Individualizing Mechanical Ventilation

Patient vs. Population

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www.respiratoryresource.ca/cccf
Disclosure

- Speaker fees from:
  - Cardinal Health
  - CareFusion
  - Covidien

- No conflict of interested for this presentation
Ventilator-associated lung injury in patients without acute lung injury at the onset of mechanical ventilation

Ognjen Gajic, MD; Saqib I. Dara, MD; Jose L. Mendez, MD; Adebola O. Adesanya, MD; Emir Festic, MD; Sean M. Caples, MD; Rimki Rana, MD; Jennifer L. St. Sauver, PhD; James F. Lymp, PhD; Bekele Afessa, MD; Rolf D. Hubmayr, MD

Crit Care Med 2004 Vol. 32, No. 9

Critical Care

Ventilation with lower tidal volumes as compared to conventional tidal volumes for patients without acute lung injury - a preventive randomized controlled trial

Critical Care 2010, 14:R1    doi:10.1186/cc8230
Tidal Volume

- Risk factors associated with the development of acute lung injury
- Transfusion of blood products
  - OR, 2.9
  - $p < 0.001$
- History of restrictive lung disease
  - OR, 3.6;
  - $p = 0.044$
- Large tidal volume
  - OR, 1.29 for each mL above 6 ml/kg PBW
  - $p < .001$
- Women more likely to receive excessive tidal volume
  
  $10 \text{ ml/kg} = \text{OR 5.2}$
Tidal Volume
Plateau Pressure

- Plateau pressure measured by the ventilator represents the respiratory system
  - Lung + Chest Wall

- Chest wall elastance normally accounts for up to 20% of the applied airway pressure in apneic patients
Normal Chest Wall

- 30 cm H$_2$O applied airway pressure
  - Lung = 25 cm H$_2$O
    - (83%)
  - Chest wall = 5 cm H$_2$O
    - (17%)
## Lung Stress

<table>
<thead>
<tr>
<th></th>
<th>Transpulmonary Pressure Plateau (end-inspiration)</th>
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</thead>
<tbody>
<tr>
<td>Lethal</td>
<td>≥ 27 cm H$_2$O</td>
</tr>
<tr>
<td>Total Lung Capacity</td>
<td>25 cm H$_2$O</td>
</tr>
<tr>
<td>Safe Upper Limit</td>
<td>≤ 20 cm H$_2$O</td>
</tr>
</tbody>
</table>

Curr Opin Crit Care 2012; 18:000 – 000
Positive End-Expiratory Pressure

- Baseline pleural pressure estimated by esophageal balloon
- Surgical patients
- Normal (BMI < 30)
  - 6.9 ± (3.1) cm H$_2$O
- Obese (BMI 38 – 80)
  - 12.5 ± (3.9) cm H$_2$O
Positive End-Expiratory Pressure

Pleural Pressure

Use Appropriate PEEP
## Mechanical Ventilation

### Population

- **Tidal volume**
  - 6 ml/kg of IBW

- **Plateau pressure**
  - ≤ 25 cm H$_2$O

- **PEEP**
  - 5 – 10 cm H$_2$O for patients with normal BMI
  - 8 – 14 cm H$_2$O for obese patients
ARDSNet Protocol

- **Tidal volume**
  - 6 ml/kg of IBW

- **Plateau pressure**
  - ≤ 30 cm H$_{2}$O

- **PEEP**

<table>
<thead>
<tr>
<th>FIO2 %</th>
<th>30</th>
<th>40</th>
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<tr>
<td>PEEP cmH$_{2}$O</td>
<td>5</td>
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<td>16</td>
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<td>20–24</td>
</tr>
</tbody>
</table>

NEJM 2000;342:1301-8
Higher versus Lower Positive End-Expiratory Pressures in Patients with the Acute Respiratory Distress Syndrome

