Mechanical Ventilation Guided by Esophageal Pressure in Acute Lung Injury *

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* n engl j med 359;20 november 13, 2008
Pleural Pressure Measurement

The Problem ~

- Lung over-distension causes ALI.
- Repetitive collapse/re-inflation causes ALI.
- Atelectasis may cause organ failure.

The ARDSnet low tidal volume ventilation study showed a mortality benefit using:
- Low Vt 6 ml/kg (4 – 8)
- Pplat ≤ 30 cm H₂O (?)
- PEEP and FiO₂ set to keep PaO₂ between 55 and 80 mmHg but optimal PEEP was not addressed.
- Can these strategies be improved?
## Pleural Pressure Measurement
### High vs Low PEEP Trials

<table>
<thead>
<tr>
<th>Trial</th>
<th>Year</th>
<th>Low PEEP Day 1 - 3</th>
<th>High PEEP Day 1 - 3</th>
<th>High PEEP Benefit</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amato</td>
<td>1998 NEJM</td>
<td></td>
<td></td>
<td>Yes</td>
<td>PEEP to LIP</td>
</tr>
<tr>
<td>ALVEOLI</td>
<td>2004 NEJM</td>
<td>8.9 - 8.5</td>
<td>14.7 - 12.9</td>
<td>No</td>
<td>No early separation of PEEPJs</td>
</tr>
<tr>
<td>ARIES</td>
<td>2006 CCM</td>
<td>9.0 - 8.7</td>
<td>14.1 - 11.2</td>
<td>Yes</td>
<td>PEEP to LIP</td>
</tr>
<tr>
<td>LOVS</td>
<td>2008 JAMA</td>
<td>10.1 - 8.8</td>
<td>15.6 - 11.8</td>
<td>No</td>
<td>Hi PEEP allowed Pplat ≤ 40</td>
</tr>
<tr>
<td>EXPRESS</td>
<td>2008 JAMA</td>
<td>7.1 - 6.7</td>
<td>14.6 - 13.4</td>
<td>Mixed</td>
<td>PEEP ↑‘d till Pplat = 28 - 30</td>
</tr>
</tbody>
</table>
Pleural Pressure Measurement Hypothesis

- Depending on the chest wall contribution to respiratory mechanics, a given PEEP level or plateau pressure may be adequate for one patient but potentially injurious for another.

- This may explain varying results in clinical trials.
Pleural Pressure Measurement
The Clinical Problem

- During MV, the pressure applied to the lung itself is unknown, but is often assumed to be the same as ventilator pressures.

- In some patients, the chest wall contributes a large part of the transrespiratory pressure, making the above assumption false.

- Knowing pleural pressure could allow calculation of transpulmonary pressure to permit ventilation with pressures appropriate to the lungs.
Pleural Pressure Measurement
Thoracic/Abdominal Pressures

- $\text{Palv}_{\text{insp}} = \text{Pplat}$
- $\text{Palv}_{\text{exp}} = \text{PEEP}_{\text{tot}}$
  $[\text{PEEP}_{\text{app}} + \text{PEEP}_{\text{intr}}]$  
- $\text{Ppl} = \text{Pes}$
- $\text{Pabd} = \text{Bladder Pr.}$
- $\text{Ptp} = \text{Palv} - \text{Ppl}$

Pao

$\text{Palv}_{\text{insp}}$ & $\text{Palv}_{\text{exp}}$

$\text{Ppl}$

$\text{Pabd}$

Negative Pressure
Pleural Pressure Measurement
Normal Pl and Ppl Relationship (Palv - Ppl = Ptp)

1. Resting FRC
   - Palv = 0
   - Ppl -2
   - 0 - (-2) = 2

2. Normal Vt
   - Palv = 0
   - Ppl -5
   - 0 - (-5) = 5

3. Spontaneous TLC
   - Palv = 0
   - Ppl -35
   - 0 - (-35) = 35
Pleural Pressure Measurement
Pulmonary vs. Non-pulmonary ARDS

Gattinoni AJRCCM 1998;158:3-18
Pleural Pressure Measurement
Pulmonary ARDS

Stiff Lungs/Normal Chest Wall

- Edema
  - interstitial
  - airspace
- Surfactant loss
- Fibrosis
- Consolidation
  - pneumonia
  - atelectasis
Pleural Pressure Measurement
Stiff Lungs, Compliant Chest Wall
Pleural Pressure Measurement
Non-Pulmonary ARDS

