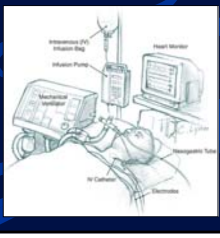
Principles of Mechanical Ventilation

The Basics



Presented by

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Origins of mechanical ventilation

The era of intensive care medicine began with positive-pressure 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

The iron lung created negative pressure in abdomen as well as the chest, decreasing cardiac output.

Iron lung polio ward at Rancho Los Amigos Hospital in 1953.

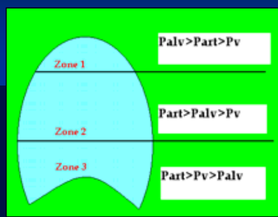
Outline

- **Theory**
  - Ventilation vs. Oxygenation
  - Pressure Cycling vs. Volume Cycling
- **Modes**
- **Ventilator Settings**
- **Indications to intubate**
- **Indications to extubate**
- **Management algorithm**
- **FAQs**

Principles (1): Ventilation

The goal of ventilation is to facilitate CO_2 release and maintain normal P_aCO_2

- **Minute ventilation (V_E)**
  - Total amount of gas exhaled/min.
  - V_E = (RR) x (T_V)
  - V_E comprised of 2 factors
    - V_A = alveolar ventilation
    - V_D = dead space ventilation
  - V_D/V_T = 0.33
  - V_E regulated by brain stem, responding to pH and P_aCO_2
- **Ventilation in context of ICU**
  - Increased CO_2 production
    - fever, sepsis, injury, overfeeding
  - Increased V_D
    - atelectasis, lung injury, ARDS, pulmonary embolism
  - Adjustments: RR and T_V

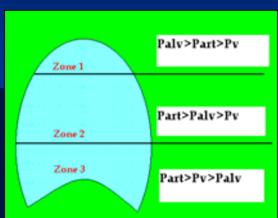


V/Q Matching. Zone 1 demonstrates **dead-space ventilation** (ventilation without perfusion). **Zone 2** demonstrates normal perfusion. **Zone 3** demonstrates **shunting** (perfusion without ventilation).

Principles (2): Oxygenation

The primary goal of oxygenation is to maximize O_2 delivery to blood (P_aO_2)

- **Alveolar-arterial O_2 gradient (P_AO_2 – P_aO_2)**
  - Equilibrium between oxygen in blood and oxygen in alveoli
  - A-a gradient measures efficiency of oxygenation
  - P_aO_2 partially depends on ventilation but more on V/Q matching
- **Oxygenation in context of ICU**
  - V/Q mismatching
    - Patient position (supine)
    - Airway pressure, pulmonary parenchymal disease, small-airway disease
  - Adjustments: FiO_2 and PEEP

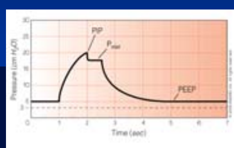


V/Q Matching. Zone 1 demonstrates **dead-space ventilation** (ventilation without perfusion). **Zone 2** demonstrates normal perfusion. **Zone 3** demonstrates **shunting** (perfusion without ventilation).

Pressure ventilation vs. volume ventilation

Pressure-cycled modes deliver a fixed pressure at variable volume (neonates)
Volume-cycled modes deliver a fixed volume at variable pressure (adults)

- **Pressure-cycled modes**
  - Pressure Support Ventilation (PSV)
  - Pressure Control Ventilation (PCV)
  - CPAP
  - BiPAP
- **Volume-cycled modes**
  - Control
  - Assist
  - Assist/Control
  - Intermittent Mandatory Ventilation (IMV)
  - Synchronous Intermittent Mandatory Ventilation (SIMV)

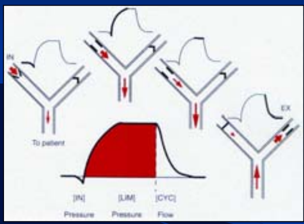


Volume-cycled modes have the inherent risk of volutrauma.

Pressure Support Ventilation (PSV)

Patient determines RR, V_E, inspiratory time – a purely spontaneous mode

- **Parameters**
  - **Triggered by pt's own breath**
  - **Limited by pressure**
  - **Affects inspiration only**
- **Uses**
  - **Complement volume-cycled modes (i.e., SIMV)**
    - Does *not* augment T_V but overcomes resistance created by ventilator tubing
  - **PSV alone**
    - Used alone for recovering intubated pts who are not quite ready for extubation
    - Augments inflation volumes during spontaneous breaths
  - **BiPAP (CPAP plus PS)**

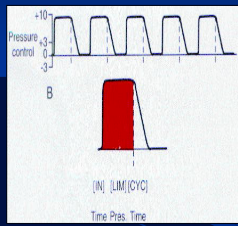


PSV is most often used together with other volume-cycled modes. PSV provides sufficient pressure to overcome the resistance of the ventilator tubing, and acts during inspiration only.

