Mechanical Ventilation

Blood Gases

The simplest way to look at mechanical ventilation is as a way to keep the blood gases normal. So what makes up a Blood Gas?

pH hydrogen Ion concentration

pCO2 partial pressure of Carbon dioxide

pO2 partial pressure of oxygen

You get several other values, but many of these are calculated and/or not reflective of pulmonary function which is what you are controlling with mechanical ventilation.

pH and **pCO2** are closely related and are affected by minute ventilation.

pO2 is governed by oxygen delivery and ventilation and perfusion (V and Q) match.

Minute Ventilation - very simply is **RR** x (**TV-dead space**), where RR is respiratory rate and TV is tidal volume.

Because **CO2** rapidly diffuses across the alveolar space, the more air you can move into and out of the lungs the more rapidly the CO2 can be removed.

Oxygen Delivery and VQ match - is controlled by your FiO2 (fraction of inspired oxygen) and is related to your airway recruitment. Airway recruitment is indirectly reflected in your mean airway pressure (**MAP**). By increasing your mean airway pressure you can increase your airway recruitment (although this is not a linear relationship) by reopening closed alveoli and splinting open alveoli (thereby preventing atelectasis). MAP is a function of the **PEEP** (positive end expiratory pressure) and a fraction of the **PIP** (peak inspiratory pressure or Pmax).

To improve oxygenation:

1) Increase FIO2
2) Increase mean airway pressure by:
    a) Increasing PEEP or
    b) Increase I:E ratio

To improve CO2 elimination:

1) Increase respiratory rate
2) Increase tidal volume

Other Controls
Inspiratory time is the time over which the tidal volume is delivered or the pressure is maintained (depending on the mode)

In pressure support mode the patient determines the duration of inspiration

I:E ratio (Inspiratory:Expiratory) usually set to 1:2 to mimic usual pattern of breathing
In general longer inspiratory times improve oxygenation by:

1) Increasing the mean airway pressure (longer period of high pressure increases mean airway pressure over the entire respiratory cycle)
2) Allowing redistribution of gas from more compliant alveoli to less compliant alveoli

However, when you decrease the expiratory time (inevitable as inspiratory time increases) beware of the following:

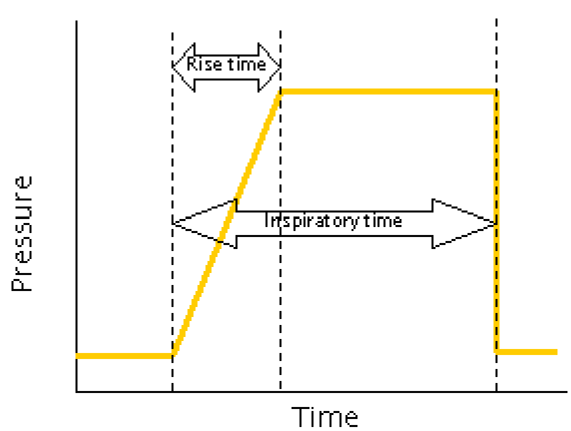
1) Increased risk of gas trapping,
2) Intrinsic PEEP (auto peep)
3) Barotrauma

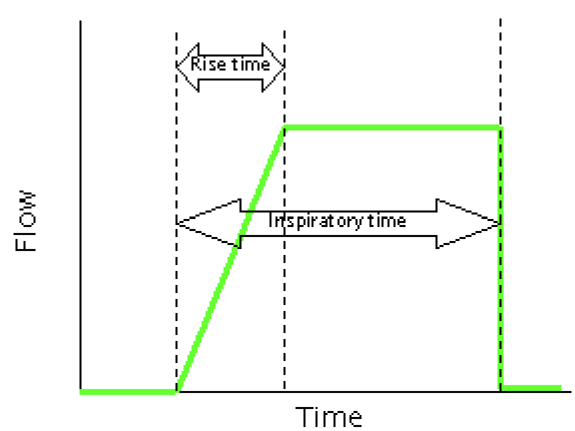
In addition, Longer I-times are less well tolerated by the patient, necessitating a deeper level of sedation.

