Principles of Mechanical Ventilation

The Basics

- Prerequisites for intubation
  - Criteria
  - Clinical deterioration: progressive fatigue and use of accessory muscles or mental status deterioration
  - Tachypnea: RR > 35
  - Hypoxia: pO2 < 60 mm Hg despite O2 supplement
  - Hypercarbia: pCO2 > 55 mm Hg
  - Minute ventilation < 10 L/min
  - Tidal volume < 5-10 ml/kg
  - Negative inspiratory force < 25 cm H2O
  - Upper airway obstruction
  - Impaired airway protection
  - Inability to clear secretion
  - Apnea

Need for tracheostomy

- Prolonged intubation may injure airway and cause airway edema

Advantages
- Issue of airway stability can be separated from issue of readiness for extubation
- Decreased work of breathing
- Avoid continued vocal cord injury
- Improved bronchopulmonary hygiene
- Improved pt communication

Disadvantages
- Long term risk of tracheal stenosis
- Procedure-related complication rate (4% - 36%)

Mechanical Ventilation

Consists of
- Maintaining patency of the airway
- Ensuring adequate alveolar ventilation
- Can be provided via mask (non invasive) or through intubation

INDICATIONS FOR MV

- Apnea
- Severe Hypoxemia
- Acute respiratory acidosis that is not quickly reversed by specific treatment
- Reverse ventilatory muscle fatigue
- Permit sedation and/or neuromuscular blockade
- Decrease systemic or myocardial oxygen consumption

INDICATIONS CONTINUED

- Reduce intracranial pressure through controlled hyperventilation
- Stabilize the chest wall
- Protect airway
  - Neurologic impairment
  - Airway obstruction
The era of intensive care medicine began with positive-pressure ventilation 

**Origins of mechanical ventilation**

- **Negative-pressure ventilators** ("iron lungs")
  - Non-invasive ventilation first used in Boston Children's Hospital in 1928
  - Used extensively during polio outbreaks in 1940s – 1950s
- **Positive-pressure ventilators**
  - Invasive ventilation first used at Massachusetts General Hospital in 1955
  - Now the modern standard of mechanical ventilation

**Principles (1): Ventilation**

- **Minute ventilation \( V_e \)**
  - \( V_e = \) alveolar ventilation
  - \( V_e = \) tidal volume
  - \( D T \) responding to pH and \( P_{CO_2} \)
- **Ventilation in context of ICU**
  - Increased \( CO_2 \) production
  - Increased \( V_e \)
  - \( \) pulmonary embolism
  - Adjustments: RR and \( T_{r} \)

**Principles (2): Oxygenation**

- **Alveolar-arterial \( O_2 \) gradient** \( (P_{A}O_2 - P_{a}O_2) \)
  - Equilibrium between oxygen in blood and oxygen in alveoli
  - \( A-a \) gradient measures efficiency of oxygenation
  - \( P_{A}O_2 \) partially depends on ventilation but more on \( V/Q \) matching
- **Oxygenation in context of ICU**
  - \( V/Q \) mismatching
  - \( \) parenchymal disease, small-airway disease
  - Adjustments: \( FIO_2 \) and PEEP

**Pressure ventilation vs. volume ventilation**

- **Pressure-cycled modes**
  - Pressure Support Ventilation (PSV)
  - Pressure Control Ventilation (PCV)
  - BIPAP
- **Volume-cycled modes**
  - Control
  - \( \) assist
  - \( \) assist/Control
  - Intermittent Mandatory Ventilation (IMV)
  - Synchronous Intermittent Mandatory Ventilation (SIMV)

**Pressure Support Ventilation (PSV)**

- Patient determines RR, \( V_{e} \), inspiratory time: a purely spontaneous mode
  - Adjustments: \( PEEP \) and \( P_{CPAP} \)
Pressure Control Ventilation (PCV)

- Parameters
  - Triggered by time
  - Limited by pressure
  - Affects inspiration only
- Advantages
  - Requires frequent adjustments to maintain adequate VT
  - Pt with noncompliant lungs may require alterations in inspiratory times to achieve adequate VT