Pressure Control Ventilation (PCV)

Ventilator determines inspiratory time – no patient participation

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



CPAP and BiPAP

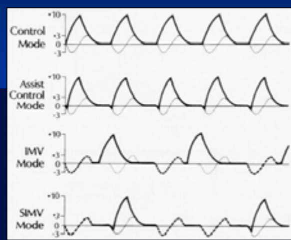
CPAP is essentially constant PEEP; BiPAP is CPAP plus PS

- **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**

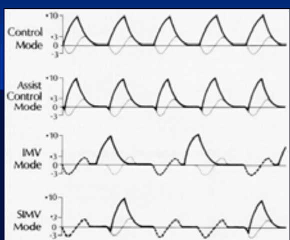


- **Rapidly breathing pts can overventilate and induce severe respiratory alkalosis and hyperinflation (auto-PEEP)**

IMV and SIMV

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 T_V**
  - **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**



Vent settings to improve <oxygenation>

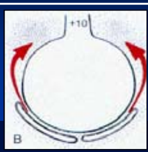
PEEP and FiO_2 are adjusted in tandem

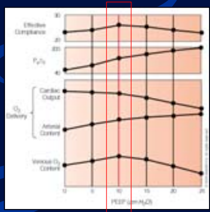
- **FIO_2**
  - **Simplest maneuver to quickly increase P_aO_2**
  - **Long-term toxicity at >60%**
    - Free radical damage
- **Inadequate oxygenation despite 100% FiO_2 usually due to pulmonary shunting**
  - **Collapse – Atelectasis**
  - **Pus-filled alveoli – Pneumonia**
  - **Water/Protein – ARDS**
  - **Water – CHF**
  - **Blood - Hemorrhage**

Vent settings to improve <oxygenation>

PEEP and FiO_2 are adjusted in tandem

- **PEEP**
  - Increases FRC
    - Prevents progressive atelectasis and intrapulmonary shunting
    - Prevents repetitive opening/closing (injury)
  - Recruits collapsed alveoli and improves V/Q matching
    - Resolves intrapulmonary shunting
    - Improves compliance
  - Enables maintenance of adequate P_aO_2 at a safe FiO_2 level
  - Disadvantages
    - Increases intrathoracic pressure (may require pulmonary a. catheter)
    - May lead to ARDS
    - Rupture: PTX, pulmonary edema





Oxygen delivery (DO_2), not PaO_2, should be used to assess optimal PEEP.

Vent settings to improve <ventilation>

RR and T_V are adjusted to maintain V_E and P_aCO_2

- **Respiratory rate**
  - Max RR at 35 breaths/min
  - Efficiency of ventilation decreases with increasing RR
    - Decreased time for alveolar emptying
- **T_V**
  - Goal of 10 ml/kg
  - Risk of volutrauma
- **Other means to decrease P_aCO_2**
  - Reduce muscular activity/seizures
  - Minimizing exogenous carb load
  - Controlling hypermetabolic states
- **Permissive hypercapnea**
  - Preferable to dangerously high RR and T_V, as long as pH > 7.15
- **I:E ratio (IRV)**
  - Increasing inspiration time will increase T_V, but may lead to auto-PEEP
- **PIP**
  - Elevated PIP suggests need for switch from volume-cycled to pressure-cycled mode
  - Maintained at <45cm H_2O to minimize barotrauma
- **Plateau pressures**
  - Pressure measured at the end of inspiratory phase
  - Maintained at <30-35cm H_2O to minimize barotrauma

Alternative Modes

- **I:E inverse ratio ventilation (IRV)**
  - ARDS and severe hypoxemia
  - Prolonged inspiratory time (3:1) leads to better gas distribution with lower PIP
  - Elevated pressure improves alveolar recruitment
  - No statistical advantage over PEEP, and does not prevent repetitive collapse and reinflation
- **Prone positioning**
  - Addresses dependent atelectasis
  - 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)**
  - High-frequency, low amplitude ventilation superimposed over elevated P_{aw}
  - 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
    - Pneumothorax
    - Neuromuscular blocking agents