Decrease peak pressure by decreasing inspiratory flow

Rise time: determines speed of rise of flow (volume control mode) or pressure (pressure control and pressure regulated volume control modes)

--Very short rise times may be more uncomfortable for the patient
--Long rise times may result in a lower tidal volume being delivered (pressure control mode) or higher pressure being required (volume control and pressure regulated volume control modes)





Trigger sensitivity: determines how easy it is for the patient to trigger the ventilator to deliver a breath

In general increased sensitivity is preferable in order to improve patient-ventilator synchrony (i.e. to stop the patient "fighting" the ventilator) but excessively high sensitivity may result in false or auto-triggering (i.e. ventilator detects what it "thinks" is an attempt by the patient to breathe although the patient is apneic).

Triggering may be flow-triggered or pressure triggered. Flow triggering is generally more sensitive.

--the smaller the flow or the smaller the negative pressure the more sensitive the trigger

Quick review

So, to control **pH** and **pCO2**, you manipulate the minute ventilation, ergo the respiratory rate and tidal volume.

To control **pO2**, you manipulate the oxygen delivery and the VQ match, ergo you adjust the FiO2 and the mean airway pressure (PEEP and PIP).

Modes of ventilation

In general a ventilator can be set to deliver:

1) A certain volume of gas in a set period of time

--The pressure generated in the lung will then be dependent on the resistance and compliance of the respiratory system

--Known as **volume control** mode

2) A certain level of pressure for a set period of time

--The tidal volume delivered will then be dependent on the resistance and compliance of the respiratory system

--These are **pressure control** and **pressure regulated volume control** modes

In **assist-control** modes (volume control, pressure control, and pressure regulated volume control) the ventilator guarantees that the patient will receive the set minimum number of breaths, although he/she is able to demand (trigger) more.

In **pressure support** or **volume support** modes the patient only receives breaths when he/she triggers the ventilator.

Basic Ventilator Types

Volume Control	Pressure Control
Controls	Controls
Rate	Rate
PEEP	PEEP
FiO2	FiO2
Inspiratory Time	Inspiratory Time
Tidal Volume	Peak Inspiratory Pressure
Relative Advantages/Disadvantages	**Relative Advantages/Disadvantages**
Simulates natural respiration—more comfortable for patient	Not as comfortable for patient
Known TV	No guarantee of TV
Risk for barotrauma	pressure limited decreases risk of barotrauma
Uses	**Uses**
Most ventilated patients	neonates
Patients in OR (including neonates)	patients where pressure is a concern ARDS, asthmatics sometimes

Another Quick Review

Volume Control Ventilation

- Controlling pH and pCO2 is done by controlling minute ventilation. You can set both the respiratory rate and the tidal volume.
- Controlling pO2 you can adjust the FiO2, the PEEP and, indirectly, the PIP by adjusting the tidal volume (bigger TV yields bigger Pmax) although we don't do this so much in practice

Pressure Control Ventilation

- Controlling the pH and pCO2 is done by controlling the minute ventilation. You can set the RR, but the TV is managed indirectly. TV is directly proportional to your ΔP (PIP-PEEP). Over a pressure range this will vary, and the higher the pressures the less TV for a given ΔP.
- Controlling the pO2, again you can adjust the FiO2 and the PEEP. In addition you control the PIP (again we rarely use this clinically)

Now you know the basics of mechanical ventilation. So we can move on.

Modes

In general we are trying to accomplish one of two things for a patient using mechanical ventilation: either to control their ventilation and oxygenation, which they are unable to do, or to support them as they wean from ventilatory support. We can look at ventilator modes as either Control Modes, or Support Modes.

