Little Things Matter: Mechanical Ventilation for the Anesthetized Infant

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Disclosure
- Covidien/Medtronic
- Draeger Medical

The Children’s Hospital of Philadelphia

SCT

Ventilation during Surgery
- Unique situation compared with the ICU
- Dynamic and Significant Physiologic Changes
  - Surgical trauma and manipulation
  - Physiologic consequences of anesthetic drugs
- Hemodynamic
  - Blood volume
  - Vascular tone
  - Inotropy and Chronotropy
- Pulmonary compliance

Anesthesia for the Neonate
“Just keep the baby warm, hydrated and oxygenated”
Devil is in the Details

- Temperature: Hypothermia is not uncommon but temperature is easy to monitor and manage
- Room temperature
- Convection warmer
- Fluid warmer
- Respiratory gas humidity and heat
- Hydration
  - IV Access: must be adequate
  - Transfusion therapy: easy to overdo it
- Oxygenation & Ventilation

Scope of Discussion

- Physiologic Considerations
- Breathing Circuit considerations
- Airway
- Managing Dead Space
- Ventilator Technology
- Anesthesia ventilator requirements
- Anesthesia vs ICU Ventilator
- Ventilation Mode Selection
- Putting it all together: Monitoring!
  - Compliance
  - Oxygenation
  - CO2 Elimination

Physiologic Considerations

- Lung Maturity
- Transitional Circulation
- Bronchopulmonary Dysplasia

Lung Maturity

- Gestational Age:
  - < 26 wks: Formation of gas exchanging units
  - 26-36 wks: Refinement of gas exchange units
- What is the surface area for gas exchange?
- Are conditions sufficient to maximize gas exchange from the available functioning lung units?
- Ventilator Settings, Vent Mode, and PEEP
- V/Q relationships
- Pulmonary blood flow relies upon hemodynamic stability
- Nitric Oxide
- Surfactant administration
- Mitigating Factor
- Antenatal steroid therapy

Transitional Circulation

- Management
  - Avoided orasis
  - Decreased V/Q
    - Constriction
    - Hypoperfusion
    - Redistribution
  - Inhaled NO
  - Increased Fetal Dopamine
  - Monitoring Post-Ductal SpO2

The Injured Infant Lung

- Bronchopulmonary Dysplasia
- Old BPD
  - Injury and disordered repair of lung tissues
  - Permanent respiratory dysfunction
- New BPD
  - Less severe form of the disease
  - Results from less injurious mechanical ventilation
  - Improved further with Surfactant and Steroid therapy
  - Fewer alveoli for gas exchange
- Reduced Pulmonary compliance and Oxygen requirement
Evaluating the Infant
- Gestational Age
- Antenatal steroids and surfactant for immediate surgery (Partnership with NICU is key)
- Oxygen dependence
- Preoperative Ventilator settings and lung compliance
- Gas exchange information - PaO2 and PaCO2

Basic Principles
- Optimal Gas Exchange
  - Maximum PaO2 with minimum FiO2
  - Desired tidal volume with least pressure
  - Physiologic PaCO2
- Accurate and consistent volume delivery
- Minimize Dead Space
- Humidification

Topics to be Discussed
- Equipment
  - Endotracheal tube selection and patency
  - Apparatus Dead Space
  - Humidification
  - Available anesthesiology Ventilator
    - Breathing circuit compliance
- Do you need an ICU ventilator?
- Selection of Ventilation Mode
  - Pressure v Volume Control
- Monitoring considerations

Airway Considerations
- Cuffed v Uncuffed
  - Cuffed are acceptable/desirable
    - Proper size
    - Manage cuff pressure - Fixed leak pressure may not be acceptable
- Micro-Cuff Technology
  - Low dead space adapter
  - Seals at the trachea not the cricoid cartilage
  - Cuff profile - seals at lower pressure than traditional cuff
  - Intubation mark and Distal cuff location - less risk of endobronchial intubation
  - Expensive

Dead Space
- Definition: Bidirectional flow without gas exchange
- 3 A's of Dead Space
  - Alveolar - V/Q relationships
  - Anatomic
  - Apparatus
- Wasted or ineffective ventilation
  - X: Exhaled CO2 per breath
  - Z: Anatomic + Apparatus
  - Y: Alveolar

Dead Space & Gas Exchange
- Impact on Gas Exchange

TOTAL DEAD SPACE = Apparatus + Anatomic + Alveolar


Dead Space and VILI

- Increase RR can normalize CO2
- Etiology of Ventilator Induced Lung Injury
  - Barotrauma - ?
  - Volutrauma - Overdistention injury
  - Atelectotrauma - Repetitive collapse and recruitment of alveoli
- Current Approach - Peep and minimize tidal volume