Treatment of respiratory failure

The critical period before the patient needs to be intubated

- **Prevention**
  - Incentive spirometry
  - Mobilization
  - Humidified air
  - Pain control
  - Turn, cough, deep breathe
- **Treatment**
  - Medications
    - Albuterol
    - Theophylline
    - Steroids
  - CPAP, BiPAP, IPPB
  - Intubation

Indications for intubation

How the values trend should significantly impact clinical decisions

- **Criteria**
  - Clinical deterioration
  - Tachypnea: RR >35
  - Hypoxia: pO2<60mm Hg
  - Hypercarbia: pCO2 > 55mm Hg
  - Minute ventilation<10 L/min
  - Tidal volume <5-10 ml/kg
  - Negative inspiratory force < 25cm H2O (how strong the pt can suck in)
- **Initial vent settings**
  - FiO_2 = 50%
  - PEEP = 5cm H_2O
  - RR = 12 – 15 breaths/min
  - V_T = 10 – 12 ml/kg
    - COPD = 10 ml/kg (prevent overinflation)
    - ARDS = 5-6 ml/kg (prevent volutrauma)
      - Permissive hypercapnea
  - Pressure Support = 10cm H_2O

Indications for extubation

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
    - FiO_2< 50%, PEEP < 8, P_aO_2 > 75, pH > 7.25
- **General approaches**
  - SIMV Weaning
  - Pressure Support Ventilation (PSV) Weaning
  - Spontaneous breathing trials
    - Demonstrated to be superior

Numerical Parameters	Normal Range	Weaning Threshold
P/F	> 400	> 200
Tidal volume	5 - 7 ml/kg	5 ml/kg
Respiratory rate	14 - 18 breaths/min	< 40 breaths/min
Vital capacity	65 - 75 ml/kg	10 ml/kg
Minute volume	5 - 7 L/min	< 10 L/min

Greater Predictive Value	Normal Range	Weaning Threshold
NIF (Negative Inspiratory Force)	> - 90 cm H2O	> - 25 cm H2O
RSBI (Rapid Shallow Breathing Index) (RR/TV)	< 50	< 100

Marino P, The ICU Book (2/e). 1998.

Spontaneous Breathing Trials

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

- **Settings**
  - PEEP = 5, PS = 0 – 5, FiO_2 < 40%
  - Breathe independently for 30 – 120 min
  - ABG obtained at end of SBT
- **Failed SBT Criteria**
  - RR > 35 for >5 min
  - S_aO_2 <90% for >30 sec
  - HR > 140
  - Systolic BP > 180 or < 90mm Hg
  - Sustained increased work of breathing
  - Cardiac dysrhythmia
  - pH < 7.32

Causes of Failed SBTs	Treatments
Anxiety/Agitation	Benzodiazepines or haldol
Infection	Diagnosis and tx
Electrolyte abnormalities (K^+, PO^{4-})	Correction
Pulmonary edema, cardiac ischemia	Diuretics and nitrates
Deconditioning, malnutrition	Aggressive nutrition
Neuromuscular disease	Bronchopulmonary hygiene, early consideration of trach
Increased intra-abdominal pressure	Semirecumbent positioning, NGT
Hypothyroidism	Thyroid replacement
Excessive auto-PEEP (COPD, asthma)	Bronchodilator therapy

Sena et al, **ACS Surgery: Principles and Practice** (2005).

Continued ventilation after successful SBT

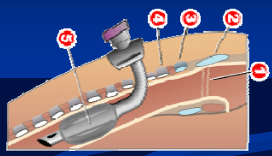
Inherent risks of intubation balanced against continued need for intubation

- **Commonly cited factors**
  - Altered mental status and inability to protect airway
  - Potentially difficult reintubation
  - Unstable injury to cervical spine
  - Likelihood of return trips to OR
  - Need for frequent suctioning

Need for tracheostomy

Prolonged intubation may injure airway and cause airway edema

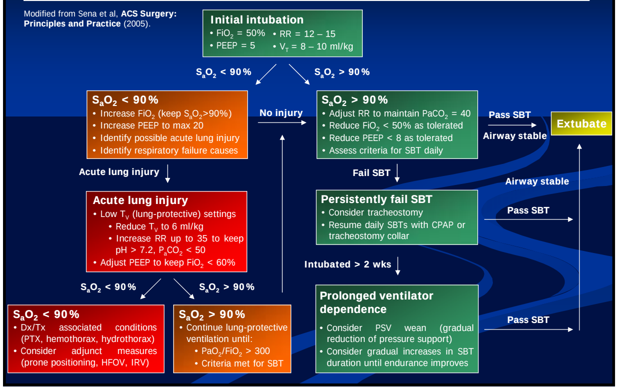
- **Advantages**
  - Issue of airway stability can be separated from issue of readiness for extubation
    - May quicken decision to extubate
  - Decreased work of breathing
  - Avoid continued vocal cord injury
  - Improved bronchopulmonary hygiene
  - Improved pt communication
- **Disadvantages**
  - Long term risk of tracheal stenosis
  - Procedure-related complication rate (4% - 36%)



1 - Vocal cords. 2 - Thyroid cartilage. 3 - Cricoid cartilage. 4 - Tracheal cartilage. 5 - Balloon cuff.