Control modes, also commonly known as Assist Control Modes:

These include: CMV and IMV (which are rarely, if ever, used today), VC, PC and PRVC (the details of the abbreviations will come later)

Control modes deliver a set breath, the size and duration determined by the physician, each part of the respiratory cycle. If the patient is breathing spontaneously above the set rate, he or she will generally receive a full set breath, regardless of how much effort they are generating

Support modes include: VS, PS, CPAP, BiPAP and SIMV with PS (which is partly Control and partly support

The ventilator mode determines both when a patient gets a breath and what kind of breath they receive. The goal is to select a mode that is both comfortable for the patient and allows adequate ventilation and oxygenation with minimal trauma. Here is a partial list of available modes, with a brief discussion. Unless otherwise mentioned these modes are all in volume control, meaning that you set the tidal volume, rather than the peak inspiratory pressure. Some newer ventilators, particularly the Servo 300 can do these modes in either pressure or volume control.

Control Modes

AC (assist control) or VC (Volume Control)

- **Characteristics**: preset rate and tidal volume (sometimes PIP), either on the patient's initiative or at the set interval a full mechanical breath is delivered.
- **Uses**: for patients who have a very weak respiratory effort, allows synchrony with the patient but maximal support. Not a weaning mode, as at any rate they are getting complete mechanical support.
- **Contraindications:** none in particular
- **Advantages**: a fairly comfortable mode, providing a lot of support
- **Disadvantages**: can lead to hyperventilation if not closely monitored, not able to wean in this mode.

PC (Pressure Control)

- **Characteristics:** basically IMV, where the breath is controlled by the Pmax or Swing pressure (ΔP)\ and not the set tidal volume

- **Uses:** in neonates, or in patients with high airway pressures(such as ARDS) to avoid barotrauma
- **Contraindications**: none in particular, not a friendly mode in an awake patient
- **Advantages:** Pressure limited, decreases the risk of barotrauma
- **Disadvantages**: no guaranteed tidal volume

PRVC (Pressure Regulated Volume Control)

- **Characteristics**: a volume control assist control mode that adjusts the flow rate of the delivered air to deliver the set tidal volume at or below the set maximum pressure.
- **Uses**: in patients with high airway pressures, although it can be used in any patient. **Contraindications:** none in particular
- **Advantages:** gives you a guaranteed tidal volume but minimizes barotrauma.
- **Disadvantages:** new, no particular disadvantages.

IMV (Intermittent Mandatory Ventilation)

- **Characteristics:** set breath delivered at a fixed interval. No patient interaction, pressure or volume modes
- **Uses**: commonly in neonates on the Sechrist, can be a weaning mode
- **Contraindications:** none really, unfriendly to older patients
- **Advantages:** regular guaranteed breath
- **Disadvantages:** does not allow patient to breath with the ventilator except by chance .Does not work with the patient

The following modes fall into both Control and Support categories in that they have set rates, but the spontaneous breaths are not controlled, so they can be used in weaning.

SIMV (Synchronous IMV)

- **Characteristics:** set breath delivered within an interval based on the set respiratory rate. Ventilator spends part of the interval waiting for spontaneous breath from the patient, which it will use as a trigger to deliver a full breath. If not sensed it will automatically give a breath at the end of the period. Any other breaths during the cycle are not supplemented.
- **Uses:** commonly used in many settings. Can be a weaning mode (see also with PS)
- **Contraindications:** none in particular
- **Advantages:** allows work with the patient, somewhat friendlier.
- **Disadvantages:** Any other breaths during the cycle are not supplemented

SIMV/PS

- **Characteristics:** combination of the previous two modes. Extra breaths in the cycle are supplemented with pressure support.
- **Uses:** useful in most circumstances, including weaning.
- **Contraindications:** none in particular.

- **Advantages:** allows both synchrony with the patient and help in overcoming the resistance in the endotracheal tube, to allow easier spontaneous breathing
- **Disadvantages:** none in particular. PS does not add anything in the patient who is not spontaneously breathing. Sometimes patients will have difficulty with the pressure support on some ventilators.

