“Invasive Ventilation:
State of the Art”
Bob Kacmarek PhD, RRT
Harvard Medical School
Massachusetts General Hospital
Boston, Massachusetts

Conflict of Interest Disclosure
Robert M Kacmarek
I disclose the following financial relationships with commercial entities that produce healthcare-related products or services relevant to the content I am presenting:

<table>
<thead>
<tr>
<th>Company</th>
<th>Relationship</th>
<th>Content Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medtronic</td>
<td>Consultant</td>
<td>Artificial Airways</td>
</tr>
<tr>
<td>Medtronic</td>
<td>Grant</td>
<td>Mech Vent</td>
</tr>
<tr>
<td>Orange Medical</td>
<td>Consultant</td>
<td>Mech Vent</td>
</tr>
<tr>
<td>Teleflex</td>
<td>Consultant</td>
<td>Humidification</td>
</tr>
</tbody>
</table>

Invasive Ventilation:2017
- $V_T$ 4 to 8 ml/kg PBW greater Pplat lower $V_T$
- Plateau Pressure < 28 cmH$_2$O
- Driving pressure <15 cmH$_2$O
- PEEP appropriate for the pt presentation
- Avoid asynchrony
- Avoid autoPEEP and air trapping
- Appropriate F$_{1}$O$_{2}$ maintain PaO$_2$ 55 to 80 and SpO$_2$ 88 to 95%

ARDSnet NEJM 2000;342:1301
A $V_T$ of 6 mL/Kg PBW results in a lower mortality than a $V_T$ of 12 mL/Kg PBW
Mortality 31% vs. 39.8%
$p = 0.0054$

Mortality vs Day 1 Plateau Pressure
NIH Trial of 6 vs 12 ml/kg Tidal Volume

Scaling of the Lung in Mammals
Adapted from SB Tenney & JE Remmers, Nature 1963; 197:54-6; K Schmidt-Nielsen, 1972

Lung Volume = 6.3% BW
Tidal Volume = 6.3 mL/kg

Body Weight, kg

Lung Volume

Slope = 1.02

Bat
Shrew
Mouse
Rat
Guinea Pig
Marmot
Armadillo
Rabbit
Monkey
Cat
Raccoon
Dog
Goat
Pig
MAN
Bear
Porpoise
Manatee
Cow
Dugong
Whale

SLOPE = 1.02

Body Weight, kg

Lung Volume, liter

Adapted from SB Tenney & JE Remmers, Nature 1963; 197:54-6; K Schmidt-Nielsen, 1972
In Severe Acute Hypoxemic Respiratory Failure Tidal Volumes MUST be Maintained between 4 to 6 m/kg PBW or lower to insure Plateau Pressures do not exceed 28 cm H$_2$O”

“Permissive Hypercapnia is generally the rule”

“Acceptable pH > 7.15”

ARDSnet NEJM 2000;342:1301

Impact of Plat/VT on Mortality in ARDS

- $P_{PLAT} < 28$ cmH$_2$O, mortality reduced
- Lower the $P_{PLAT}$, better the outcome
- RR limit based on autoPEEP, up to 40 or greater?
- $P_{PLAT} \leq 28$ cmH$_2$O, $V_T$ 4-5 ml/kg
- $P_{PLAT} 25$ to 28 cmH$_2$O, $V_T$ 6 ml/kg
- $P_{PLAT} \leq 25$ cmH$_2$O $V_T$ 6-8; if patient has a strong ventilatory demand, better to allow a little larger $V_T$ then to heavily sedate and force a very low $V_T$!

Kacmarek (Editorial) RC 2005;50:1624-1616


- Multi-regression analysis of 9 RCT on ARDS: Variable $V_T$ and Variable PEEP
- Tidal volume not the primary variable associated with mortality
- Plateau pressure not the primary variable associated with mortality
- PEEP not the primary variable associated with mortality
- Driving Pressure (DP) on day of enrollment into the studied RCT’s the primary variable associated with mortality!!!