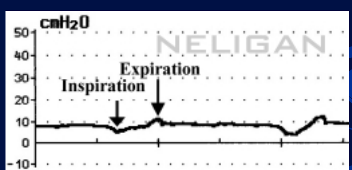
Ventilator management algorithim

Modified from Sena et al, **ACS Surgery: Principles and Practice** (2005).



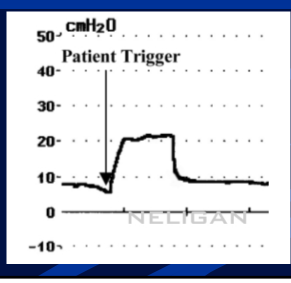
Ventilator Waveforms

1. determine the CPAP level
   - this is the baseline position from which there is a downward deflection on, at least, beginning of inspiration, and to which the airway pressure returns at the end of expiration.



Ventilator Waveforms

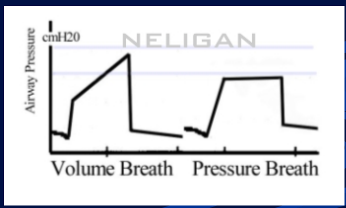
2. is the patient triggering?
   - There will be a negative deflection into the CPAP line just before inspiration.



Ventilator Waveforms

3-A. what is the shape of the pressure wave?

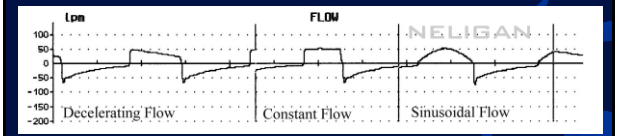
•If the curve has a flat top, then the breath is pressure limited, if it has a triangular or shark's fin top, then it is not pressure limited and is a volume breath.



Ventilator Waveforms

3-B. what is the flow pattern?

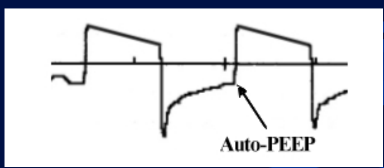
- If it is constant flow (square shaped) this must be volume controlled, if decelerating, it can be any mode.



Ventilator Waveforms

3-C. Is the patient gas trapping?

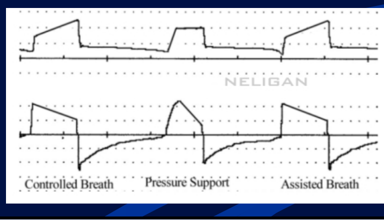
- expiratory flow does not return to baseline before inspiration commences (i.e. gas is trapped in the airways at end-expiration).



Ventilator Waveforms

4. the patient is triggering – is this a pressure supported or SIMV or VAC breath?

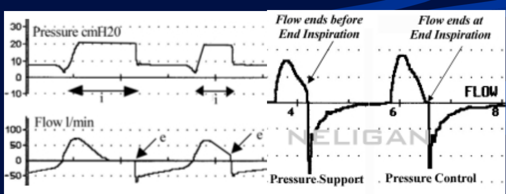
- This is easy, the pressure supported breath looks completely differently than the volume control or synchronized breath: the PS breath has a decelerating flow pattern, and has a flat topped airway pressure wave. The synchronized breath has a triangular shaped pressure wave.



Ventilator Waveforms

5. the patient is triggering – is this pressure support or pressure control?

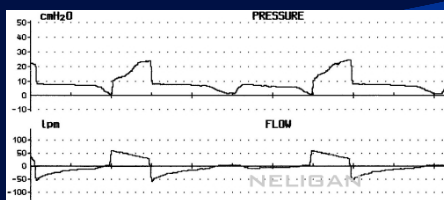
- The fundamental difference between pressure support and pressure control is the length of the breath – in PC, the ventilator determined this (the inspired time) and all breaths have an equal "i" time. In PS, the patient determined the duration of inspiration, and this varies from breath to breath.



Ventilator Waveforms

6. is the patient synchronizing with the ventilator?