Support Modes

PS (Pressure Support)

- **Characteristics:** supports each spontaneous breath with supplemental flow to achieve a preset pressure. Gives a little push to get the air in, so to speak.
- **Uses:** In the spontaneously breathing patient this helps overcome the airway resistance of the endotracheal tube. Usually use 5 for older patients and 10 for smaller (smaller ETT has higher resistance, more impediment to flow). Can be very helpful for weaning.
- **Contraindications:** patient who is not spontaneously breathing, i.e. on muscle relaxants
- **Advantages:** helps overcome resistance of tube, making spontaneous breathing easier

Volume Support

- **Characteristics:** variable level of pressure support is delivered on each breath in order to maintain a minimum set goal minute ventilation. *Note:* because the goal the ventilator works from is a minute ventilation goal the patient's respiratory rate can fall below the 'set' rate as long as their breaths are large enough to maintain the goal minute ventilation
- **Uses:** a weaning mode. The concept is that as the patient becomes stronger, or more awake they will make more respiratory effort on their own. The more effort they make the less support they will need from the ventilator and hence the level of pressure delivered will get smaller, often into the single digits
- **Contraindications:** patient who is not spontaneously breathing, as there is no back-up rate.
- **Advantages:** greatly decreases the number of interventions needed to wean patient from a ventilator versus traditional weaning
- **Disadvantages:** can be tricky on chronically ventilated patients. Takes some experience to understand when a patient is ready to be extubated when in this mode

CPAP (Continuous Positive Airway Pressure)

- **Characteristics:** just as it says. This is very similar to PEEP, except that the inspiratory pressure is also maintained at the CPAP level, leading to support on inspiration and resistance on exhalation.
- **Uses:** for patients with upper airway soft tissue obstruction or tendency for airway collapse. As a final mode prior to extubation in some patients.
- **Contraindications:** any patient without spontaneous respiratory effort. Not a good idea in a patient with obstructive pulmonary disease (like asthma, COPD)
- **Advantages:** simple, easy to use
- **Disadvantages:** provides no supportive ventilation.

Where to start?

Every patient is different and it is hard to know exactly what a patient will need in terms of ventilatory support until they are actually on the ventilator. So many of us a have preset ideas as to where to start any patient and then adjust the ventilator afterwards to achieve the desired ventilation effect. This has a lot to do with the individual style of the attending physician.

Pressure vs. Volume: I generally choose Volume to start.

Why? Generally a more straightforward in terms of meeting goals of ventilation.

Mode: PRVC, if available, otherwise SIMV with or without Pressure Support.

Why? PRVC has the advantages of guaranteed tidal volume AND limiting the peak pressure. The decelerating wave pattern on the flow is also generally friendlier.

Rate: 20

Why? This is a good place to start. You can always adjust later. For small children this is lower that their usual spontaneous rate but with the larger tidal volumes that are delivered this increases the minute ventilation. For large children I will decrease this to 15 or even less. For small infants or neonates I may increase this to 30 or higher.

PEEP: 5mm Hg

Why? This is a little above physiologic. Not so high as to cause problems.

FiO2: 100%

Why? You can start to wean once you are certain everything is stable. This allows maximal pre-oxygenation in case anything happens. The only patients who will suffer deleterious effects from 100% for brief periods are those with arterial to pulmonary shunts, such as a modified Blalock-Taussig shunt or a central shunt where pulmonary vasodilatation can lead to systemic hypotension.

Tidal Volume: 8-10ml/kg

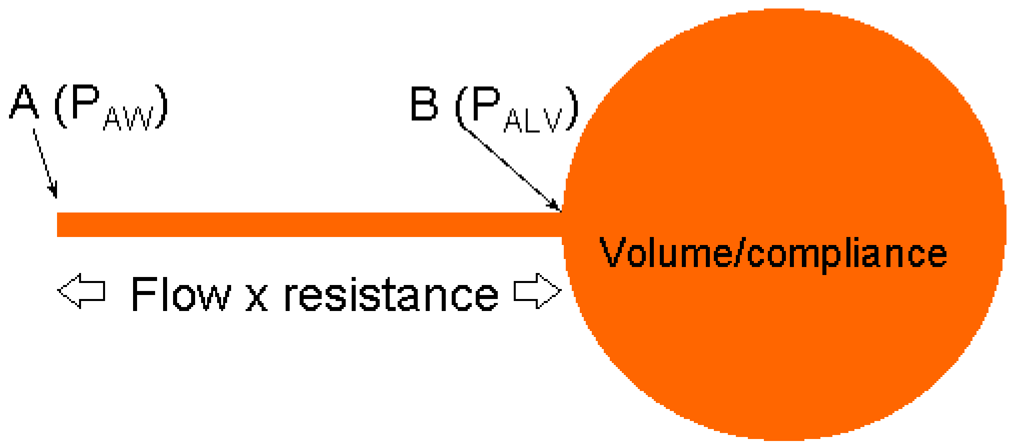
Why? This is above physiologic and gives good distention without significant barotrauma. 10-12ml/kg used to be the standard range, but people are generally using PEEP to maintain lung volume and smaller tidal volumes to avoid baro or volutrauma.

