**) at a level just a few cmH_2O greater than zero, and results in a translation of the baseline pressure up from 0 to the PEEP level.

Note: PEEP is visible in the preceding Timing Graph (the baseline is above the X-axis which we can assume is zero). It is also visible in the following graph (PEEP = 5).



Inspiratory Pressure (Pinsp) — not pictured in the graph above.
Is the pressure applied during inspiration to generate the breath. Do not confuse Pinsp with Peak pressure (aka PIP). Depending on the mode, sometimes we **set** Pinsp directly. In other modes Pinsp is titrated to achieve another physiologic target we have set.

Peak Inspiratory Pressure (PIP or Ppeak)
Is something the ventilator **measures**. PIP = Pinsp + PEEP. One might assume it corresponds to the maximum level of pressure experienced by the lung tissue, but counterintuitively it is not! Standby for an explanation…

Plateau Pressure (Pplat)
Is something the ventilator can **measure** but may require the operator (i.e. you) to manually hold a button pausing gas flow during inspiration such that the machine can obtain a reading.

It is Pplat which corresponds to the maximum level of pressure experienced by the lung tissue, and it is Pplat which should be ideally kept below a safe physiologic threshold (e.g. ≤ 30 cmH_2O)

What's the difference between PIP & Pplat? Literally, it is the elasticity of the ventilator tubing and/or leaks in the circuit. Either of these phenomenon will absorb some of the "shock" of the full PIP and thus the pressure the lung tissue is exposed to will be less (Pplat.)

That said, PIP is useful, it will never be < Pplat and thus if your PIP is at a safe level you can rest assured that your Pplat (and the pressure the lung tissue is subjected to) is also safe.

Pressure Limit (Plimit or Pmax)
Pressure limit is a threshold for an **alarm / safety setting** The ventilator will not exceed this limit, and thus if you set Pmax at say 30 cmH_2O you can be assured that the lung tissue will not be exposed to greater pressures.

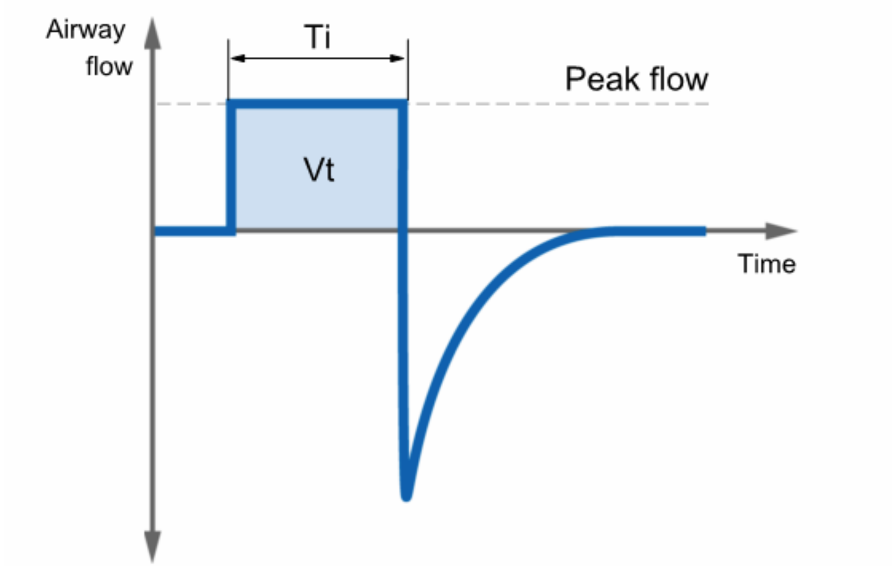
Occasionally (e.g. in sick lungs) you may require pressures greater than Pmax, in which case you will need to adjust the limit. Pmax is a safety setting.

Size of Breath (Key Concept #3)
Tidal Volume is the volume of gas delivered during a single respiratory cycle. TV is not only the volume of gas which moves into the lungs, but (under homeostatic conditions) it is also the exact same volume of gas which moves out of the lungs with each cycle.

Depending on the Control Type chosen (next segment), TV is either a value you can directly set, or it becomes a dependent variable resultant on other contributing values.

Control Type (VCV vs PCV) Key Concept #4
At any given time a ventilator can control inspiration via pressure or volume, but not both.