The National Heart, Lung, and Blood Institute ARDS Clinical Trials Network*

Ventilation Strategy Using Low Tidal Volumes, Recruitment Maneuvers, and High Positive End-Expiratory Pressure for Acute Lung Injury and Acute Respiratory Distress Syndrome
A Randomized Controlled Trial

JAMA, 2008—Vol 299, No. 6
<table>
<thead>
<tr>
<th>FiO2 %</th>
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<tr>
<td>FiO₂</td>
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<td>0.3</td>
<td>0.3</td>
<td>0.4</td>
<td>0.4</td>
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<td>0.4</td>
<td>0.5</td>
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<td>0.7</td>
<td>0.8</td>
<td>0.8</td>
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<td>PEEP</td>
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<td>20</td>
<td>22</td>
<td>22</td>
<td>22</td>
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</table>
Positive End-Expiratory Pressure Setting in Adults With Acute Lung Injury and Acute Respiratory Distress Syndrome: A Randomized Controlled Trial

JAMA, February 13, 2008—Vol 299, No. 6
Randomized Controlled Trials
Population

- Brower et al. 2004
- Meade et al. 2008
- Mercat et al. 2008
Types ARDS

ARDS

ARDS

ARDS

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ARDS
Treating the Patient
Treating the Patient

- Tidal volume
  - 6 ml/kg of IBW

- Plateau pressure
  - Based on lung physiology

- PEEP
  - Based on lung physiology
Treating the Patient

• **Decremental PEEP Titration**
  • Individualizes PEEP

• **Esophageal Pressure Measurements**
  • Individualizes PEEP
  • Individualizes Plateau pressure
PEEP and Oxygenation

![Graph showing the relationship between PEEP and PaO2/FiO2](image_url)
PEEP and Ventilation

![Graph showing Vd/VT vs PEEP (cm H2O)](image)

Respiratory Care October 2012
PEEP and Compliance

![Graph showing compliance vs. PEEP (cm H2O)](image)

*Respiratory Care October 2012*
Esophageal Pressure Measurements
Esophageal Pressure Measurements

Gentle compression of the abdomen to confirm placement

Look for cardiac oscillations
Esophageal Pressure Measurements

Abdominal Compression

Cardiac Oscillations

Need to covert mm Hg to cm H₂O
Positive End-Expiratory Pressure

Pleural Pressure

Use Appropriate PEEP
Lung Stress

- Loring et al.
  - Lung Stress (PtpPlateau) = PtpPEEP + E_L x VT
Lung Stress

- Loring / Talmor:
- Lung Stress = $P_{tpPEEP} + E_L \times VT$
- Lung Stress = $P_{tpPEEP} + \Delta P_{tp} \times \frac{VT}{VT}$
- Lung Stress = $P_{tpPEEP} + \Delta P_{tp} \times VT$
Esophageal Pressure Measurements

- **Lung Stress**
  - Perform an inspiratory hold
    - Record plateau airway pressure
    - Record plateau esophageal pressure

- **Optimal PEEP**
  - Perform an expiratory hold
    - Record baseline airway pressure (PEEP)
    - Record baseline esophageal pressure
## Esophageal Pressure Measurements

<table>
<thead>
<tr>
<th></th>
<th>Paw</th>
<th>Pes</th>
<th>Ptp</th>
</tr>
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<tbody>
<tr>
<td>Inspiratory Hold</td>
<td>40</td>
<td>30</td>
<td>10</td>
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<tr>
<td>Expiratory Hold</td>
<td>12</td>
<td>18</td>
<td>-6</td>
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</table>

\[ \Delta \text{Ptp} = 16 \]

\[ \text{Lung Stress} = \text{Ptp}_{\text{PEEP}} + \Delta \text{Ptp} \]
\[ \text{Lung Stress} = -6 + 16 \]
\[ \text{Lung Stress} = 10 \text{ cm H}_2\text{O} \]
Mechanical Ventilation Guided by Esophageal Pressure in Acute Lung Injury