Stiff Chest Wall/Normal Lungs
- IAH
- Cardiomegaly
- Hemo/pneumo, etc.
- Chest wall deformity
- Flail

\[ C_{cw} \downarrow \]
\[ C_L \leftrightarrow \]
\[ P_{pl} \uparrow \]
\[ P_{abd} \uparrow \]
(Normal = 0 - 10)
Pleural Pressure Measurement
Stiff Chest Wall, Compliant Lungs
Pleural Pressure Measurement
Pulmonary vs Non-pulmonary ARDS

Pulmonary ARDS - Stiff Lungs/Normal Chest Wall

Non-Pulmonary ARDS - Normal Lungs/Stiff Chest Wall
Pleural Pressure Measurement
Mechanical Errors in Ventilation

Over-inflated Lungs

- Air trapping
  - asthma, COPD, etc.
- Vt too high
- PEEP$_{app}$ too high
Pleural Pressure Measurement
Pulmonary Mechanic Monitors

Ventrak

Bicore

Avea Ventilator
Pleural Pressure Measurement
Esophageal Balloons

Cooper Surgical
- Low-pressure balloon
- 9 to 10 cm long.
- Optimal fill vol.
  0.5 – 1.0 ml of air.

Viasys

Contraindications
- recent gastric surgery
- esophageal varacies
- other esophageal injuries
Pleural Pressure Measurement
Balloon Insertion

• Insert to 40 - 45 cm for Pes. (oral or nasal)
  - 60 cm for Pga.
• Pass next to or under ETT or OG tube
• Advance gently in short advances, 1 - 2 cm at a time.
  • avoids coiling in the upper airway.
• Don’t advance during coughing, gagging or esophageal spasms.
• Fingers to clear soft tissue
  • insert bite block
• Assistant applies jaw thrust
• Use oral airway or “split” ETT
Pleural Pressure Measurement
Determining Correct Balloon Position

- Correct depth $\approx 40$ cm $H_2O$ for most patients.
- Note direction of Pes deflection.
- Verify cardiac oscillations in esophageal pressure.
- Pes is similar to Pga.
- Measurements must match the clinical presentation.
Pleural Pressure Measurement
Balloon Moved from Stomach to Chest

- Below Diaphragm
- Above Diaphragm
- No Cardiac Oscillations
- Abdominal Push
- Cardiac Oscillations
Pleural Pressure Measurement
Relationship between Pes and Pga

Talmor, CCM 2006, 34:1389-94
**Pleural Pressure Measurement**

**Balloon at Thoracic Outlet**

- Balloon too high
- Balloon correctly positioned 40–45 cm from incisor

- Bladder pr. = 17 mm Hg (23 cm H$_2$O)
Pleural Pressure Measurement

Balloon in Airway

Pes & Paw are essentially the same at end Exp. and end Insp.
Pleural Pressure Measurement
Effect of PEEP Change

<table>
<thead>
<tr>
<th>PEEP</th>
<th>Pplat</th>
<th>PEEP Changes</th>
<th>Pplat Changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>33</td>
<td>PEEP = 25</td>
<td>Pplat = 38</td>
</tr>
<tr>
<td>25</td>
<td>38</td>
<td>Δ</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td>27</td>
<td>25</td>
<td>27</td>
</tr>
<tr>
<td>6</td>
<td>11</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>-4</td>
<td>6</td>
<td>4</td>
<td>1</td>
</tr>
</tbody>
</table>

Pes = 24
Pes = 27
Pes = 25
Pes = 27
Pt = -4
Pt = 6
Pt = 0
Pt = 11
Pleural Pressure Measurement
Things that complicate measurement

- Gravity
- Position
- Active Exhalation
- Dis-synchrony
- Mechanical errors
- ? Pleural fluid
- ? Enlarged heart
- ? NG/OG tubes
- ? Chest tubes / suction

Pes measurements must match the patient’s clinical presentation.
Pleural Pressure Measurement
Gravitational Effect on Regional Pleural Pressure

Pressure transducing wafers implanted in dog lungs revealed differences in pleural pressure due to the gravitational effect of the dependant vs. non-dependant regions of the lung.

Pelosi Am J Respir Crit Care Med 2001; 164:122-130
Pleural Pressure Measurement
Gravitational Effect on Regional Pleural Pressure

Pressure transducing wafers implanted in dog lungs revealed differences in pleural pressure due to the gravitational effect of the dependant vs. non-dependant regions of the lung.

Pelosi Am J Respir Crit Care Med 2001; 164:122-130
Pleural Pressure Measurement
Positional Artifact

Supine position causes approximately 3 - 4 cm H$_2$O increase in the transduced Pes due to heart & lung compression of the balloon.