VCV (Volume Control Ventilation):
A better name for VCV would be *Flow-Controlled Ventilation*. During this mode, the ventilator is regulating the gas FLOW rate, delivering a certain flow rate constantly over the Ti. VCV is governed by three variables: **Tidal Volume** (set), **Timing** (set) {either Ti or I:E} and the **flow rate** (calculated automatically).



Note in the graph above the Y-axis is flow. VCV is delivering a constant flow (and circuit/airway pressure is a dependent variable.)

Advantage of VCV:

- stable tidal volumes & minute ventilation — which means it is much easier to precisely control the patient's physiology by way of ventilation / acid base management etc.

Disadvantages of VCV:

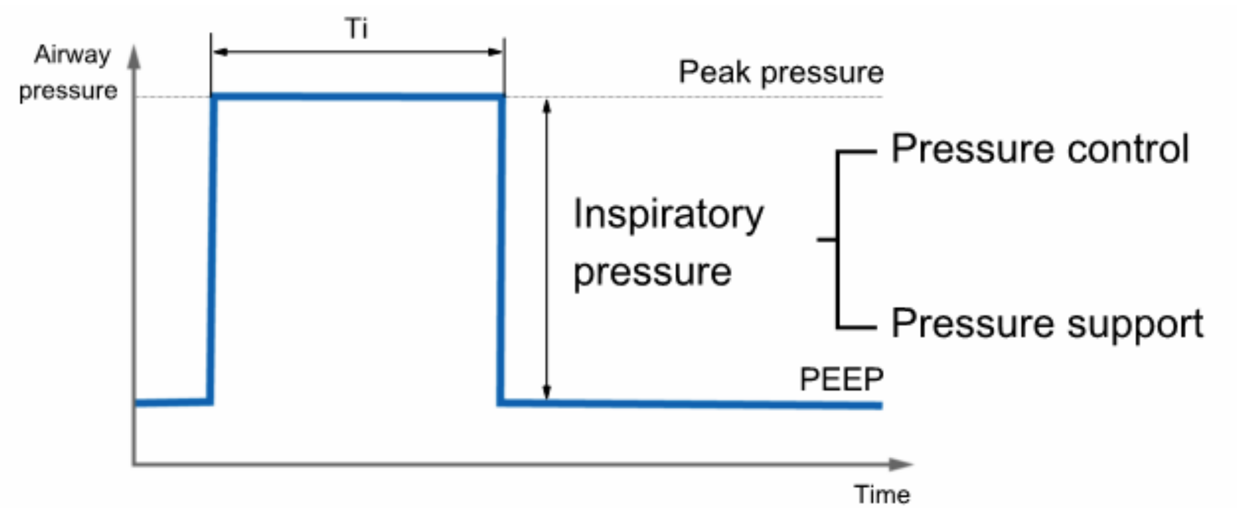
1. asynchrony in active patient
    - VCV is less comfortable for semi-conscious / lightly sedated patients
2. invisible volume loss & no leak compensation
    - ventilator circuits have some elasticity and thus during inspiration, part of the tidal volume (TV) goes to stretching out the circuit and not the lungs (recall the concept of Pinsp vs Pplat). Also small leaks are common in the circuit, around the ETT balloon etc. The consequence: TV(set) is a larger volume than TV(delivered). Fancier ventilators even measure and report these separate volumes from breath to breath.
3. variable peak pressure
    - the machine's simple mission is to deliver TV(set) into the circuit and it does that by dialling up the pressure to whatever is needed to achieve the target flow rate. As circumstances change (resistance increases or decreases due to e.g. patient repositioning, weight on patient's chest - like a loving family member hugging them, increase or loss of muscle tone as sedation and paralysis vary, mucous plugs in the ETT etc) the pressure VCV requires to achieve TV(set) varies. The ventilator will in fact vary the pressure with every breath based on the last breath and thus PIP is seen to fluctuate by 1-2 cmH_2O even in stable patients. u