VILI & Power

- Total Power influences risk of lung injury
- Healthy piglets 21 +/- 2 Kg
- 5 groups: VT 38 mls/kg x 54 Hrs
  - RR 3, 6, 9, 12, 15 bpm
  - Power J/min
  - Pressure - Volume Curve
  - Threshold for injury 12J/min
- Increased dead space will increase the power delivered to the lung

Minimizing Dead Space Impact

- Anatomic - Not much option
- Alveolar - maximize alveolar ventilation, maintain hemodynamics
- Apparatus selection
  - ETT
  - Circuit devices - HME, Gas sampling, extensions

Dead Space and Gas Exchange

- Dead space typically assumed to impact CO2 elimination
- What is the impact on oxygenation?
- Alveolar Gas Equation - FiO2 Dependent, as CO2 rises, PaO2 is impacted
- Efficiency of ventilation - ? evidence
- Arterial CO2 (PaCO2) or surrogates (ETCO2) are primarily used to assess the impact of dead space

Airway Apparatus

- Endotracheal Tube
  - Internal dead space
- Connectors
  - Elbow
  - Flexible
- HMEs/Filter
- What are the best choices?
  - VT is 6-8 mls/kg
  - Common items can significantly increase Vd/Vt
  - Each device adds dead space!

Humidification

- Rationale
  - Decrease heat loss
  - Protect mucosa
  - Prevent drying of secretions
- Passive Humidification (HME)/Filter
  - Simple:
- Active

Feldman, Jeffrey, MD, MSE  Little Things Matter: Mechanical Ventilation for the Anesthetized Infant
Humidity Targets

- Physiologic

<table>
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<tr>
<th>Location</th>
<th>Approx Temp C</th>
<th>Humidity mg/L</th>
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<tr>
<td>Nose</td>
<td>22</td>
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<tr>
<td>Larynx</td>
<td>31-33</td>
<td>26-32</td>
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<tr>
<td>Trachea</td>
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<td>34-38</td>
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<tr>
<td>Bronchi</td>
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</table>

- Recommended
  - 33-44 mg H2O/L @ 34-41 deg C
  - Minimum of 30 mg H2O/L for HMEs
  - Increased temp risks thermal injury and overhydration

Williams R. CCM. 1996;24:1920.

HMEs

- Dead Space Implications
  - Minimum tidal volume a guide
  - Gas sampling important?
    - None: 0.2 ml/min volume
    - Present: 0.36 ml/min volume
  - Are they effective humidifiers?

HME Choices

<table>
<thead>
<tr>
<th>HME</th>
<th>Humidity (mg/L) @ mls</th>
<th>Dead Space mls</th>
<th>Sampling?</th>
<th>Vol Range mls</th>
<th>Resistance (cmH2O @ L/m)</th>
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<tbody>
<tr>
<td>Aqua N</td>
<td>30 @ 25</td>
<td>2</td>
<td>No</td>
<td>10-50</td>
<td>1.8 @ 15</td>
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<tr>
<td>Humidstar 2</td>
<td>37.6 @ 50</td>
<td>2</td>
<td>No</td>
<td>10-50</td>
<td>1.1 @ 10</td>
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<tr>
<td>Twinstar 8</td>
<td>37.9 @ 50</td>
<td>8</td>
<td>Yes</td>
<td>25-200</td>
<td>1.4 @ 10</td>
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<tr>
<td>Gibeck Pedi</td>
<td>30 @ 100</td>
<td>13</td>
<td>Yes</td>
<td>50-250</td>
<td>1.6 @ 20</td>
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<tr>
<td>DAR Neo</td>
<td>30 @ 50</td>
<td>10</td>
<td>Yes</td>
<td>30-100</td>
<td>0.6 @ 5</td>
</tr>
<tr>
<td>DAR Inf</td>
<td>32 @ 250</td>
<td>31</td>
<td>Yes</td>
<td>75-300</td>
<td>1.6 @ 20</td>
</tr>
</tbody>
</table>

- Which HME you select matters
  - Dead space
  - Presence of a gas sampling adapter

HMEs - Temperature, WOB

- Temperature
  - Passive humidifiers have increased latency
  - Temperature similar
- Work of Breathing
  - Increased resistance
  - Important during spontaneous/unsupported ventilation

Do you need Gas Sampling?