$DP = \text{Plateau Pressure} - \text{PEEP}$
PEEP in ARDS: Still Controversial!

- High PEEP vs. low PEEP?
- Approach to Setting PEEP?
- Should the lung be recruited?
- When to decrease PEEP?

End Expiratory Transpulmonary Pressure!

- Normal Spontaneous breathing about 1-2 cm H₂O positive end expiratory pressure maintains alveoli at end expiration
- A negative end expiratory TPP results in alveolar collapse at end exhalation

\[ \text{TPP} = \text{PEEP} - \text{Ppl} \]

1 cmH₂O = 0 cmH₂O – (1 cmH₂O)

Method of Setting PEEP Level

- PEEP/FI₂O₂ Table
- Transpulmonary pressure/FI₂O₂ Table
- Brochard/Mercat method
- Stress Index
- P–V curve
- Incremental PEEP trial
- Decremental PEEP trial

End Expiratory Transpulmonary Pressure

- End expiratory esophageal pressure used to determine the correct setting of PEEP

\[ \text{TPP} = \text{PEEP} - \text{Pes} (\text{Ppl}) \]

-3 cmH₂O = 5 cmH₂O – (8 cmH₂O)

\[ \text{TPP} = \text{PEEP} - \text{Pes} \]

2 cmH₂O = 10 cmH₂O – (8 cmH₂O)

Relative risk of Death

Phoenix Ann 2009;110:1008

PEEP titration transpulmonary pressure

PEEP level is set to achieve a non-collapsing pressure at end-expiration (lowest PEEP value with positive end-exp transpulmonary pressure)
68 pts with ARDS/ALI in which recruitable lung was evaluated at 5, 15 and 45 cmH2O using CT scan.

Recruitment varied considerably, accounting for 13±11% of the lung weight.

On average 24% of the lung could not be recruited.

Pts with a higher % of recruitable lung (median > 9%) had higher lung wt (p=0.002), poorer oxygenation (p < 0.001), poorer compliance (p = 0.002), higher levels of DS (p = 0.002) and a higher death rate (p = 0.02)
Gattinoni et al. NEJM 2006; 354:1775

- RM at PIP 45 cm H₂O, PEEP 5 cm H₂O, rate 10/min, I:E 1:1 for 2 min
- After RM patient randomized to 5 or 15 cm H₂O PEEP.
- CT at 45 cm H₂O during an end-inspiratory pause of 15 to 25 second thereafter at a PEEP of 5 and 15 cm H₂O during a 15 to 25 sec end-expiratory pause
- Length of ventilation before study 5±6 days

Table 1. Characteristics of study patients.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, years</td>
<td>54.0 ± 15.7</td>
</tr>
<tr>
<td>Female, %</td>
<td>6 (42.9)</td>
</tr>
<tr>
<td>Height, cm</td>
<td>170.9 ± 12.5</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>146.1 ± 40.8</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>50.7 ± 16.0</td>
</tr>
<tr>
<td>Thoracic circumference, cm</td>
<td>144.8 ± 23.3</td>
</tr>
<tr>
<td>Abdominal circumference, cm</td>
<td>151.8 ± 23.8</td>
</tr>
<tr>
<td>SAPS II, mean</td>
<td>34.6 ± 18.1</td>
</tr>
<tr>
<td>APACHE II, mean</td>
<td>15.8 ± 7.9</td>
</tr>
<tr>
<td>IAP, mean cm H₂O</td>
<td>13.8 ± 5.6</td>
</tr>
</tbody>
</table>