Inspiratory Time: somewhere from 0.5 to 1 second

Why? It’s physiologic. You want a longer i-time for bigger kids, but this will vary on the situation. Asthmatics for example merit very short I-times to allow maximal time for exhalation.

Basic physics related to mechanical ventilation

In simple terms the lung-ventilator unit can be thought of as a tube with a balloon on the end with the tube representing the ventilator tubing, ET tube and airways and the balloon the alveoli.



$$P_{aw} = \text{Flow} \times \text{Resistance} + \frac{\text{Volume}}{\text{Compliance}} + \text{PEEP}$$

Pressure at point B is equivalent to the alveolar pressure and is determined by the volume inflating the alveoli divided by the compliance of the alveoli plus the baseline pressure (PEEP)

Pressure at point A (equivalent to airway pressure measured by the ventilator) is the sum of the product of flow and resistance due to the tube and the pressure at point B.

Flow, volume and pressure are variables while resistance and compliance are constants.

Flow = Volume/time

It follows from the relationships between pressure, flow and volume that by setting one of pressure, volume or flow and the pattern in which it is delivered (which includes the time over which it is delivered) the other two become constants.

It also follows that it is not possible to preset more than one of these variables as well as time. Thinking of the lung-ventilator unit in terms of this simple model is also useful in aiding an understanding of the use of monitoring **end-inspiratory pause pressure**. In volume and flow preset modes pressure becomes a dependent variable. It is important to monitor pressure in order to minimize the risk of barotrauma. However, in this context *it is alveolar pressure not airway* *pressure that is important*. By measuring the airway pressure during an end-inspiratory pause it is possible to eliminate the component due to resistance because during an end-inspiratory pause there is no flow and thus $P_{AW}=P_{ALV}$.

In most circumstances the contribution of the resistance component to airway pressure is relatively small and constant, so it is reasonable to monitor airway pressure. However in patients with high resistance (i.e. patients with obstructive lung disease), it is important to monitor end-inspiratory pressure. Measurement of end-inspiratory pressure may also help determine the cause of a sudden rise in airway pressure. If both are high then the problem is due to a fall in compliance (eg endobronchial intubation, pneumothorax). If only the airway pressure is high, then the problem is due to increased resistance (eg partially blocked ETT, bronchospasm)

Early things to worry about

Peak Pressures: You would like to keep these under 35 if at all possible. If they start climbing into the 40's to 50's you should consider changing to Pressure control ventilation. While there are several other manipulations that could also be tried, the implication is that the patient either has very restrictive lung disease and non-compliant lungs or a very severe obstructive lung pattern, in which case the pause pressure should be evaluated and attempts to improve bronchodilation should be increased.

Oxygenation: Inability to wean the FiO2 should be a concern. Once on the ventilator the goal should be to get the FiO2 under 60%. If you are unable to do this it implies shunting either from lack of airway recruitment (PEEP too low) or alveolar inflammation or disease (like ARDS). This is where increasing the MAP will be of benefit.

Ventilation: Am I over or under ventilating this patient based on his needs. Remember a patient who is being intubated because of an upper airway problem may have an excellent respiratory drive and not need much support. While a patient in shock with profound metabolic acidosis may need a higher rate to help compensate. Keep in mind the reason you are putting the patient on the ventilator. Obtaining a blood gas early after intubation (15-20 minutes after being on the ventilator) will help you decide if you are moving in the right direction.

