**Mechanical ventilation**

The primary aims are to deliver a sufficient volume (6 - 10ml/kg) at a sufficient minute ventilation (4 - 10 L/min) without breaching potentially harmful airway pressures (35cm H2O), in order to adequately oxygenate, clear CO2 and minimise the risks of volu- and barotrauma. Everything else is fine tuning to optimise these three aims.

**Target parameters:**
- **Tidal volume (Vt) = 6 - 10 ml/kg. Average range = 400 - 600ml. Lower volumes for lower compliance; eg asthma, ARDS.**
- **Respiratory rate (f): 10 - 20bpm. Higher rates increase risk of VALI**
  
  **Minute ventilation (Vt x f): 85 - 100 ml/kg/min. Average range = 4.2 - 10L**

  Peak inspiratory flow rate: 40 - 80 L/min. Alert patients prefer high flow rates. In controlled mechanical ventilation (CMV), high flow rates result in higher Peak Inspiratory Pressure (PIP), higher airway resistance and greater potential for VALI.

  **I:E ratio: 1:1 - 1:3. Longer I:E ratio reduces gas trapping but shortens inspiratory time (Ti). For volume-controlled ventilation (VCV) this may cause higher PIP, while for pressure-controlled ventilation (PCV) it may result in lower Vt delivery. Inverse ratio ventilation (IRV) may improve alveolar recruitment but increases the risk of gas trapping. IRV can improve CO2 clearance but no evidence of improved oxygenation or haemodynamics.**

  **PEEP: 5 - 20 cm H2O. Recruits FRC, minimises shunt and aids redistribution of lung water. Higher PEEP may cause alveolar splinting, reducing overall ventilation.**

  **FiO2: Aim to maintain PaO2 > 70mmHg and SpO2 > 90% while minimising risk of O2 toxicity. Increasing FiO2 will not significantly improve hypoxia due to shunt.**

  **PIP: Not a preset parameter but affected by the setting of Vt, f, Peak flow rate and Ti. Aim for < 35 -40 cmH2O. However, plateau pressure (Pplat) more closely reflects alveolar distention pressure.**

  Static lung compliance: Cstat = Vt/(Pplat - PEEP) = 50 - 80ml/cmH2O in intubated normal lung. Decreased when lung or chest wall elastance increased eg ARDS, oedema, consolidation, pneumothorax, iPEEP.

  **Humidification: Water content 30 - 40 mg/L, Temp 37°C, Resistance < 3 cmH2O /L/sec, overheating and overhydration alarms.**

**Specific ventilation strategies:**
- Low Vt, increased PEEP, RR high, permissive hypercarbia -> protective lung ventilation
- Low Vt, low PEEP, long I:E, slow RR, increased inspiratory flow rate -> obstructive airway strategy, eg severe asthma / COPD

Low Vt, low PEEP, increased RR, avoid hypercarbia -> Pulmonary hypertension strategy
Low Vt, low f, enough PEEP to maintain lung inflation and an intercostal catheter present -> bronchopleural fistula.

**Ventilation modes**

**Classes:**

**VCV:** Target Vt delivered by setting the desired Vt. Flow-driven (square or decelerating), volume-cycled, time-triggered. May be flow-triggered if spontaneous respiratory effort; eg SIMV.
Typically uses a square inspiratory flow pattern, which results in a linear inspiratory pressure with Ppeak and Pplat. The higher the flow, the higher the peak pressure. However, modern ventilators can also deliver a decelerating flow pattern, resulting in lower pressures.

Varying Ti alters the I:E ratio and vice versa, with no change to the overall duration of the respiratory cycle. Shorter Ti lengthens the I:E ratio, but in order to deliver the target Tv results in a higher flow rate, causing a higher PIP.

*Advantages:* Constant Vt and Mv (if f and Ti constant). Precise control of PaCO₂.

*Disadvantages:* Airway pressure varies with changes in compliance with potential for barotrauma and VALI. Cannot compensate for leaks - important as machine displays volume delivered to tubing, not volume delivered to alveoli.

*Pressure-limited volume-controlled ventilation* adds an airway pressure limit in order to reduce the potential for VALI, while still delivering close to the target Vt.
PCV: Target Vt delivered by manipulating Ti and the inspiratory pressure. Inspiratory pressure is fixed and varying Ti determines the I:E ratio and the Inspiratory Flow Rate. Actual Vt delivered is determined by lung compliance. The inspiratory flow adopts a decelerating pattern.
Pressure-driven, time-cycled, time or flow triggered.

With PCV, PIP = Pplateau. Theoretically PCV results in lower PIP than VCV, particularly in low compliance conditions, however no demonstrable difference in oxygenation, lung recruitment or haemodynamics.

**Advantages:** More even lung distribution of ventilation. Controlled airway pressure with potentially less VALI. Can compensate for leaks.

**Disadvantages:** Variable Vt and Mv as compliance changes with potential for under-ventilation and volume-trauma.

**PSV** (Pressure support ventilation)
Patient breathes spontaneously, ventilator delivers fixed inspiratory pressure to augment Vt; usually 15 - 20 cmH2O. Often given on top of PEEP of 5 - 10 cmH2O, which is used to overcome ETT and tubing resistance. Pressure-driven, flow-cycled, pressure or flow-triggered.