•Each time the ventilator is triggered a breath should be delivered. If the number of triggering episodes is greater than the number of breaths, the patient is asynchronous with the ventilator. Further, if the peak flow rate of the ventilator is inadequate, then the inspiratory flow will be "scooped" inwards, and the patient appears to be fighting the ventilator. Both of these problems are illustrated below



References

1. Sena, MJ et al. Mechanical Ventilation. **ACS Surgery: Principles and Practice** 2005; pg. 1-16.
2. Marino, PL. **The ICU Book**. 2nd edition. 1998.
3. Byrd, RP. Mechanical ventilation. **Emedicine**, 6/6/06.

Ventilator Graphics: Optimizing Ventilator Settings

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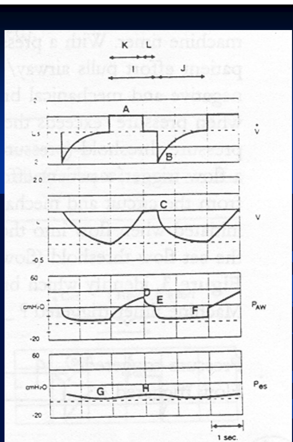
Overview

- Graphical Assessment
- Calculating Loads
- PEEP
- Ventilator Dysynchrony

Graphical Displays

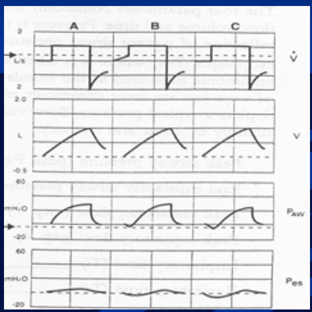
- Four Parameters commonly monitored
  - pressure
    - Ventilator circuit (Paw)
    - Esophagus (Pes) --pleural pressure
  - flow
  - volume
  - time
- Commonly plotted as pressure, flow, and volume over time



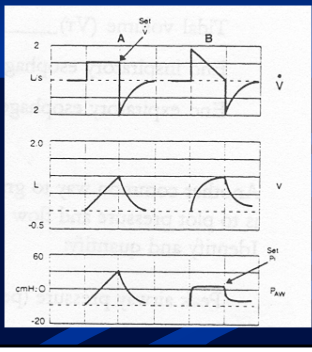
Breath Delivery

- Four phases of ventilatory cycle
  - trigger
  - flow delivery
  - cycle
  - expiratory phase
- Breaths described by what determines the above phases

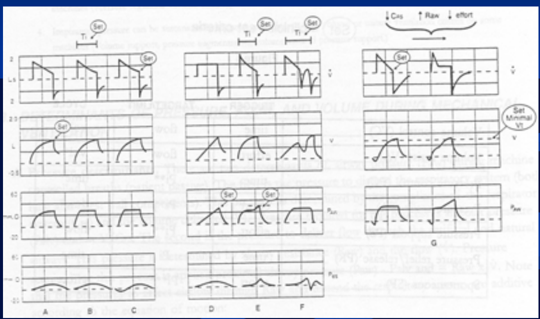
Triggers



Flow



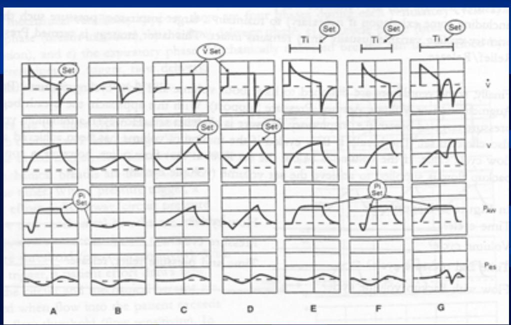
Cycling



Breath Types

	TRIGGER	TARGET/LIMIT	CYCLE
Volume control (VC)	time	flow	vol*
Volume assist (VA)	effort	flow	vol*
Pressure control (PC)	time	Pi**	time*
Pressure assist (PA)	effort	Pi**	time*
Pressure support (PS)	effort	Pi**	flow*
Pressure relief/release (PR)	time	Pi	time
Spontaneous (SP)	effort	Pi***	effort