Ptp Plateau $< 25$ cm H$_2$O

<table>
<thead>
<tr>
<th>Esophageal-Pressure–Guided Group</th>
<th>( \text{FiO}_2 )</th>
<th>0.4</th>
<th>0.5</th>
<th>0.5</th>
<th>0.6</th>
<th>0.6</th>
<th>0.7</th>
<th>0.7</th>
<th>0.8</th>
<th>0.8</th>
<th>0.9</th>
<th>0.9</th>
<th>1.0</th>
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<tr>
<td>( P_{L\text{exp}} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>2</td>
<td>4</td>
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</table>

<table>
<thead>
<tr>
<th>Control Group</th>
<th>( \text{FiO}_2 )</th>
<th>0.3</th>
<th>0.4</th>
<th>0.4</th>
<th>0.5</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
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<tr>
<td>PEEP</td>
<td>5</td>
<td>5</td>
<td>8</td>
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<td>10</td>
<td>10</td>
<td>10</td>
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<td>20–24</td>
<td></td>
</tr>
</tbody>
</table>


Mechanical Ventilation Guided by Esophageal Balloon in Acute Lung Injury

• Primary outcome
  • oxygenation

• Secondary outcomes
  • respiratory system compliance
  • patient outcomes

• Results
  • improved oxygenation ($p = 0.002$)
  • improved respiratory system compliance ($p = 0.01$)
  • trend towards lower 28 day mortality ($p = 0.06$)

• Significant reduction in 28 day mortality when adjusted for illness severity (APACHE II) ($p = 0.049$)

NEJM November, 2008
Mechanical Ventilation Guided by Esophageal Balloon in Acute Lung Injury
14 patients meeting criteria for ECMO
- PaO2/FiO2 < 70
- Oxygenation Index > 30
- PEEP ≥ 15 cm H$_2$O

7 patients had Ptp Plateau (lung stress) higher than 25 cm H$_2$O
- 27 ± 1.2

7 patients had Ptp Plateau (lung stress) lower than 25 cm H$_2$O
- 16.6 ± 2.9

Plateau pressure similar in both groups
- (31.0 ± 1.0 vs. 31.5 ± 0.5 cm H$_2$O)
ECMO criteria for influenza A (H1N1)-associated ARDS: role of transpulmonary pressure

- Patient’s with PtpPlateau (lung stress) higher than 25 cm H2O received ECMO
- Patient’s with PtpPlateau (lung stress) lower than 25 cm H2O had PEEP increased until the PtpPlateau was 25 cm H2O
  - OI pre PEEP increase 37
  - OI post PEEP increase 16
- Titrating PEEP to a plateau pressure may overestimate the incidence of hypoxemia refractory to conventional ventilation leading to inappropriate use of ECMO

PAO OLA
Normal Chest Wall

\[ E_{CW} = 9.1 \, \text{cmH}_2\text{O}/L \]
\[ P_{AO,PLAT} = 30.2 \, \text{cmH}_2\text{O} \]
\[ P_{L,PLAT} = 25.5 \, \text{cmH}_2\text{O} \]
\[ \text{PEEP} = 16 \, \text{cmH}_2\text{O} \]

PAO OLA
Stiff Chest Wall

\[ E_{CW} = 37.3 \, \text{cmH}_2\text{O}/L \]
\[ P_{AO,PLAT} = 29.3 \, \text{cmH}_2\text{O} \]
\[ P_{L,PLAT} = 16.5 \, \text{cmH}_2\text{O} \]
\[ \text{PEEP} = 8 \, \text{cmH}_2\text{O} \]

PL OLA
Stiff Chest Wall

\[ E_{CW} = 35.4 \, \text{cmH}_2\text{O}/L \]
\[ P_{AO,PLAT} = 44.5 \, \text{cmH}_2\text{O} \]
\[ P_{L,PLAT} = 25.9 \, \text{cmH}_2\text{O} \]
\[ \text{PEEP} = 24 \, \text{cmH}_2\text{O} \]
Recruitment Maneuvers