Commentary / rebuttal: Okay so several pedantic disadvantages BUT…

1. In the rural ER if we're ventilating someone it's because they're sick, perhaps critically ill. We generally don't intubate and ventilate patients who are "active", that is, well enough to support their own oxygenation / ventilation. Our patients will generally be heavily sedated either due to their own decreased cerebral perfusion etc or because we know they are going to be safer when heavily sedated & paralyzed for purpose of resting the patient & transport.
2. Gas volume loss is real and loss due to elasticity & circuit leaks are inevitable. However, as rural emergency physicians and not theoretical mathematicians, does it matter? Our goal isn't to ventilate a patient with exactly 7.00 mL/kg tidal volume, but rather to ventilate them with a volume that is safe and that holds their $PaCO_2$ at an acceptable level. As such it doesn't matter so much what TV(delivered) is or how much it varies from TV(set), as long as significant volumes of gas is actually moving in and out of the lungs. — The trends as seen in $ETCO_2$ & $PaCO_2$ monitoring, not the absolutely precise TV delivered is most important.
3. Variable peak pressures are the necessary trade off with VCV. However provided the peak pressures stay in a nice conservative box (e.g. < 30 cmH_2O ideally), again it doesn't much matter. Where VCV truly becomes a disadvantage is when Peak or Plateau Pressures (due to anatomic or physiologic issues) are climbing into the red-zone. In patients like this, PCV may offer some advantages. We'll discuss Peak Pressures soon.

<u>PCV (Pressure control ventilation)</u>
PCV delivers a constant pressure during Ti, but the tidal volume now becomes dependent and thus variable from breath to breath. Thus the trade off is fixed volume (VCV) vs a fixed pressure (PCV).

PCV is governed by three variables: **Inspiratory Pressure** (aka P_{insp}, Pressure Control, Pressure Support etc; name varies depending on the context and manufacturer), **Timing** (either Ti or I:E), and the flow rate (calculated automatically).



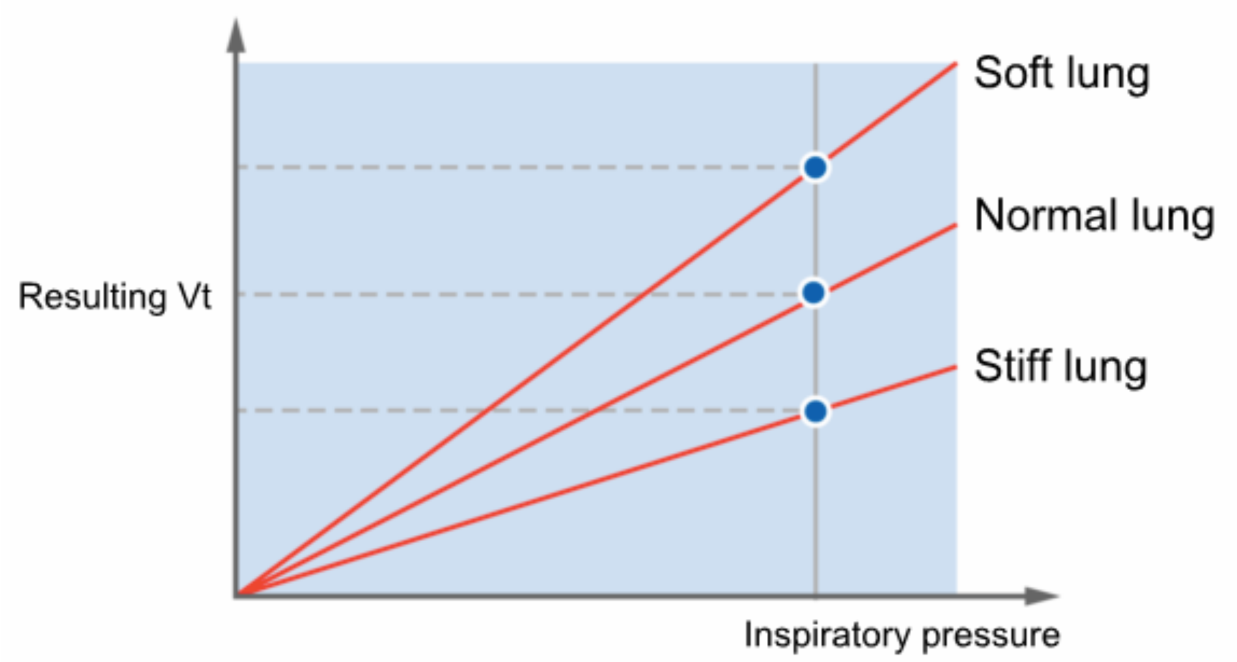
<u>Advantages of PCV</u> (according to a manufacturer)
1. Superior ventilator-patient synchrony
2. Leak compensation
    - PCV is targeting a specific peak airway pressure, and thus it just titrates flow to accomplish that pressure. Any flow lost via leak is somewhat irrelevant (provided the leak is small/moderate in size), since the flow will be increased to achieve target pressure.