- Capnography is a monitoring standard
  - Critical to be able to assess ETI integrity
- Sidestream adapter
  - Increases dead space - HME or alone
  - Alone - XX mls
  - Offers anesthetic agent monitoring
- Mainstream Capnography is an alternative
  - Often requires another monitor
  - No Agent Analyzer
- Philips Infant/Neonate: < 1 ml
- Draeger CO2 cuvette: < 5 mls
- What about humidity?
Active Humidifiers

- Highly Effective - Heat and Humidity
- Can exceed physiologic humidity
- Adds complexity
  - More connections
  - Heated Circuit - reduce rainout, maintain humidification
  - Infectious potential
  - False Alarms
  - Impact on Circuit Compliance
- Use low compliance circuit
- Pediatric heated circuit
  - Empty Reservoir: 1.5 mls/cmH2O
  - Full reservoir: 1.6 mls/cmH2O

Active Humidifier and Compliance

- Increases circuit compliance
- No humidifier
- Empty Humidifier
- Full Humidifier
- Minimize by filling reservoir
- Influences choice of anesthesia machine and ventilation mode
  - Need Compliance compensation
  - Test in the configuration you will use
  - If not then Pressure mode

Passive v Active Humidification

- Cochrane Review 2010
  - Kelly et al. Cochrane Review, 2010
  - 33 Trials - 30 adult, 3 pediatric
  - Minimal difference between active and passive
  - Passive: Reduced Cost and Risk of Pneumonia, Increased Min Vent and paCO2, Increased airway occlusion?
  - Active: Incr pneumonia risk
  - More research needed especially pediatric patients

Passive v Active Humidification

- Active v Passive for 18 hours
  - Schiffman, CCM 1997;25:1755
  - 6 Passive, 6 Active, 6 Passive
  - 40 infants and neonate
  - Active: 33.8 +/- 2.9 mg/L
  - Passive: 34.0 +/- 2.6mg/L
  - No difference in complications – Temp, CO2, Airway occlusion

Humidification recommendations

- Active Humidifier + Mainstream Adapter
  - Least added dead space
  - Complexity
  - No agent monitoring
- Active Humidifier + Sidestream Adapter
  - Dead space increases (4-5 mls)
  - Agent monitoring possible
- Passive Humidifier w/ Sampling Adapter
  - Maximum dead space impact (8 mls)
  - Match size of device to expected tidal volume
  - Use within volume specifications of the device
  - Avoid adding other airway devices
Anesthesia v ICU Ventilator?

- **The Key Difference: - Anesthetic Agent**
- Isolated patient circuit - Separate patient gas from drive gas
- Inspiratory volume limited to ventilator capacity
- Rate of change in gas concentrations related to FGF
- Circle system to support rebreathing of exhaled anesthetic vapor
- CO2 absorbent
- Scavenging system to prevent room contamination
- MANUAL Ventilation is easy

- **ICU Ventilator**
  - Drive gas is patient supply
  - "Unlimited" volume/pressure for ventilation mode
  - Most sophisticated ventilation modes
  - Monitoring advantages
    - Flow sensor mounted on the airway

Anesthesia Ventilator?

- **Differences in capabilities of anesthesia ventilators**
- Compliance Compensation is ESSENTIAL to accurate volume delivery and monitoring

Breathing Circuit Compliance

- **Compliance**
- Gas compression
- Tubing expansion
- Reduces volume delivered to the airway
- Compliance Compensation - Set tidal volume delivered to the airway.

Compliance Compensation Enhances Monitoring

- **Accurate Volume Delivery to the Airway**
- Improved volume monitoring
- Self test requires intended configuration

Compliance Compensation Limits

- **Example**
  - Draeger Apollo
    - INFANT: max 135 mL ( @ set Vt < 100 mL) or 5.4 mls/cmH2O at 25 cmH2O
    - CHILD: max 165 mL ( @ set Vt < 200 mL)
    - ADULT: max 240 mL or 6 mls/cmH2O @ 40 cmH2O
  - Pressure limit will protect patient at normal circuit compliance

Compliance Compensation

- **Essential feature for small infants - supports volume targeted ventilation modes and improved volume monitoring**
- Present in most modern anesthesia ventilators
- Initial self test to measure circuit compliance is essential
- Self test must be done with intended configuration
- Implications for monitoring
  - Tidal volume
  - Spirometry from a remote flow sensor
Anesthesia Ventilator Technology

- Traditional
  - Bellows
  - Piston
- Blower (Draeger)
  - Mechanical pressure generator
  - Rapid change in patient gas concentrations
- Volume Reflector (Maquet)
  - Pneumatic pressure generator
  - Drive gas directly coupled to patient gas