Superimposed pressure

<table>
<thead>
<tr>
<th></th>
<th>Opening pressure</th>
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<tbody>
<tr>
<td>Normal</td>
<td>0</td>
</tr>
<tr>
<td>Small airway collapse</td>
<td>10–20 cm H$_2$O</td>
</tr>
<tr>
<td>Alveolar collapse (reabsorption)</td>
<td>20–30 cm H$_2$O</td>
</tr>
<tr>
<td>Consolidation</td>
<td>(Infinite pressure)</td>
</tr>
</tbody>
</table>

Transpulmonary Pressure
Case

- 45 y/o female with urosepsis, hypotension, ARDS
- 36 hours after admission
  - PIP 42 cm H₂O
  - PC 18 cm H₂O (target 6 ml/kg of IBW)
  - PEEP 24 cm H₂O
  - FiO₂ 1.0
  - PaO₂/FiO₂ 80
  - Oxygenation Index (OI) 35
- SpO₂ 85% for one hour despite recruitment maneuvers
Case

- Esophageal balloon inserted
  - Pes = 32 cm H2O
  - Ptp = PEEP (24 cm H2O) – Pes (32 cm H2O)
  - Ptp = -8 cm H2O

- PEEP increased to 32 cm H2O
  - Ptp PEEP = 0 cm H2O

- PIP now 50 cm H2O
  - Ptp Plateau = 13 cm H2O

- Hemodynamics unchanged
Case

- Immediate improvements in SpO₂
- FiO₂ weaned to .40 within 6 hours
- 24 hours later PaO₂/FiO₂ 301 and OI 13
- Fluid drained from abdomen intermittently over the next 4 days
  - PEEP titrated according to Ptp
  - PEEP requirements 24 – 28 cm H₂O
- Lasix Infusion started midway through course of ventilation
- Patient switched to PS where PEEP was weaned 2 cm H₂O every 6-8 hours
- Extubated within 10 days with no adverse events
Summary and Recommendations Treating the Population

- Tidal volume
  - 6 ml/kg of IBW

- Plateau pressure
  - ≤ 25 cm H$_2$O non-ARDS
  - ≤ 30 - 35 cm H$_2$O mild – moderate ARDS

- Positive response $\rightarrow$ wean FiO$_2$ ≤ 0.40

- Decrease PEEP 2 cm H$_2$O every 6 – 8 hours

<table>
<thead>
<tr>
<th>FiO2 (%)</th>
<th>30</th>
<th>40</th>
<th>40</th>
<th>50</th>
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<th>60</th>
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<td>PEEP cmH$_2$O</td>
<td>5</td>
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<td>20–24</td>
<td></td>
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</table>
Summary and Recommendations
Treating the Patient

• Criteria for treating the patient
  • $\text{PaO}_2/\text{FiO}_2 < 200$
  • $\text{FiO}_2 \geq 0.50$
  • $\text{PEEP} \geq 14 \text{ cm H}_2\text{O}$
Summary and Recommendations
Treating the Patient with Moderate or Severe ARDS

- Paralyze
  - no more than 48 hours with cisatracurium (Nimbex)
- Recruitment maneuvers (transpulmonary pressure)
- Esophageal pressure measurements to optimize PEEP
- Six ml/kg of IBW
- Lung Stress (measure and minimize)
- ECLS, prone positioning, HFO
- You have done EVERYTHING you can!
Slides available online:
www.respiratoryresource.ca/cccf

Contact:
piraino@mcmaster.ca
Additional Slides
Decremental PEEP Titration Observational Studies

- Reversibility of Lung Collapse and Hypoxemia in Early Acute Respiratory Distress Syndrome
  - Am J Respir Crit Care Med 2006; 174

- A Decremental PEEP Trial Identifies the PEEP Level That Maintains Oxygenation After Lung Recruitment
  - Respiratory Care 2006; 51(10)