Note: Theoretically this 2nd "advantage" could actually be a disadvantage in a situation that does not have unlimited volumes of medical gas (e.g. inside an ambulance.) Indeed if there was a tremendous leak and the excessive flow rate wasn't noticed, one might end up with their gas supply exhausted.

<u>Disadvantages of PCV</u>
Recall a disadvantage of VCV was variable Peak Pressure. In PCV the primary disadvantage is variable tidal volumes.

As circumstances change (resistance increases or decreases due to e.g. patient repositioning, weight on patient's chest - like a loving family member hugging them, increase or loss of muscle tone as sedation and paralysis vary, mucous plugs in the ETT etc) **the volume PCV achieves with a constant P_{insp} varies.**

This graph pictorially represents the major drawback to PCV:



Toe-may-toe / Toe-mah-toe? I think not!

Remember when attempting to stabilize a critically ill patient, it is extremely helpful to have direct control over certain patient parameters such as $PaCO_2$. $PaCO_2$ is proportional to Minute Volume = RR (fixed) x TV. The fixed TV is VCV is a nice luxury that cannot be relied upon in PCV.

Furthermore, PCV tends to be much more finicky with patient changes and ventilator alarms. It does tend to require greater attention from the operator (i.e. you the solitary rural ER physician.)

All else being equal, for critical rural patients my go to choice of "control" is VCV. The only major exception to choosing VCV is if the Peak Airway pressures are in the neighbourhood of 30+ cmH_2O. In this case (and as an anesthetist having significant ventilator experience and comfort) I will likely switch the patient to a PCV knowing that the patient will require greater surveillance. My advice: start with VCV and if you are contemplating PCV phone an expert to discuss.

Adaptive Control

Finally, it is worth mentioning a 3rd type of control (a modern "smart" method) which unfortunately is not commonly seen in the crop of ventilators currently in use in rural Canada.

Nevertheless if you are lucky enough to come across Adaptive Control, you almost certainly will want to use it. Adaptive Control is a smart algorithm PCV which adjusts the Pinsp and other complex variables automatically from breath to breath to achieve a target TV.

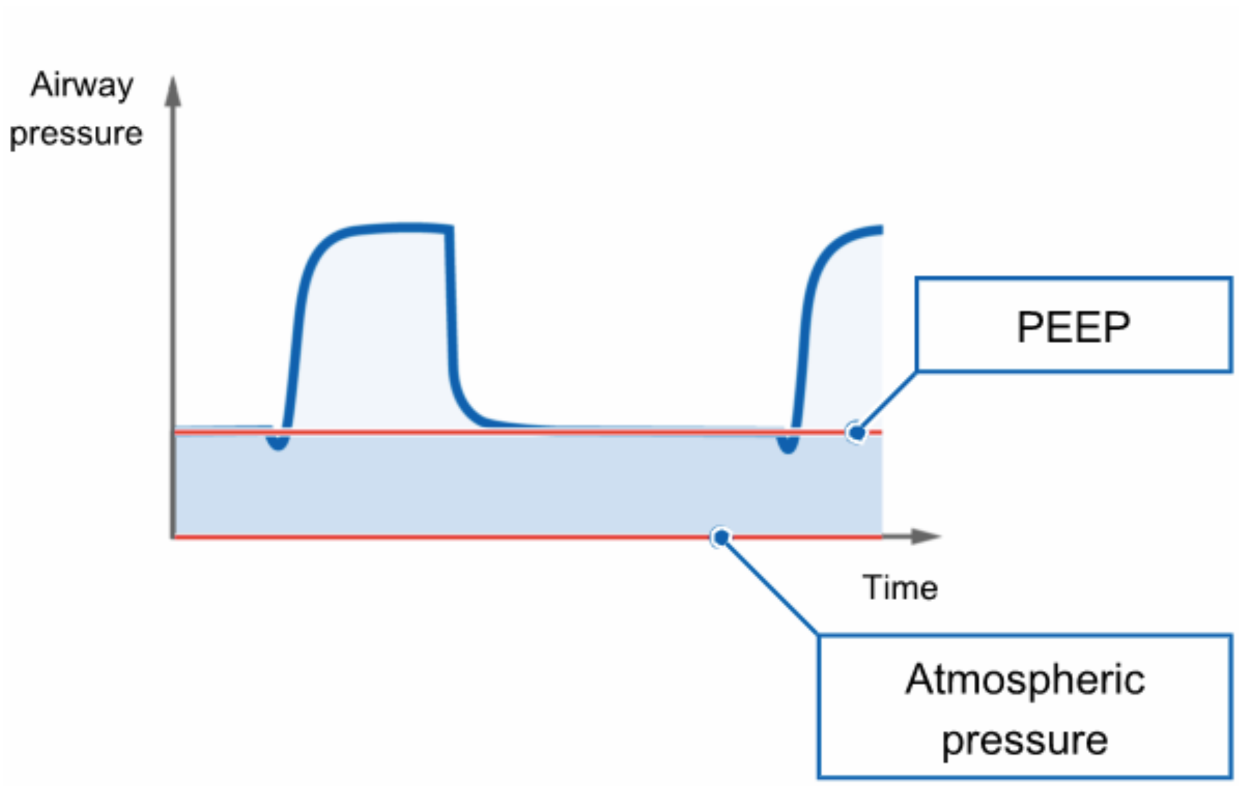
Thus Adaptive Control is PCV (with most of PCV's advantages) but with the convenience and reliability of setting the target TV and letting the machine worry about balancing the rest to achieve that target.