Complications

Respiratory

1) Ventilator-associated pneumonia
2) Barotrauma: not only due to high pressures, but also due to high volumes and shear injury (due to repetitive collapse and re-expansion of alveoli and due to tension at the interface between open and collapsed alveoli

Barotrauma causes:
-- pneumothorax

--pneumomediastinum
--pneumopericardium
--surgical emphysema
--acute lung injury

3) Gas trapping: occurs if there is insufficient time for alveoli to empty before the next breath

More likely to occur:

--in patients with asthma or COPD
--when inspiratory time is long (and therefore expiratory time short)
--when respiratory rate is high (absolute expiratory time is short)

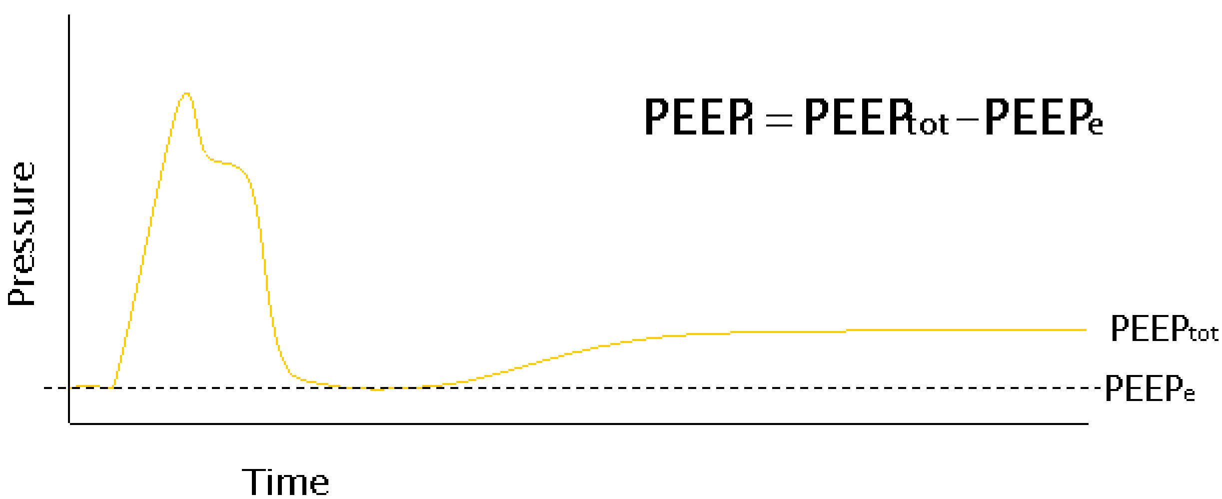
Results in progressive hyperinflation of alveoli and progressive rise in end-expiratory pressure (known as intrinsic PEEP), which may result in:

--barotrauma
--cardiovascular compromise due to high intrathoracic pressure. In an extreme case can lead to cardiac arrest with pulseless electrical activity.