- Respiratory and haemodynamic changes during decremental open lung positive end-expiratory pressure titration in patients with acute respiratory distress syndrome
  - Critical Care 2009, 13:R59

- Dead Space Fraction Changes During PEEP Titration Following Lung Recruitment in Patients With ARDS
  - Respiratory Care 2012; 57(10)
Decremental PEEP Titration Technique

1. Start with recruitment
2. Set PEEP at 20 - 24 cm H₂O
3. Use Volume Control 4-6 ml/kg of IBW
4. Monitor dynamic compliance for a minimum of 2 minutes
5. Decrease PEEP by 2 cm H₂O
6. Repeat steps 4 and 5 until the dynamic compliance no longer increases (best compliance)
7. Perform another recruitment maneuver
8. Set PEEP 2 cm H₂O above the best compliance level
Pes vs. Ppl

- Measured in the mid-lung area
- $R^2 = 0.77$
Weaning the Population

- Spontaneous breathing patient
  - Pressure support ventilation
- Aggressive titration of pressure
  - adjust for ~ 6 ml/kg of IBW
  - decrease pressure support by 2 cm H₂O every 3 - 4 hours
  - allow respiratory rates 20 - 30 cm H₂O
- Look for signs of weaning intolerance
  - return to previously tolerated level
  - attempt weaning again after 12 hours
- Weaning comprises ~ 40% of the duration of mechanical ventilation
Weaning the Population

• Stability:
  • minute ventilation < 13 L/min
  • FiO$_2$ ≤ 0.40
  • PEEP ≤ 8 cm H$_2$O

• Most common weaning parameter is the rapid shallow breathing index
  • RSBI

• Other parameters:
  • P 0.1, FiO$_2$, PaO$_2$, VC, NIF (PIMax)
Weaning the Patient

$$CROP = \left[ C_{\text{dyn}} \times P_{\text{Imax}} \times \left( \frac{P_{\text{aO}_2}}{P_{\text{AO}_2}} \right) \right]/f$$

$$CORE = \left[ C_{\text{dyn}} \times \left( \frac{P_{\text{Imax}}}{P_{0.1}} \right) \times \left( \frac{P_{\text{aO}_2}}{P_{\text{AO}_2}} \right) \right]/f$$

Table 3. Accuracy of 4 SBT Prediction Indexes

<table>
<thead>
<tr>
<th>Index</th>
<th>Threshold</th>
<th>Sensitivity (CI 95%)</th>
<th>Specificity (CI 95%)</th>
<th>Positive Predictive Value</th>
<th>Negative Predictive Value</th>
<th>Area Under the Curve (CI 95%)</th>
<th>Likelihood Ratio</th>
<th>Positive</th>
<th>Negative</th>
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</thead>
<tbody>
<tr>
<td>CORE</td>
<td>&gt; 8</td>
<td>1.00 (0.87–1.00)</td>
<td>1.00 (0.75–0.99)</td>
<td>0.95 (0.75–0.99)</td>
<td>0.96 (0.82–1.00)</td>
<td>1.00 (0.99–1.00)</td>
<td>20.0</td>
<td>0.0</td>
<td></td>
</tr>
<tr>
<td>CROP</td>
<td>&gt; 25.2</td>
<td>1.00 (0.87–1.00)</td>
<td>1.00 (0.75–0.99)</td>
<td>0.95 (0.75–0.99)</td>
<td>0.96 (0.82–1.00)</td>
<td>1.00 (0.99–1.00)</td>
<td>3.3</td>
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<tr>
<td>p_0.1</td>
<td>≤ 3.8</td>
<td>0.93 (0.76–0.99)</td>
<td>0.70 (0.46–0.88)</td>
<td>0.93 (0.76–0.99)</td>
<td>0.70 (0.46–0.88)</td>
<td>0.93 (0.76–0.99)</td>
<td>3.1</td>
<td>0.1</td>
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<td>RSBI</td>
<td>≤ 69</td>
<td>0.89 (0.71–0.98)</td>
<td>0.65 (0.41–0.85)</td>
<td>0.65 (0.41–0.85)</td>
<td>0.65 (0.41–0.85)</td>
<td>0.65 (0.41–0.85)</td>
<td>2.5</td>
<td>0.2</td>
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SBT = spontaneous breathing trial
CORE = compliance, oxygenation, respiration, and effort index
CROP = compliance, rate, oxygenation, and pressure index
p_0.1 = airway-occlusion pressure 0.1 s after the start of inspiratory flow
RSBI = rapid shallow breathing index
Automated Weaning