It's beyond the scope of this session to go into further detail, but definitely worth reading about if you are lucky enough to encounter a machine that offers Adaptive Control.

Baseline Pressure (Key Concept #5)
Positive Pressure Ventilation has some nasty physiologic consequences however, and one in particular is its tendency to permit the most dependent and deepest alveoli to collapse and remain closed throughout the respiratory cycle. (Atelectasis.)

In addition to atelectasis causing decreased gas-exchange surface area, it also creates a physiologic shunt whereby blood passing through the vessels of atelectatic lung will remain deoxygenated and thus blood returning to the heart at the left atrium is now at a lower saturation.

The solution: Positive End Expiratory Pressure (**PEEP**). In PPV PEEP prevents atelectasis by ensuring a small amount of positive pressure when the lungs would otherwise collapse (i.e. at the end of expiration.) 3-5cm H_2O is generally considered the correct amount to simulate "physiologic" norms and keep the alveoli open[2]. PEEP is also beneficial in that it increases Functional Resididual Capacity (FRC), improves gas exchange and can even improve lung compliance.



[2] Note: In contrast to mechanical ventilation, in healthy normal breathing, the negative pressure generated for each inhalation acts to open the alveoli, thus atelectasis is generally not a concern except in disease states.

Notice how when PEEP is applied, the PEEP setting becomes the new “baseline” for PPV breaths. (The PEEP baseline is parallel but increased a few points over atmospheric (“zero”) pressure.

While the general recommendation for starting PEEP is just 3-5 cmH_2O, the reality is that in disease states (e.g. restrictive lung disease), and in conditions where there is excess pressure causing the alveoli to collapse (e.g. obesity) much higher levels of PEEP may be required. This can be problematic because recall that Pinsp (that pressure level you want to keep ≤ 30 cmH_2O if at all possible is the sum of Pinsp (required to generate your desired tidal volume) + PEEP. (Thus as you increase PEEP you are increasing PIP (and Pplat))

Managing a vent can be a tricky dance sometimes, and it can’t always be done within that optimal safety zone of ≤ 30 cmH_2O. Don’t ever hesitate to call someone for advice!

SET vs ACTUAL (aka DELIVERED)

The final point to make in this supplement has already been introduced above. This is the concept of certain variables having a “set” quantity which may vary from the “actual” (measures or delivered) quantity.

Tidal Volume under VCV is one example. You may program 500mL but due to invisible loss the patient may only receive 450mL. PCV also has this phenomenon: you may set Pinsp of 12 cmH_2O, but as the ventilator titrates from breath to breath the measured level may vary.

Just be aware that the ventilator is designed to titrate and thus there may be discrepancies from time to time between what is set and what the patient actually receives. For the most part though (and with only a few exceptions) ventilators will adjust themselves to ensure ACTUAL resembles SET as much as possible.