- Disadvantages
  - Requires frequent adjustments to maintain adequate VT
  - Pt with noncompliant lungs may require alterations in inspiratory times to achieve adequate VT

CPAP and BiPAP

- Parameters
  - CPAP – PEEP set at 5-10 cm H2O
  - BiPAP – CPAP with Pressure Support (5-20 cm H2O)
  - Shown to reduce need for intubation and mortality in COPD pts
- Indications
  - When medical therapy fails (tachypnea, hypoxemia, respiratory acidosis)
  - Use in conjunction with bronchodilators, steroids, oral/parenteral steroids, antibiotics to prevent/delay intubation
  - Weaning protocols
  - Obstructive Sleep Apnea

Assist/Control Mode

- Ventilator delivers a fixed volume
  - Control Mode
    - Pt receives a set number of breaths and cannot breathe between ventilator breaths
    - Similar to Pressure Control
  - Assist Mode
    - Pt initiates all breaths, but ventilator cycles in at initiation to give a preset tidal volume
    - Pt controls rate but always receives a full machine breath
  - Assist/Control Mode
    - Assist mode unless pt’s respiratory rate falls below preset value
    - Ventilator then switches to control mode
  - Rapidly breathing pts can overventilate and induce severe respiratory alkalosis and hyperinflation (auto-PEEP)

IMV and SIMV (synchronized intermittent mandatory ventilation)

- Volume-cycled modes typically augmented with Pressure Support
  - IMV
    - Pt receives a set number of ventilator breaths
    - Different from Control: pt can initiate own (spontaneous) breaths
    - Different from Assist: spontaneous breaths are not supported by machine with fixed VT
    - Ventilator always delivers breath, even if pt exhaling
  - SIMV
    - Most commonly used mode
    - Spontaneous breaths and mandatory breaths
    - If pt has respiratory drive, the mandatory breaths are synchronized with the pt’s inspiratory effort

Complication of VENTILATOR

- Migration of the tip of ET tube: atelectasis of the controlateral lung and overdistension of the intubated lung
- Barotrauma (volutrauma): subcutaneous emphysema, pneumomediastinum, subpleural air cysts, pneumothorax, systemic air embolism
- Acute respiratory alkalosis
- Hypotension
- Ventilatory associated pneumonia

VENTILATOR SETTINGS

- Tidal volume
  - 10 to 15 mL/kg
- Respiratory rate
  - 10 to 20 breaths/minute
- Normal minute ventilation 4 to 6 L/min
- Fraction of inspired oxygen
- Flow rate and I:E ratio
CONTRAINDICATIONS FOR PEEP
- Increased intracranial pressure
- Unilateral pneumonia
- Bronchopleural fistulae

VENT SETTINGS TO IMPROVE <OXYGENATION>
PEEP and FiO₂ are adjusted in tandem
- FiO₂
  - Simplest maneuver to quickly increase PₐO₂
  - Long-term toxicity at >60%
  - Free radical damage
- Inadequate oxygenation despite 100% FiO₂
  - Usually due to pulmonary shunting
    - Collapse – Atelectasis
    - Pus-filled alveoli – Pneumonia
    - Water/Protein – ARDS
    - Water – CHF
    - Blood – Hemorrhage
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VENT SETTINGS TO IMPROVE <VENTILATION>
RR and Tᵥ are adjusted to maintain Vₑ and PₐCO₂
- Respiratory rate
  - Max RR at 35 breaths/min
  - Efficiency of ventilation decreases with increasing RR
  - Decreased time for alveolar emptying
- Tᵥ
  - Goal of 10 ml/kg
  - Risk of volutrauma
- Other means to decrease PₐCO₂
  - Reduce muscular activity/seizures
  - Minimizing exogenous carb load
  - Controlling hypermetabolic states
  - Permissive hypercapnea
  - Preferable to dangerously high RR and Tᵥ as long as pH > 7.15
- I: E ratio (IRV)
  - Increasing inspiration time will increase Tᵥ but may lead to auto-PEEP
- PIP
  - Elevated PIP suggests need for switch from volume-cycled to pressure-cycled mode
  - Maintained at <45 cm H₂O to minimize barotrauma
- Plateau pressures
  - Pressure measured at the end of inspiratory phase
  - Maintained at <30-35 cm H₂O to minimize barotrauma