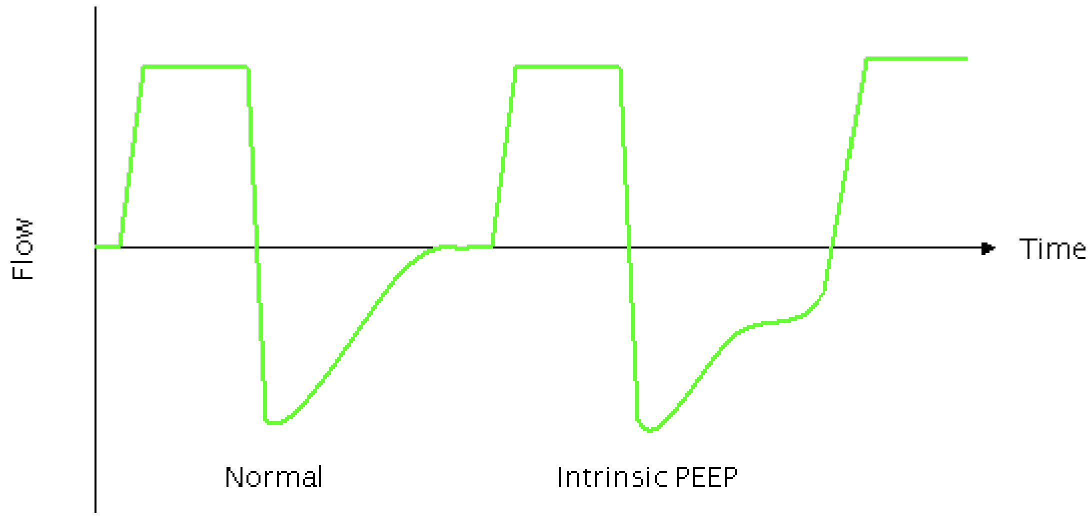
Measuring intrinsic PEEP

Quantitative measurement of intrinsic PEEP can be obtained in an apneic patient by using the expiratory pause hold control on the ventilator. This allows equilibration of pressures between the alveoli and the ventilator allowing the total PEEP to be measured. The value for total PEEP can be read from the airway pressure dial or the PEEP display

Intrinsic PEEP=Total PEEP-Set PEEP



Examination of the flow-time curve from the ventilator gives an indication that there is intrinsic PEEP but does not give an indication of the magnitude. The patient does not need to be apneic.



Cardiovascular effects

Preload

1) Positive intrathoracic pressure reduces venous return
2) Exacerbated by:
    --high inspiratory pressure
    --prolonged inspiratory time
    --PEEP

Afterload = ventricular wall tension (T) during contraction

$$T = \frac{P_{tm} \times R}{2H}$$

where Ptm=transmural pressure, R=radius and H=wall thickness, Ptm=intracavity pressure-pleural pressure

By increasing pleural pressure, positive pressure ventilation decreases transmural pressure and hence afterload.

Cardiac output

Reduced preload will tend to decrease cardiac output.
Reduced afterload will tend to increase cardiac output

--The net effect depends on LV contractility. In patients with normal contractility positive pressure ventilation tends to decrease cardiac output while in patients with decreased contractility it tends to increase cardiac output .

--Effect on cardiac function also important to remember when weaning patients. Failure to wean may be due to failure to cope with increased preload and afterload.

--Myocardial oxygen consumption is reduced by positive pressure ventilation.

TROUBLESHOOTING

Assessment

The first priority in dealing with mechanical ventilation problems is to assess the patient.

1)How severe is the problem?
2)Does the patient require immediate resuscitation?

Check:

1) Is the chest moving and is it moving symmetrically?
2) Is the patient cyanotic?
3) What is the arterial saturation?
4)Is the patient haemodynamically stable?

The next step is to diagnose the problem.

Ventilator/circuit problems can be distinguished from endotracheal tube/patient problems by taking the patient off the ventilator and manually bagging the patient.

High airway pressure

Why does it matter?

1) High airway pressure may cause barotrauma
2) It signifies a deterioration in the patient's clinical state
3) It may result in hypoventilation of the patient
    --Many ventilators cycle from inspiration to expiration immediately if the upper pressure alarm limit is reached. As a result inspiration is terminated early and the tidal volume is reduced.

Causes

Ventilator problems

1) Inappropriate settings
-- Excessive tidal volume
--excessive flow or excessively short inspiratory time
--high airway pressure alarm limit too low

2) Ventilator malfunction - rare

Circuit problems
1) Fluid pooling in circuit
2) Fluid pooling in filter
3) Kinking of circuit

Endotracheal tube obstruction i.e. due to sputum, kinking, biting

Increased airway resistance i.e. bronchospasm

Decreased respiratory system compliance
1) Parenchymal disease
2) Pleural disease i.e. pneumothorax
3) Decreased chest wall compliance i.e. due to patient "fighting" ventilator
4) Decreased ventilated lung volume
--sputum plugging
--lobar/lung collapse
--endobronchial intubation

Management
1) Assess patient.
2) Disconnect patient from ventilator and manually ventilate.
--Assess the "feel" of the lungs. Is the patient difficult to ventilate?
-- If the patient is not difficult to ventilate, it is a problem with the ventilator or the circuit.
--If the patient is difficult to ventilate, it is a problem with the endotracheal tube or the respiratory system.