Disadvantages include variable Vt, variable Mv and patient-ventilator assynchrony.

**Modes:**

1) Controlled mechanical ventilation
The ventilator provides all of the driving inspiratory flows and pressures.Expiration is passive.
Used in:
- patients with no / minimal ventilatory capacity (eg. neuromuscular blocking agent, central apnoea, neuropathy, myopathy)
- to manipulate PaCO\textsubscript{2} (eg raised ICP)
  to reduce the metabolic demand of breathing (eg severe cardiorespiratory failure)

2) IMV / SIMV
Patient can breathe spontaneously - may need some PEEP or PSV to overcome ETT and tubing resistance. Delivers a set rate (f) of mandatory breaths but attempts to coordinate those breaths with the patient’s efforts. Can be used in VCV or PCV mode. Used for weaning. Disadvantages include patient-ventilator asynchrony.

3) Proportional assist ventilation (PAV)
Patient breathes spontaneously, ventilator delivers proportional volume (VCV) or pressure (PCV) to achieve effective alveolar ventilation. Theoretically reduces patient-ventilator asynchrony and improves work of breathing. Technically difficult to manage:
- No set Vt, Pressure or flow rate, as these parameters may vary with each breath
- Aim is to reduce work due to lung elastance and/or resistance, but these are difficult to estimate. Practically adjusted to patient comfort, RR, SpO\textsubscript{2}, haemodynamics, PEEPi and blood gas values.

4) Bilevel positive airway pressure ventilation
Time-cycles between low and high level CPAP. Provides equivalent of PCV-CMV if patient apnoeic, but patient can also breathe spontaneously with it.

5) High frequency ventilation (HFV)
Small Vt 1 - 3 ml/kg, high \( f \) 100 - 200bpm.
Requires specific ETT or tube catheter.
Adults: High frequency jet ventilation
Infants: High frequency oscillation
Used in low compliance conditions; eg ARDS, pneumonia.

6) Dual Control Modes
Set target Vt and Pressure threshold to achieve Mv. Ventilator switches between volume and pressure modes in response to measured feedback to achieve the desired settings. May switch modes breath-to-breath (eg. PRVC, PSVG) or within breaths (eg VAPSV). Can be used for both CMV and assistance of spontaneously breathing patient.

7) Liquid ventilation
Perflourocarbons
Partial liquid ventilation - perflourocarbon volume (FRC) fills dependant alveoli improving oxygenation and compliance, while ventilation and oxygenation of distended alveoli improves.

Extrinsic PEEP

ePEEP can be applied to almost all invasive and non-invasive ventilation techniques. It counters the tendency of alveoli to collapse at end expiration, by limiting the Law of LaPlace.
A pressure valve placed in the expiratory limb prevents end expiratory pressure equilibrating with atmospheric pressure, keeping airways and alveoli open.

This effect improves lung compliance (reducing work of breathing) and reduces shunt (improving hypoxaemia). It also increases mean intrathoracic pressure which may compromise cardiac output.

Tissue hypoxia may be improved or worsened by ePEEP depending upon its relative effects on hypoxaemia and cardiac output by DO\(_2\) = C.O. x CaO\(_2\) (see Respiratory Physiology chapter).

Efficacy of ePEEP should not be monitored only by SaO\(_2\) or SpO\(_2\), but also by effect on C.O. (S-G catheter, PiCCO) or SvO\(_2\) (decrease => poor perfusion)

Intrinsic PEEP (iPEEP)

Causes:
- Vt too high
- I:E ratio too short
- RR too high
- Small airways constriction - asthma, COPD

Detecting iPEEP:
Difficult!
- End expiratory hold (see Respiratory Monitoring chapter). Paw - ePEEP = iPEEP at equilibration. Can be tricky to determine exact point of end expiration.
- In the presence of iPEEP, PIP does not increase with increased ePEEP until ePEEP matches iPEEP. So, can diagnose presence of, quantify and counter iPEEP by watch effect of gradual increase in ePEEP on PIP.

Flow-pressure curve

Specific ventilation patterns
- Low volume (6ml/kg) + high PEEP with raised RR and accepting mild hypercarbia -> Protective lung ventilation for ARDS (ARDS-NET)
- Low volume + low PEEP + slow RR + long I:E ratio + high inspiratory flow rate + permissive hypercarbia ("slow, low and high flow") -> mechanical ventilation in severe asthma
Low volume + low PEEP + high RR + avoid hypercarbia -> mechanical ventilation in pulmonary hypertension
Indications for mechanical ventilation
- Often following intubation
- To improve oxygenation (FRC, Va, FiO2)
- Manipulating PaCO2 (ICP, Resp acidosis)
- Reduce work of breathing
- Stabilise chest wall in severe chest injury

Complications of mechanical ventilation
Equipment
- Intubation
- Disconnection / obstruction
- Machine failure
- Incorrect parameters
- Contamination