Breath Types

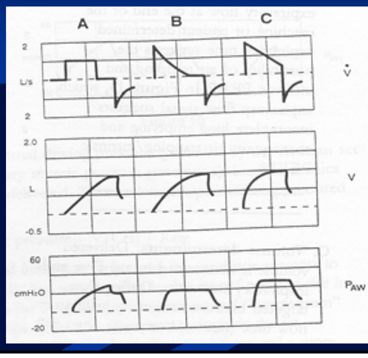


- Graphical Assessment
- Calculating Loads
- PEEP
- Ventilator Dysynchrony

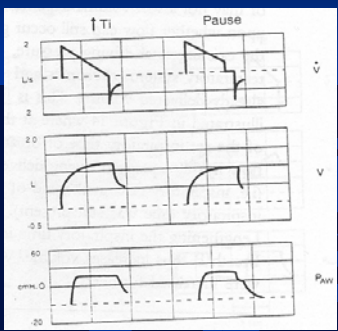
Plateau Pressure

- Lung "overstretch" has been linked to VILI
- An approximation of lung stretch is the "end inspiratory" pressure
- Must be measured in a "no flow" state

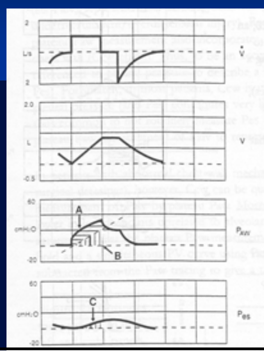
Plateau Pressure



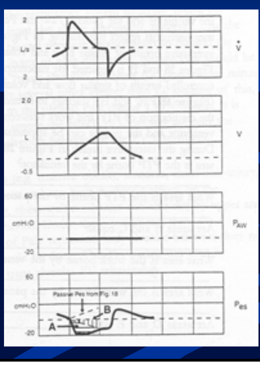
Plateau Pressure



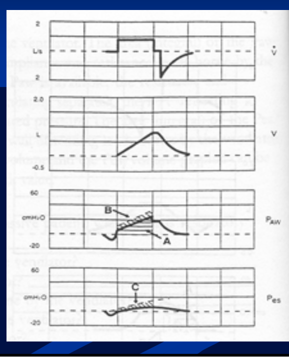
Measuring Loads



Measuring Loads



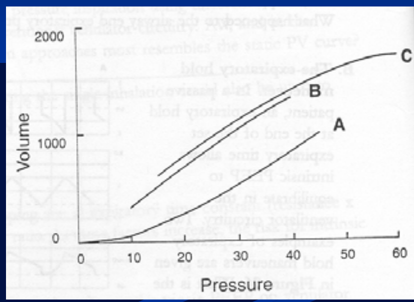
Measuring Loads



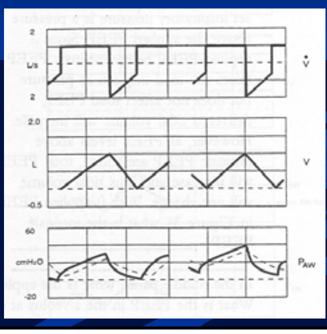
Overview

- Graphical Assessment
- Calculating Loads
- PEEP
- Ventilator Dysynchrony

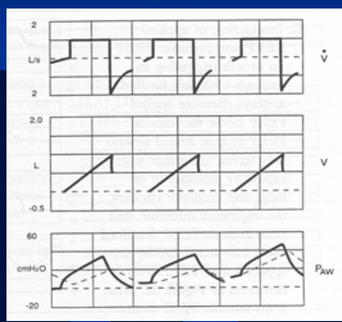
PEEP and Compliance



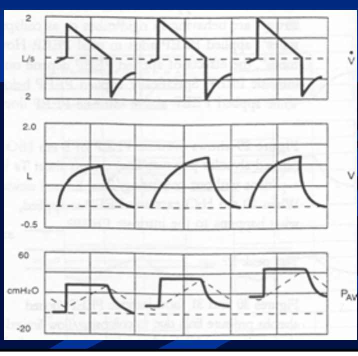
PEEP
Interaction Between Applied and Intrinsic



PEEPi and Flow Limitation



PEEPi and Flow Limitation



Overview

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Patient Related Factors

- Anxiety
- Pain
- Secretions
- Bronchospasm
- Pulmonary edema
- Dynamic hyperinflation
- Abnormal respiratory drive
- Drugs
- Nutrition

Ventilator Related Causes

- Ventilator disconnection
- System leak
- Circuit malfunction
- Inadequate FiO_2
- Inadequate ventilator support

Ventilator Support

- Minute ventilation has a quadratic relationship to work of breathing
- Patient with increased drive, asynchrony may result from:
  - overly sensitive trigger
  - inadequate peak flow or peak flow rate
  - prolonged inspiratory time
  - inadequate pressure support
  - inadequate expiratory time

Background

- Total vs partial support
- Interactive modes can be either synchronous or asynchronous with patient efforts
- Synchronizing is important to avoid “imposed” muscle loading