3) For ventilator and circuit problems, check ventilator settings and function, and check circuit for obstruction or kinking.

4) For patient or ETT problems examine the patient looking particularly for bronchospasm, asymmetrical chest expansion and evidence of collapse.

5) Pass a suction catheter through the ETT to check its patency.

6) CXR

If the cause is still not clear, measure inspiratory pause pressure (approximates alveolar pressure).
--If both airway and alveolar pressure are high the problem is due to poor compliance.
--If only the airway pressure is high the problem is one of high resistance.

Hypotension

The most important causes of hypotension occurring soon after the initiation of mechanical ventilation are:

1) Relative hypovolemia
    --Reduction in venous return exacerbated by positive intrathoracic pressure

2) Drug induced vasodilation and myocardial depression
    --All anesthetic induction agents have some short lived vasodilatory ± myocardial depressant effects

3) Gas trapping (dynamic hyperinflation)

4) Tension pneumothorax

Hypotension due to relative hypovolemia or anesthetic induction agents usually responds rapidly to fluid. Hypotension due to gas trapping can be diagnosed and treated by disconnecting the patient from the ventilator. This results in a rapid reversal of the hypotension.

Patient-ventilator dysynchrony

There are a large number of causes of patient-ventilator dysynchrony which need to be considered. It is important to identify and treat these causes and not simply to sedate the patient more heavily. As well as all the possible causes of agitation there are a number of ventilator parameters which must be considered. These include:

1) Mode of ventilation
    --Spontaneous modes are more comfortable than control modes
2) I:E ratio
    --Ratios that are similar to the 1:2 ratio of a normal breathing pattern are more comfortable.
3) Triggering
    --if the patient is having difficulty triggering the ventilator despite a sensitive setting consider the possibility that there is auto-PEEP due to dynamic hyperinflation.

Desaturation

Causes

1) Endobronchial intubation
2) Accidental extubation
3) Pneumothorax
4) Pulmonary embolus
5) Any cause of increased intrapulmonary shunt
6) Any cause of hypoxic respiratory failure
7) Ventilator malfunction

Management

1) Increase F_IO_2 to 100%

2) Check to make sure chest is moving
3) Briefly examine chest to determine cause of desaturation
4) If cause is not obvious manually ventilate patient with 100% oxygen to exclude ventilator malfunction as the cause
5)Treat underlying cause
6) Alter ventilator settings to improve oxygenation
7) CXR

Weaning

- process by which a ventilator-dependent patient is removed from ventilator
- only 10-20% of patients who require ventilation are difficult to wean and most of these have required ventilation for over 1 month
- potentially reversible reasons for difficult weaning:
    1) Inadequate respiratory drive
    2) Poor gas exchange
    3) Psychological dependency
    4) Ventilatory pump failure (usually due to inspiratory muscle weakness or fatigue)

Causes for inspiratory muscle weakness or fatigue:

1) Nutritional or metabolic deficiencies: hypokalemia, hypomagnesaemia, hypocalcemia, hypophosphatemia, hypothyroidism
2) Steroids
3) Chronic renal failure
4) Decreased protein synthesis and increased degradation
5) Decreased glycogen stores
6) Anemia
7) Persistently increased work of breathing
8) Cardiovascular failure
9) Neuromuscular blockers
10) Polyneuropathy of critical illness

There is no objective data to determine when to attempt weaning. In general, the problem which led to the initiation of mechanical ventilation should have been reversed or stabilized.

Standard criteria for initiating weaning:

1) Clinically and radiologically resolving lung disease
2) FiO2 <40%
3) PEEP ≤ 5
4) Minimal endotracheal secretions
5) Patient awake and cooperative
6) Vital Capacity > 10ml/kg
7) NIF (negative inspiratory force) > -20cm H20