Pirrone et al. CCM 2016(2); 44:300

Table 2. Ventilatory Data

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>ZEEP</th>
<th>Lowest PEEP with positive Pipe</th>
<th>Lowest PEEP with positive PEEP after RM</th>
<th>Best decremental PEEP</th>
<th>Best decremental PEEP – Head of Bed 30°</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEP cm H₂O</td>
<td>11.6 ± 2.9</td>
<td>0</td>
<td>20.7 ± 4.0</td>
<td>20.7 ± 4.0</td>
<td>21.3 ± 3.8</td>
<td>21.5 ± 3.7</td>
</tr>
<tr>
<td>EELV ml/kg BW</td>
<td>19.5 ± 8.3</td>
<td>14.6 ± 3.9</td>
<td>27.1 ± 9.2</td>
<td>30.1 ± 8.2</td>
<td>30.6 ± 8.7</td>
<td>30.5 ± 11.5</td>
</tr>
<tr>
<td>Ppeak cm H₂O</td>
<td>34.6 ± 5.8</td>
<td>22.4 ± 4.9</td>
<td>41.7 ± 6.0</td>
<td>40.2 ± 6.1</td>
<td>40.4 ± 5.2</td>
<td>41.6 ± 5.5</td>
</tr>
<tr>
<td>Pplat cm H₂O</td>
<td>22.5 ± 4.1</td>
<td>11.7 ± 2.1</td>
<td>30.4 ± 4.2</td>
<td>25.1 ± 4.1</td>
<td>29.8 ± 3.8</td>
<td>30.8 ± 3.2</td>
</tr>
<tr>
<td>Vt ml/kg BW</td>
<td>6.6 ± 1.2</td>
<td>0.55 ± 0.09</td>
<td>270 ± 67</td>
<td>296 ± 72</td>
<td></td>
<td></td>
</tr>
<tr>
<td>FiO₂</td>
<td>179 ± 60</td>
<td>270 ± 67</td>
<td>296 ± 72</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Pirrone et al. CCM 2016(2); 44:300
Animal Study
- Ten pigs (32.6 ± 3.7 kg)
- 4.0 ± 0.9 kg on the abdomen to increase gastric pressure 4.0 ± 0.8 cmH₂O.
- Esophageal pressure increased producing a right shift in the pressure-volume curve due to increased elastance of the lung and respiratory system.
- Chest wall elastance was not affected by the increased abdominal mass.
- EIT all, CT 5 animals.

Obese Animals’ Incremental PEEP Trial
- Post Lung Recruitment

Obese Animals’ Decremental PEEP Trial
- Post Lung Recruitment

Animals’ Respiratory Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Baseline</th>
<th>PEEP 5</th>
<th>Obese</th>
<th>Obese Incremental</th>
<th>Obese Decremental</th>
</tr>
</thead>
<tbody>
<tr>
<td>PEEP (cmH₂O)</td>
<td>13.9 ± 2.1</td>
<td>5</td>
<td>5</td>
<td>15.9 ± 3.3</td>
<td>17.4 ± 2.1</td>
</tr>
<tr>
<td>EEL</td>
<td>34.2 ± 9.9</td>
<td>44.3 ± 16.9</td>
<td>57.2 ± 21.4</td>
<td>49.6 ± 8.5</td>
<td>36.4 ± 8.9</td>
</tr>
<tr>
<td>EEL</td>
<td>19.6 ± 8.2</td>
<td>31.3 ± 15.7</td>
<td>41.6 ± 18.4</td>
<td>33.3 ± 7.6</td>
<td>23.0 ± 8.9</td>
</tr>
<tr>
<td>EEL (cmH₂O/L)</td>
<td>14.6 ± 6.3</td>
<td>13.0 ± 3.5</td>
<td>15.5 ± 6.9</td>
<td>16.3 ± 5.4</td>
<td>13.4 ± 5.8</td>
</tr>
<tr>
<td>EEL (cmH₂O/L)</td>
<td>13.3 ± 2.9</td>
<td>15.0 ± 4.6</td>
<td>12.3 ± 4.3</td>
<td>10.0 ± 1.4</td>
<td>11.5 ± 3.0</td>
</tr>
<tr>
<td>EEL (cmH₂O/L)</td>
<td>18.7 ± 5.4</td>
<td>10.8 ± 4.7</td>
<td>7.7 ± 4.1</td>
<td>11.1 ± 2.9</td>
<td>18.3 ± 6.4</td>
</tr>
</tbody>
</table>
When to Repeat RM and Adjust PEEP