ALTERNATIVE MODES
- I: E inverse ratio ventilation (IRV)
  - Better gas distribution with lower PIP
  - Improved recruitment and FRC, relief of diaphragmatic pressure from abdominal viscera, improved drainage of secretions
  - Logistically difficult
  - No mortality benefit demonstrated
  - ECMO
  - Airway Pressure Release (APR)
- High-Frequency Oscillatory Ventilation (HFOV)
  - Ventilation superimposed over elevated PₐW
  - Avoids repetitive alveolar open and closing that occur with low airway pressures
  - Avoids overdistension that occurs at high airway pressures
  - Well tolerated, consistent improvements in oxygenation, but unclear mortality benefits
  - Disadvantages
  - Potential hemodynamic compromise
  - Pneumothoraces
  - Neuromuscular blocking agents

TREATMENT OF RESPIRATORY FAILURE
- Prevention
  - Incentive spirometry
  - Mobilization
  - Humidified air
  - Pain control
  - Turn, cough, deep breathe
- Treatment
  - Medications
    - Albuterol
    - Theophylline
    - Steroids
  - CPAP, BIPAP, IPPB
  - Intubation
No weaning parameter completely accurate when used alone.

### Clinical parameters
- Resolution/Stabilization of disease process
- Hemodynamically stable
- Intact cough/gag reflex
- Spontaneous respirations
- Acceptable vent settings
  - $\text{FiO}_2 < 50\%$, $\text{PEEP} < 8$, $P_{O_2} > 75$, $\text{pH} > 7.25$

### General approaches
- SIMV Weaning
- Pressure Support Ventilation (PSV) Weaning
- Spontaneous breathing trials
  - Demonstrated to be superior

### Indications for extubation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Normal Range</th>
<th>Meaning Threshold</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tidal volume</td>
<td>$5 - 7 \text{ml/kg}$</td>
<td>$&lt; 5 \text{ml/kg}$</td>
</tr>
<tr>
<td>Respiratory rate</td>
<td>$40 - 70 $呼吸</td>
<td>$&gt; 70 $呼吸</td>
</tr>
<tr>
<td>Vital capacity</td>
<td>$40 - 70 $呼吸</td>
<td>$&gt; 70 $呼吸</td>
</tr>
<tr>
<td>Minute volume</td>
<td>$&lt; 100$</td>
<td>$&lt; 100$</td>
</tr>
<tr>
<td>Minute volume</td>
<td>$&lt; 60$</td>
<td>$&lt; 60$</td>
</tr>
</tbody>
</table>

### Continued ventilation after successful SBT

Inherent risks of intubation balanced against continued need for intubation

- Commonly cited factors
  - Protect airway
  - Potentially difficult reintubation
  - Unstable injury to cervical spine
  - Likelihood of return trips to OR
  - Need for frequent suctioning