ICU Ventilator

- Advantages
  - Unlimited drive gas
  - Drive gas and patient gas are the same
  - Modes of ventilation
  - Monitoring - airway flow sensor
- Airway flow sensor is a major advantage
  - Direct measurement of inspired and expired volume
  - Ability to control volume delivery directly
  - Direct measurement of spirometry
  - Flow Sensor adds dead space!
  - Draeger Flow Sensor - 0.8 mls
  - Draeger CO2 sensor - 0.5 mls

Spec Comparison

<table>
<thead>
<tr>
<th>Device</th>
<th>Type</th>
<th>Pmax</th>
<th>RR Max</th>
<th>PEEP</th>
<th>Vt min</th>
<th>Compl</th>
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<td>A7 P-Bellows</td>
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<td>100</td>
<td>50</td>
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<td></td>
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<tr>
<td>Flow-i P-Reflectr</td>
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<td>100</td>
<td>20</td>
<td>5-20</td>
<td>Yes</td>
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<tr>
<td>Apollo M-Piston</td>
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<tr>
<td>Perseus M-Blower</td>
<td>70</td>
<td>100</td>
<td>20</td>
<td>5-20</td>
<td>Yes</td>
<td></td>
</tr>
</tbody>
</table>

P - Pneumatic
M - Mechanical

Ventilator Recommendations

- Anesthesia Ventilator
  - Compliance compensation essential
    - Volume mode
    - Recruitment
    - Anesthetic vapor delivery
  - Monitoring
  - Familiarity
  - Plan for humidification and gas sampling to minimize dead space
- ICU Ventilator
  - Significant lung disease
  - Recruitment per exchange
  - Stable on ICU ventilator settings
  - Airway flow sensor is helpful especially in volume mode
  - Does allow for minimal dead space configuration
- What ventilation mode?

LPV & Anesthetized Patient

- Randomized Prospective Study
  - 400 Patients (200 per group) abdominal surgery
  - Traditional (10-12 mls/kg no PEEP, Recr) v LPV (6-8 mls/kg + PEEP/Recr)
  - 55 v 21 patients had one or more major pulm or extrapolmonary Cx within 7 days
- Complications: Pneumonia, resp failure, sepsis
- LOS 13 v 11 days


Lung Protective Ventilation

- Lung protective ventilation beneficial in adults
  - Volume target 7 mls/kg
  - Pressure Limit < 30 cmH2O
  - PEEP
  - Recruitment maneuver
  - Most impact in “at risk” patients
  - Limited data in pediatric surgical patients
Neonatology Experience

- Cochrane Review: VTV vs PLV in Neonates
  - Volume targeted lung protective ventilation reduced death and chronic lung disease vs Pressure Limited Ventilation
    (Ref: Wheeler et al., Cochrane Review, 2011)
- Neovent Study Group
  - Volumes 4-7 ml/kg typical
  - PEEP 4-6 cmH2O
  (Ref: van Kamm AH, J Pediatrics. 2010;157:767.)

Ventilation Modes

- Controlled Modes
  - VCV: Volume Controlled Ventilation
  - PCV: Pressure Controlled Ventilation
  - PCV-VG, Autoflow, PRVT, PRVC: Volume Targeted Ventilation with constant Pressure
- Supported Modes
  - Pressure Support Ventilation
- Hybrid Modes
  - VCV/PS: Synchronized Volume Controlled Ventilation with Pressure Support
  - PCV/PS: Synchronized Pressure Controlled Ventilation with Pressure Support
  - Airway Pressure Release Ventilation (APRV)

Volume Controlled Ventilation

- VOLUME CONSTANT (Set)
- Flow = Set Volume ÷ Set i-Time
- PRESSURE VARIES with lung compliance
- Peak Pressure at end inspiration
- Ventilator does not know anything about lung compliance

Pressure Controlled Ventilation

- VOLUME VARIES with lung compliance
- Peak flow set, flow changes with lung compliance
- PRESSURE CONSTANT (Set)
- = Set Pressure for Set i-Time
- Max Inspiratory Pressure for entire inspiratory time
- Ventilator does not know anything about lung compliance

Picking the Ventilation Mode

"If I change to volume mode the PIP goes down"

- PIP results from flow through the resistance of the airways
- In the absence of flow
  - Pressure is reduced
- Pressure – volume relationship determined by lung compliance
- Best way to impact inspiratory pressure is to maximize lung compliance

Insp Pressure - PCV and VCV

Ref: Nunn's Respiratory Physiology
Volume Target - Constant Pressure

- **VOLUME CONSTANT (Set)**
  - Peak flow set, flow changes with lung compliance

- **PRESSURE CONSTANT**
  - Pressure derived

- Ventilator must learn lung compliance
- Measures relationship between volume and pressure
- Limited if frequent changes in lung compliance