Washko J Appl Physio 2006; 100:753-8
## Pleural Pressure Measurement

### EPVent Subjects

<table>
<thead>
<tr>
<th></th>
<th>EP protocol N=30</th>
<th>Conventional N=31</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male gender, (%)</td>
<td>19 (63.3)</td>
<td>17 (54.8)</td>
<td>0.44</td>
</tr>
<tr>
<td>Age, years</td>
<td>54.5±16.1</td>
<td>51.2±23.0</td>
<td>0.52</td>
</tr>
<tr>
<td>Caucasian, (%)</td>
<td>26 (86.7)</td>
<td>27 (87.1)</td>
<td>0.96</td>
</tr>
<tr>
<td>Ideal body weight, kg</td>
<td>67.1±8.9</td>
<td>63.2±11.1</td>
<td>0.14</td>
</tr>
<tr>
<td>APACHE II on admission, points</td>
<td>26.3±6.4</td>
<td>26.8±6.5</td>
<td>0.76</td>
</tr>
<tr>
<td>Primary physiological injury (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulmonary</td>
<td>7 (23.3)</td>
<td>5 (16.1)</td>
<td></td>
</tr>
<tr>
<td>Abdominal</td>
<td>13 (43.3)</td>
<td>11 (35.5)</td>
<td></td>
</tr>
<tr>
<td>Trauma</td>
<td>6 (20.0)</td>
<td>9 (29.0)</td>
<td>0.54</td>
</tr>
<tr>
<td>Sepsis</td>
<td>3 (10.0)</td>
<td>2 (6.5)</td>
<td></td>
</tr>
<tr>
<td>Other</td>
<td>1 (3.3)</td>
<td>4 (12.9)</td>
<td></td>
</tr>
</tbody>
</table>

nejm 359;20 nov 13, 2008
### Baseline Physiologic Status at Baseline

<table>
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<tr>
<th></th>
<th>EP protocol</th>
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<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaO2 / FiO2 ratio</td>
<td>147 ± 56</td>
<td>145 ± 57</td>
<td>0.89</td>
</tr>
<tr>
<td>Respiratory Compliance, ml/cmH₂O</td>
<td>36 ± 12</td>
<td>36 ± 10</td>
<td>0.94</td>
</tr>
<tr>
<td>Dead space to tidal volume ratio, %</td>
<td>67 ± 11.</td>
<td>67 ± 9</td>
<td>0.95</td>
</tr>
<tr>
<td>PaO2, mmHg</td>
<td>91 ± 25</td>
<td>107 ± 44</td>
<td>0.09</td>
</tr>
<tr>
<td>FiO2, %</td>
<td>66 ± 17</td>
<td>77 ± 18</td>
<td>0.02</td>
</tr>
<tr>
<td>PEEP, cmH₂O</td>
<td>13 ± 5</td>
<td>13 ± 3</td>
<td>0.73</td>
</tr>
<tr>
<td>Tidal volume, cc³</td>
<td>484 ± 98</td>
<td>491 ± 105</td>
<td>0.80</td>
</tr>
<tr>
<td>Tidal volume/ ideal body weight, cc/kg</td>
<td>7.3 ± 1.3</td>
<td>7.9 ± 1.4</td>
<td>0.12</td>
</tr>
</tbody>
</table>

ARDSnet Protocol: Mode - CMV; Pplat ≤ 30 cm H\textsubscript{2}O

<table>
<thead>
<tr>
<th>FiO\textsubscript{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>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>0.9</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEP</td>
<td>5</td>
<td>5</td>
<td>8</td>
<td>8</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>12</td>
<td>14</td>
<td>14</td>
<td>14</td>
<td>16</td>
<td>18</td>
</tr>
</tbody>
</table>

Esophageal Balloon Directed Protocol: Mode - CMV; Ptp\textsubscript{insp} ≤ 25 cm H\textsubscript{2}O

<table>
<thead>
<tr>
<th>FiO\textsubscript{2}</th>
<th>0.4 - 0.5</th>
<th>0.5 - 0.6</th>
<th>0.6 - 0.7</th>
<th>0.7 - 0.08</th>
<th>0.8 - 0.9</th>
<th>0.9 - 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ptp\textsubscript{exp}</td>
<td>0</td>
<td>+2</td>
<td>+4</td>
<td>+6</td>
<td>+8</td>
<td>+10</td>
</tr>
</tbody>
</table>

\[ Ptp\textsubscript{exp} = PEEP\textsubscript{tot} - P\textsubscript{esoph} \]
\[ Ptp\textsubscript{insp} = P\textsubscript{plat} - P\textsubscript{esoph} \]
Pleural Pressure Measurement Study Protocol (Revised for Multi-center Trial *)