Overview

- Mechanical breath parameters
  - breath triggering (trigger criteria)
  - ventilator delivered flow pattern (target criteria)
  - ventilator flow termination (cycling criteria)
- Imposed expiratory loads (ET tube, PEEP valve)
- “Backup” ventilator breaths (if not timed appropriately with patient efforts)

Breath Triggering

- Ventilator must sense a spontaneous effort to initiate flow
  - sensitivity (trigger phase)
  - responsiveness (post-trigger phase)
- Inherent asynchrony
  - pleural pressure change dampened
  - avoid “autocycling”
  - demand valve delay

Breath Triggering

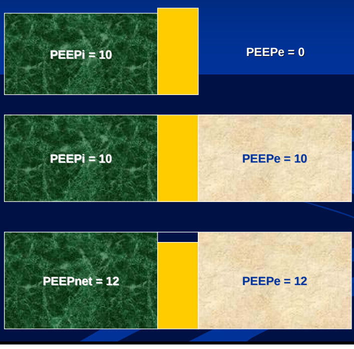
Minimizing Asynchrony

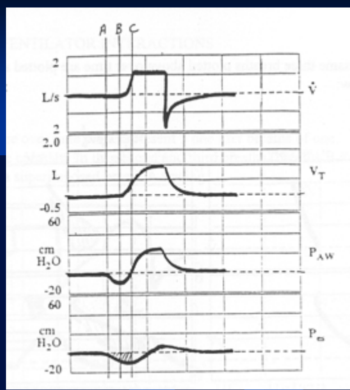
- Microprocessor flow controls
- Inspiratory pressure support
- Sensors in the pleural space or on the phrenic nerve
- Does the type of triggering matter?
  - Pressure
  - Flow

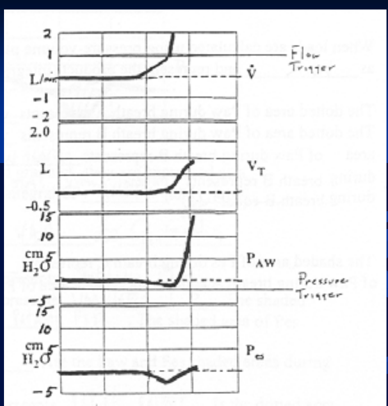
Auto-PEEP and Triggering

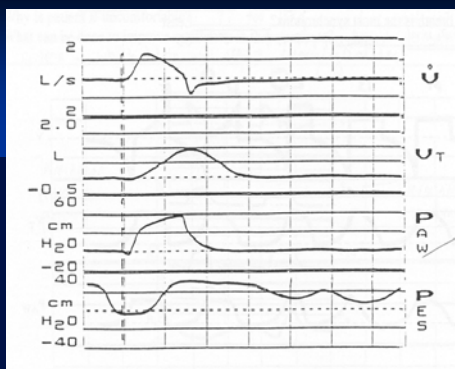
- In the setting of PEEPi, the elevated alveolar pressure at end inspiration can serve as a significant triggering load
- The addition of extrinsic PEEP may help with triggering, but will not affect the degree of hyperinflation

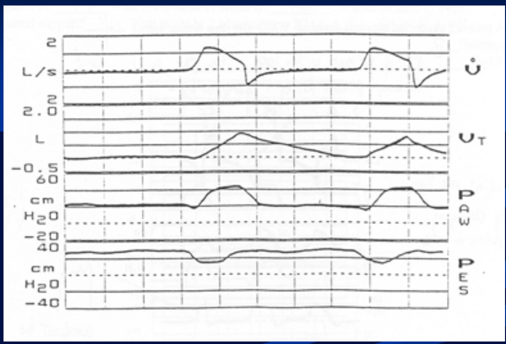
Auto-PEEP and Triggering











Effect of Delivered Flow

- Interactive breaths can be "assisted", "supported", or "unassisted"
- Ventilator breaths can meet one of three goals after triggering
  - fully unload the ventilatory muscles
  - partially unload the ventilatory muscles
  - not affect ventilatory muscle loads

Effect of Delivered Flow

- Inadequate flow rates may cause the patient to sense "air hunger" and lead to greater work of breathing
- Flow rates exceeding demand are also poorly tolerated and can lead to increased ventilatory drives and "double cycling"

Fully Unloaded Breaths

- Goal is to deliver adequate flow over the entire inspiratory effort to unload the contracting muscles
- Assess by comparing the pressure pattern of a patient and machine triggered breath