• Mandatory Minute Volume
• Adaptive Pressure Ventilation
• AutoMode
• Adaptive Support Ventilation
• Intellivent
• SmartCare/PS
Non-invasive ventilation after extubation in hypercapnic patients with chronic respiratory disorders

<table>
<thead>
<tr>
<th>Outcome variables</th>
<th>Non-invasive ventilation (n=54)</th>
<th>Control (n=52)</th>
<th>Odds ratio (95% CI)</th>
<th>p</th>
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<tbody>
<tr>
<td>Respiratory failure after extubation</td>
<td>8 (15%)</td>
<td>25 (48%)</td>
<td>5.32 (2.11–13.46)</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>Mortality</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intensive-care unit mortality</td>
<td>3 (6%)</td>
<td>4 (8%)</td>
<td>1.42 (0.30–6.67)</td>
<td>0.7132</td>
</tr>
<tr>
<td>Hospital mortality</td>
<td>6 (11%)</td>
<td>11 (22%)</td>
<td>2.15 (0.73–6.33)</td>
<td>0.2587</td>
</tr>
<tr>
<td>Mortality at 90 days</td>
<td>6 (11%)</td>
<td>16 (31%)</td>
<td>3.56 (1.27–10.0)</td>
<td>0.0244</td>
</tr>
<tr>
<td>Causes of death within 90 days after entry into the study</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Respiratory failure‡</td>
<td>0</td>
<td>7</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shock or multiple organ failure</td>
<td>3</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cardiac arrest</td>
<td>2</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>1</td>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Lancet 2009; 374: 1082–88
Asynchrony

• “Failure to wean” patients require immediate assessment for asynchrony

• Ventilators have default settings that are designed to treat a “population”

• Pressure Support is Pressure Control without a respiratory rate
  • the inspiratory time (cycle criteria) has a different name...
Inspiratory Time – Pressure Support

EndFlow
Expiratory Threshold
Esens
Ecycle
Inspiratory Cycle Off
Expiratory Trigger Sensitivity
(none)
PSV Cycle
Inspiratory Time – Cycle Off %

- 10%
- 25%
- 50%

Flow (L/min)
Pressure (cm H2O)
Time (s)

Respir Care 2005;50(2):166-183
Inspiratory Time
Example
Example
Proportional Assist Ventilation

\[ P_{\text{total}} = (V) (E) + (\dot{V}) (R) \]

\[ P_{\text{mus}} + P_{\text{vent}} = (V) (E) + (\dot{V}) (R) \]
Proportional Assist Ventilation

\[ \text{WOB}_{\text{total}} = \text{WOB}_{\text{p}} + \text{WOB}_{\text{v}} \]
Proportional Assist Ventilation

\[ \text{WOB}_{\text{total}} = \text{WOB}_{\text{p}} + \text{WOB}_{\text{v}} \]
Neurally Adjusted Ventilatory Assist

Central Nervous System → Phrenic nerve → Diaphragm excitation → Diaphragm contraction → Lung expansion → Pressure/flow trigger → Ventilator breath

Respir Care 2011;56(2):140-14
Neurally Adjusted Ventilatory Assist

- Central Nervous System
- Phrenic nerve
- Diaphragm excitation
- Diaphragm contraction
- NAVA
- Lung expansion
- Ventilator breath
- Pressure/flow trigger

Respir Care 2011;56(2):140-14