- If patient status deteriorates requiring higher FIO2, complete the entire process again: RM plus decremental PEEP
- If the patient is suctioned, turned or disconnected and desaturates, do another RM and reset the previous PEEP level
- Do not decrease PEEP until FIO2 ≤ 0.4
- Decrease PEEP 2 cmH2O every 6 to 8 hours
- If patient desaturates with PEEP decrease, RM and return to previous PEEP level

Relative Contraindications
- Preexisting pulmonary cysts
- Preexisting bulbous lung disease
- Preexisting barotrauma
- Hemodynamic instability
- Unilateral/localized lung disease

Performance of RM - PCV
- Pressure control ventilation, FIO2 1.0:
  - PEEP 25-35 cmH2O
  - Pressure control level 15 cmH2O
  - Inspir Time: 3 sec
  - Rate: 10/min
  - Time 1 min
- Initial RM PEEP 25 cmH2O, PIP 40 cmH2O
- Slowly increase 3-5 cm H2O every 5 breaths
- Set PEEP at 25, ventilate VC, VT 6 ml/kg PBW
- Measure dynamic compliance
Performance of RM - PCV
- Decrease PEEP 2 cm H2O
- Measure dynamic compliance
- Repeat until max compliance determined
- Optimal PEEP max comp PEEP+2 cm H2O
- Repeat recruitment maneuver and set PEEP at the identified settings, adjust ventilation
- After PEEP and ventilation set and stabilized, decrease FIO2 until PO2 in target range
- If response is poor, repeat RM, PEEP 30, Peak Pressure 45
- If response is poor, repeat RM, PEEP 35, Peak Pressure 50

Kacmarek Villar et al CCM 2016:44(1):32
- Post op Cardiac Surgical patients, LPV
- ALL RM, P-V curve (5-30 cmH2O), admit, 4hr
- Intensive RM PCV 45/30 60 sec x 3, PEEP 13
- Moderate RM CPAP 20 30 sec x 3, PEEP 8

Amato et al NEJM 1998;338:347
- Open lung approach (OLA) vs. ARDSnet
- PIP, Pplat and driving pressure all higher in ARDSnet
- PEEP approximately 5 cmH2O higher in OLA
- FIO2 lower, PaO2 higher, P/F higher, VT lower, RR higher, PCO2 higher (day 1) in OLA
- No difference pneumothorax, cardiac arrest, hypotension, desaturation, arrhythmias

Kacmarek et al CCM 2016(1);44:32
- Post op Cardiac Surgical patients, LPV
- ALL RM, P-V curve (5-30 cmH2O), admit, 4hr
- Intensive RM PCV 45/30 60 sec x 3, PEEP 13
- Moderate RM CPAP 20 30 sec x 3, PEEP 8

Leme JAMA Published online 3-21-17
- Post op Cardiac Surgical patients, LPV
- ALL RM, P-V curve (5-30 cmH2O), admit, 4hr
- Intensive RM PCV 45/30 60 sec x 3, PEEP 13
- Moderate RM CPAP 20 30 sec x 3, PEEP 8

Leme JAMA Published online 3-21-17
- P05 table and graph
All patients admitted to Med/Sur ICU expected to be intubated ≥ 72 hours

- Conser O₂, PO₂ 70 to 100 (87), SpO₂ 94 to 98%
- Standard O₂ up to 150 (103), SpO₂ 97 to 100%

Invasive Ventilation: 2017

- VT 4 to 8 ml/kg PBW greater Pplat lower Vₜ
- Plateau Pressure < 28 cmH₂O
- Driving pressure < 15 cmH₂O
- PEEP appropriate for the pt presentation
- Avoid asynchrony
- Avoid autoPEEP and air trapping
- Appropriate FIO₂ maintain PaO₂ 55 to 80 and SpO₂ 88 to 95%

Thank You