### Spontaneous Breathing Trials

SBTs do not guarantee that airway is stable or pt can self-clear secretions

<table>
<thead>
<tr>
<th>Settings</th>
<th>Causes of Failed SBTs</th>
<th>Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{FiO}<em>2 &lt; 50%$, $\text{PEEP} &lt; 8$, $P</em>{O_2} &gt; 75$, $\text{pH} &gt; 7.25$</td>
<td>$\text{SpO}_2 &lt; 90%$ for $&gt;30$ sec</td>
<td>Inotropic support</td>
</tr>
<tr>
<td>$RR &gt; 35$ for $&gt;5$ min</td>
<td>Acute lung injury</td>
<td>Intubation</td>
</tr>
<tr>
<td>$S_{O_2} &lt; 90%$ for $&gt;30$ sec</td>
<td>Systolic BP $&gt; 180$ or $&lt; 90$ mm Hg</td>
<td>Intubation</td>
</tr>
<tr>
<td>$HR &gt; 140$</td>
<td>Prolonged ventilator dependency</td>
<td>Intubation</td>
</tr>
<tr>
<td>$RR &gt; 35$ for $&gt;5$ min</td>
<td>Cardiac dysrhythmia</td>
<td>Intubation</td>
</tr>
<tr>
<td>$S_{O_2} &lt; 90%$ for $&gt;30$ sec</td>
<td>– O2 dependent</td>
<td>Intubation</td>
</tr>
<tr>
<td>$\text{SpO}_2 &lt; 90%$ for $&gt;30$ sec</td>
<td>– Neurologic deficit</td>
<td>Intubation</td>
</tr>
<tr>
<td>$\text{SpO}_2 &lt; 90%$ for $&gt;30$ sec</td>
<td>– Airway stable</td>
<td>Intubation</td>
</tr>
</tbody>
</table>

### Sedation in Mechanically Ventilated Patients

- Benzodiazepines
- Opioids
- Neuromuscarinic agents
- Propofol
- Ketamine
- Dexmedetomidine

### Maintaining Sedation

- Titrate dose to ordered scale
- Motor Activity Assessment Scale (MAAS)
- Sedation-Agitation Scale (SAS)
- Ramsay
- titrate to all increases in the maintenance infusion
- Daily interruption of sedation

### Ventilator Management Algorithm

[Diagram of ventilator management algorithm]

1. **Initial Information**
2. **Acute lung injury**
3. **Airway stable**
4. **Intubated > 2 weeks**
5. **Unstable injury to cervical spine**
6. **Systemic inflammatory response**
7. **Systolic BP > 180 or < 90 mm Hg**
8. **Prolonged ventilator dependency**
9. **Intubation**

### Causes of Failed SBTs

- Hypoxemia
- Hypercarbia
- Hypertension
- Cardiac dysrhythmia
- Central Nervous System (CNS) depression
- Airway instability
- Airway compromise
- Lung injury
- Cardiac failure
- Systemic inflammatory response
- Neuromuscular disease
- Deconditioning, malnutrition
- Ischemia
- Pulmonary edema, cardiac failure
- Anemia
- Altered mental status and inability to protect airway

### Maintenance of Sedation

- Titrate dose to ordered scale
- Motor Activity Assessment Scale (MAAS)
- Sedation-Agitation Scale (SAS)
- Ramsay
- Titrate to all increases in the maintenance infusion
- Daily interruption of sedation
**NEUROMUSCULAR BLOCKING AGENTS**

- Difficult to assess adequacy of sedation
- Polyneuropathy of the critically ill
- Use if unable to ventilate patient after patient adequately sedated
- Have no sedative or analgesic properties

**Depolarizing NMBA**

**Succinylcholine**

- Rapid onset less than 1 minute
- Duration of action is 7-8 minutes
- Pseudocholinesterase deficiency
  - 1 in 3200
- Side Effects
  - Hyperthermia, Hyperkalemia, arrhythmias
  - Increased ICP

**Nondepolarizing Agents**

- Pancuronium
  - Drug of choice for normal hepatic and renal function
- Atracurium or Cisatracurium
  - Use in patients with hepatic and/or renal insufficiency
- Vecuronium
  - Drug of choice for cardiovascular instability

**CASE EXAMPLE**

- 34 y/o female admitted with status asthmaticus and respiratory failure
- You are called to see patient for inability to ventilate
- Tidal volume 800 cc, FIO2 100%, AC 12 Peep 5 cm
- PAP 70, returned TV 200 cc

**Case example continued**

- Examine patient
- CXR
- Sedate
- Assess auto-peep
- Increase E/E
- Lower PAP and MAP
- Reverse bronchospasm & elect. Hypovent.

**CONCLUSION**

- Three options for ventilation
  - Volume, pressure, flow
- Peep, know when to say no
- Always assess to prevent barotrauma
  - ventilate below upper inflection point
  - assess static compliance daily
  - monitor for auto-peep