Esophageal Balloon Directed Protocol: Mode - CMV; $P_{tp_{insp}} \leq 25 \text{ cm H}_2\text{O}$

**Original FiO$_2$ to PEEP Management Grid**

(NEJM 2008,359(20);2095:104)

<table>
<thead>
<tr>
<th>FiO$_2$</th>
<th>0.4 - 0.5</th>
<th>0.5 - 0.6</th>
<th>0.6 - 0.7</th>
<th>0.7 - 0.8</th>
<th>0.8 - 0.9</th>
<th>0.9 - 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{tp_{exp}}$</td>
<td>0</td>
<td>+2</td>
<td>+4</td>
<td>+6</td>
<td>+8</td>
<td>+10</td>
</tr>
</tbody>
</table>

**Revised FiO2 to PEEP Management Grid for Proposed Multi-center trial**

<table>
<thead>
<tr>
<th>FiO$_2$</th>
<th>0.4</th>
<th>0.5</th>
<th>0.6</th>
<th>0.7</th>
<th>0.8</th>
<th>0.9</th>
<th>1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{tp_{exp}}$</td>
<td>0 - 1</td>
<td>1 - 2</td>
<td>2 - 3</td>
<td>3 - 4</td>
<td>4 - 5</td>
<td>5 - 6</td>
<td>6 - 7</td>
</tr>
</tbody>
</table>

$P_{tp_{exp}} = P_{EEP_{tot}} - P_{esoph}$  
$P_{tp_{insp}} = P_{plat} - P_{esoph}$
Pleural Pressure Measurement
EP Vent Study Patient

Before

\[ P_{aw} = 13 \text{ to } 40 \]
\[ P_{plat} = 40 \]
\[ P_{es} = 20 \text{ to } 33 \]
\[ P_{tp} = -7 \text{ to } 7 \]

After

\[ P_{aw} = 26 \text{ to } 46 \]
\[ P_{plat} = 46 \]
\[ P_{es} = 22 \text{ to } 33 \]
\[ P_{tp} = 4 \text{ to } 13 \]
Pleural Pressure Measurement
MV Guided by Pes Pr in ALI

A. Esophageal pressure

B. Respiratory System Compliance (cm of water)

C. Ratio of Dead Space to tidal Volume Ratio

D. PEEP (cm of Water)

E. Transpulmonary End Expiratory Pressure (cm of water)

F. Mean Airway Pressure (cm of water)

nejm 359:20 nov 13, 2008
## Pleural Pressure Measurement

### MV Guided by Pes Pr in ALI NEJM 2008, 359(20):2095-104

<table>
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<th>Conventional</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N=30</td>
<td>N=31</td>
<td></td>
</tr>
<tr>
<td>28-day mortality, (%)</td>
<td>5 (16.7)</td>
<td>12 (38.7)</td>
<td>0.055</td>
</tr>
<tr>
<td>6-month mortality (%)</td>
<td>8 (26.7)</td>
<td>14 (45.3)</td>
<td>0.13</td>
</tr>
<tr>
<td>ICU length of stay, days, median (IQR)</td>
<td>15.5 (10.8-28.5)</td>
<td>13.0 (7.0-22.0)</td>
<td>0.16</td>
</tr>
<tr>
<td>ICU free days at 28 days, median (IQR)*</td>
<td>5.0 (0.0-14.0)</td>
<td>4.0 (0.0-16.0)</td>
<td>0.96</td>
</tr>
<tr>
<td>Ventilator free days at 28 days, median (IQR)*</td>
<td>11.5 (0.0-20.3)</td>
<td>7 (0-17)</td>
<td>0.50</td>
</tr>
<tr>
<td>Days on ventilator for survivors, days, median (IQR)*</td>
<td>12.0 (7.0-27.5)</td>
<td>16 (7.0-20.0)</td>
<td>0.71</td>
</tr>
</tbody>
</table>
Pleural Pressure Measurement
MV Guided by Pes Pr in ALI  NEJM 2008, 359(20);2095-104

6 Month Survival

- Esophageal pressure guided protocol
- Conventional protocol
Pleural Pressure Measurement

Summary

- Pes closely approximates Ppl.
- Ppl can vary in the pleural space.
- Ptp can help to limit re-inflation lung injury.
- Ptp can help avoid over-inflation.

- Clinical targets:
  - End Expiratory Ptp ≅ 0 cm H₂O
  - End Inspiratory Ptp < 25 cm H₂O
    - The lower the End Insp Ptp, the lower the lung stress!!
The End (Whew!!!)

Thank You

For a copy of this presentation, please email me at:
rritz@bidmc.harvard.edu