Pulmonary
- VAP
- VILI / VALI
- Barotrauma
- O2 toxicity
- Patient-ventilator asynchrony

CVS
- Impaired venous return -> decreased CO
- Increased RV afterload -> decreased CO
- High PEEP or Paw -> reduced splanchnic blood flow
- Fluid retention

Other
- PPV interferes with haemodynamic monitoring, esp. CVP, pulmonary artery and pulmonary capillary wedge pressure.
- Raised ICP with high PEEP
- GIT mucosal ulceration
- Respiratory muscle weakness / deconditioning with prolonged ventilation
- Critical illness polyneuropathy with prolonged use of neuromuscular blocker
- Sleep disturbance
- Long term neuropsych disturbance

Patient-ventilator dysynchrony

Only occurs in patients with at least some degree of spontaneous respiratory effort.

Detected by clinical examination and ventilator measurements and waveforms.

Caused by mismatching between patient effort and ventilator inspiratory parameters, but can effect any part of the respiratory cycle.

Inspiratory trigger:
- Fall in airway pressure or fall in baseline flow rate.
- Hindrances to inspiratory trigger:
  - PEEPi - Increased respiratory work (effort) required to generate fall in P or Flow.
  - Technical aspects of detecting transducer; distance from airway, sensitivity
- Sensitivity settings - oversensed -> inspiration triggered by small variations in airway P or Flow. Vice versa for undersensing
**Inspiratory delivery (Limit):**
Delivered by pressure (eg PSV) or flow (eg ACV).
- Flow delivery may increase respiratory effort if the delivered inspiratory flow doesn't meet the requirement generated by the patient's spontaneuos effort (ie. drawing breath against the ventilator)
Pressure delivery rewards increased patient effort. Additionally, a steeper rate of inspiratory pressure rise (lambda) reduces work of breathing in spontaneously breathing patients.

**Cessation of inspiration (Cycle)**
Usually detected by a rise in airway resistance.
Hindered by:
- Technical aspects of detecting transducer; distance from airway, sensitivity
- High PSV level (>20cmH2O)
- Equipment leak (mask, tubing)
- Weak respiratory effort

**Weaning from ventilation**
Consider from the time that intubation and mechanical ventilation is initially considered.

**Is the patient ready?**
To begin weaning, the patient requires:
- Resolution of original indication for mechanical ventilation
- Pulmonary stability
- CVS stability
- Metabolic stability (liver, renal, pH, other. Especially hypoMg and hypoPO4)
- Adequate neuromuscular function / strength

**Will the wean fail?**
Weaning failure rate = 20% despite appropriate clinical assessment.
Reintubation rate = 3% with subsequent 7 - 11 fold increase in hospital mortality.

Predictors of weaning failure:
- Old age
- COPD
- Prolonged mechanical ventilation
- FiO2 > 0.5
- PaO2 : FiO2 < 200
- Suboptimal Vt (<5ml/kg)
- Large Mv (>10L/min)
- High RR (>40bpm)
- Poor respiratory drive / strength (Spontaneous Pi max < -20cmH2O)
- Predictive indices: none proven better than clinical assessment. Eg RR/Tv ratio >100 predicted likely weaning failure in original study, but subsequent studies less supportive.

The converse of these features do not necessarily predict successful weaning

**Which weaning mode to chose?**
Weaning strategies:
- Trial of spontaneous breathing (Esteban NEJM 1995)
- T-piece
SIMV
SIMV with PSV

**Optimising weaning success**
The key to successful weaning is reducing work of breathing
Work of breathing can be measured but methods are complex (Cambell diagram, pressure-time product), and clinical assessment of the patient's general appearance, vital signs and ABG are usually a good guide.

Patient factors:
- Airway resistance - minimise secretions & treat bronchospasm
- Optimise lung compliance - treat consolidation & ALI, drain Pbx + pleural effusions, sit patient up.
Minimise CO2 production - fever, shivering, inotropes, agitation, carbohydrates
Reduce expiratory work - treat bronchospasm, reduce tubing.
Optimise nutrition
Begin weaning as early as is practical

Equipment factors:
- Maximum tolerable tubing diameter
- Minimise tubing length
Change humidifier regularly (avoid certain humidifiers, eg underwater baffles)
Provide CPAP (3-5 cmH2O) and pressure support (5 cmH2O minimum). Note, continuous flow CPAP reduces work of breathing better than demand valves.

**Considerations when approaching mechanical ventilation**
- Is intubation indicated?
- Is mechanical ventilation indicated?
Is mechanical ventilation contraindicated?
What starting mode is most appropriate? (Is there spontaneous effort or apnoea?)
What target parameters?
What monitoring is required?
When should weaning start?
Is weaning failure likely?
What weaning mode is most appropriate?

References:
1) T. Oh's Intensive Care Manual, 5th Ed.
2) Miller's Anaesthesia, 6th Ed.
3) Clinical intensive care and acute medicine, 2nd Ed. (CIAP)
4) The ICU Book, P. Marino, 2nd Ed.
5) See folder articles