Selecting the Ventilation Strategy

- **Volume is important**
  - Lung protective ventilation
  - Accurate tidal volumes must be reliably delivered
- **PEEP is important**
- **Excessive pressure should be avoided**
- **Pressure limit protective but not a strategy**
- **Square wave pressure may improve gas exchange in difficult to ventilate patients**

- New anesthesia ventilators offer volume guarantee and favorable pressure waveform
  - Accurate volume delivery
  - PHT, AutoFlow, PCV-VG, PRVC
- **Volume modes may be limited in the smallest patients**
  - 3 Kg or volumes less than 20 mls
  - Difficult to monitor precisely
  - PCV is reliable and will provide consistent tidal volume if lung compliance does not change

Which Ventilation Mode

- **VCV**
  - Guaranteed tidal volume is desirable
  - Leaks are unlikely - Cuffed tubes helpful
  - Pressure limit can protect against transient compliance changes eg. cough, surgical maneuver
  - If you reach the pressure limit the set volume is not delivered!
- **PCV**
  - Equipment without accurate volume delivery
  - Small tidal volumes at lower limit of specifications (< 3 Kg)
  - Pressure waveform promotes lung recruitment
  - Underlying lung pathology i.e., heterogeneous compliance (ARDS)
  - Leaks eg. uncuffed ET, bronchopleural fistula
  - Need to monitor tidal volume and respond to changes

Monitoring Considerations

Goals of Optimizing Ventilation

- **Oxygenation**
  - Maximum PaO2
  - Minimum FiO2
- **CO2 Elimination**
  - Acceptable PacCO2
- **Lung Compliance**
  - Desired volume
  - Minimum pressure
- Are bedside monitors helpful to meet these goals?

Pulse Oximetry

- **Convenient**
- **Measures saturation not partial pressure**
- Cannot detect moderate oxygenation changes when using supplemental oxygen
- Maintain low FiO2 - desirable & better monitoring
Pulse Oximetry
- Saturation vs inspired oxygen curves

Ref: Jones JG. JCMC 16:337, 2000

Capnography
- Convenient
- Well established
- Good monitor of airway integrity
- Limited utility for effectiveness of ventilation
- Unpredictable arterial to end-tidal CO2 gradient
- Small tidal volumes (decr Vd/Vt) will influence the gradient
- Arterial blood gas analysis is required when control of carbon dioxide is essential

Minimizing the ET to PaCO2 Gradient
- Key Factors
  - Tidal Volume
  - Dead space to tidal volume ratio
- GOAL: Best alveolar sample, minimal dilution by dead space gas
- Minimize dead space
- Insure adequate tidal volume and evaluate if tidal volume influences ETCO2.

ETCO2 and Exhaled Volume
- Study of Portable Capnometer in Spont Breathing, non-intubated patients
- Compared ETCO2 to PaCO2 after tidal volume and vital capacity maneuver
- Reduced PaCO2-ETCO2 gradient with vital capacity maneuver

Volumetric Capnography
- Volumetric Capnography
  - Volume measurement informs the quality of the signal
  - Blood gas data provides efficiency of ventilation
  - Requires mainstream CO2/flow sensor

Lung Recruitment and Monitoring
- Evaluation of lung recruitment in Obese patients using Pulse Oximetry and Volumetric Capnography
  (Tusman et al. A&A 2014;118:137)
  - Lung recruitment in 20 obese patients undergoing bariatric surgery
  - Used SpO2 - FiO2 relationship to find opening and closing pressures
  - Volumetric CO2 to determine dead space and CO2 exhaled per breath
  - Assessed value of monitored parameters for detecting closing pressure based upon lung compliance changes
Continuous Spirometry

- Pressure/volume and Flow/volume Loops
- Breath to breath lung compliance
- No information on gas exchange
- New ventilator technology facilitates measurement
- Influenced by Ventilator mode

PV Loops and Ventilator Mode

- VCV v PCV

Conclusions

- The approach to Ventilation and oxygenation in small infants is important especially immediately after delivery
- Equipment Considerations
  - Modern anesthesia ventilator with compliance test at circuit configuration intended for use
  - Minimize apparatus dead space especially HME
  - Consider active humidifier with a gas sampling port or mainstream capnography
- Ventilator Mode
  - VCV preferred but PCV acceptable with careful monitoring of exhaled volume
  - Manual ventilation is often required during surgery which favors an anesthesia ventilator
- Monitoring
  - Optimize the ventilator strategy for the individual patient