Fully Unloaded Breaths

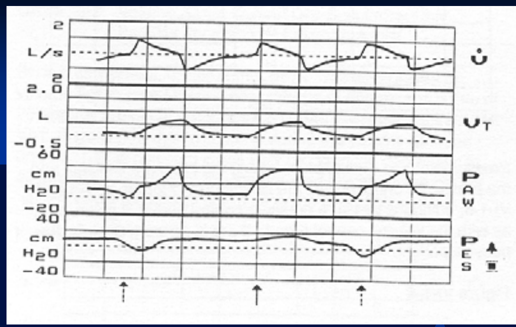
- Synchrony requires careful selection of flow rate and pattern
- Patients with high respiratory drives often require high initial flow rates
- Pressure targeted breaths may be easier
  - high initial flows
  - flow is continuously adjusted

Fully Unloaded Breaths

- Problems with pressure targeting:
  - patients with lower drives require lower flows
  - pressure target is the proximal airway…thus there is inherent under-responsiveness
- Studies comparing pressure and flow targeted breaths are lacking
- Proportional assist may be an alternative in the future

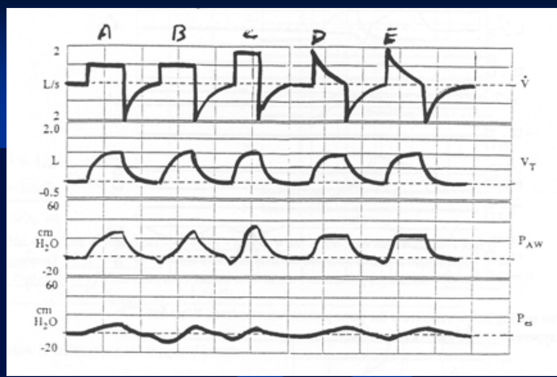
Breaths to Partially Unload

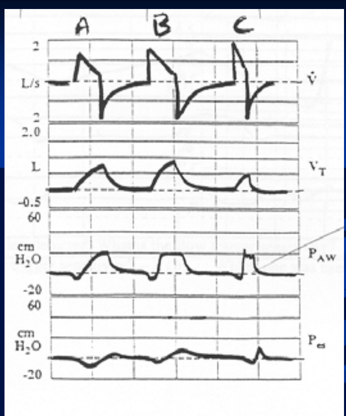
- Intermittently shift work between patient and ventilator
- Patient triggers the breath and then "shares" the work of the breath
- Studies directly comparing the two methods are lacking….though IMV tends to increase overall work done by the patient



Flow Dysynchrony in a Volume Targeted Breath

Flow Dysynchrony in a Pressure Targeted Breath



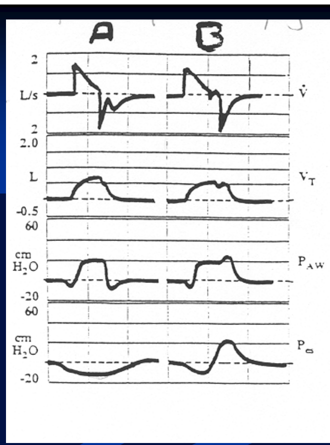


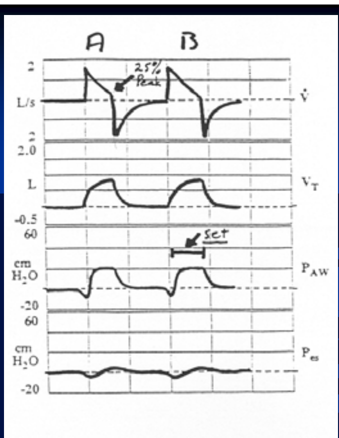
Flow Termination: Cycling

- Cycling should be done in accordance with patient demand and adequate tidal volume
- Premature termination may lead to decreased tidal volume or inspiratory load
- Delayed termination may result in increased tidal volume or expiratory load

Flow Termination: Cycling

- With pressure targeted breaths, termination may be accomplished in several ways:
  - 25-30% of peak flow (duration and magnitude of patient effort can affect Ti)
  - PS level and rate of pressure rise can also affect Ti
  - Pressure assisted breaths….set Ti





Most Common Reasons for Dysynchrony

- ACV: Inappropriate flow settings
- IMV: Little breath-breath adaptation…as back-up rate decreases, WOB increases
- PSV: prolongation of inspiratory flow beyond patient's neural inspiratory time…this may also lead to PEEPi and triggering difficulty

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- Patient comfort, synchrony with the ventilator is important to avoid imposed loads on the respiratory system
- Must consider trigger, flow, and cycling criteria when the patient "fights" the ventilator
- If problem unclear from the airway pressure tracing, consider placing an esophageal balloon

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