Setting PEEP and Tidal Volume in ARDS

New York State Thoracic Society
Annual Assembly

Westchester Medical Center
Valhalla, New York
March 24, 2018

Roy Brower
Johns Hopkins University
Disclosures

• No conflicts of interest
• No off-label
Case Presentation

- 27 year old M with alcoholic hepatitis and pneumonia
- Height 193 cm (6’4”). Predicted Body Wt = 87 kg
- 6 ml/kg = 520 mL PEEP = 10.
  - Pplat = 34 cm H$_2$O
  - Driving Pressure (Pplat – PEEP, ΔP) = 24
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• 27 year old M with alcoholic hepatitis and pneumonia
• Height 193 cm (6’4”). Predicted Body Wt = 87 kg
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• Chest volumes not large
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- Chest volumes not large
- Tidal volume decreased to 5, 4 mL/kg PBW
  - Pplat = 28, Driving Pressure (ΔP) = 18
# ACUTE RESPIRATORY DISTRESS IN ADULTS

**David G. Ashbaugh**  
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Assistant Professor of Surgery

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M.D. Colorado

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M.D. Colorado  
Assistant Professor of Medicine

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M.D. Michigan  
American Thoracic Society-National Tuberculosis Association fellow in pulmonary disease

Lancet 1967
Continuous positive-pressure breathing (CPPB) in adult respiratory distress syndrome

D. G. Ashbaugh, M.D.* (by invitation), T. L. Petty, M.D.** (by invitation), D. B. Bigelow, M.D.*** (by invitation), and T. M. Harris, M.D.**** (by invitation), Denver, Colo.
Sponsored by W. R. Waddell, M.D., Denver, Colo.

J Thor CV Surg 1969

“The lungs become very stiff and require 40 to 60 cm. of water to achieve adequate tidal volumes.”
Impaired Oxygenation During Anesthesia with Controlled Ventilation

Bendixen et al. N Eng J Med 1963
“Extensive clinical experience … indicates that volumes of 7 ml per kilogram … [are] poorly tolerated…. Larger tidal volumes (10-15 ml per kilogram) are preferable, having been used in several thousand ventilated patients with no evidence of development of pulmonary damage.
# Tidal Volumes

## 1965-1983

<table>
<thead>
<tr>
<th>Year</th>
<th>Authors</th>
<th>Journal</th>
<th>Tidal Volume (mL/kg)</th>
</tr>
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<tbody>
<tr>
<td>1965</td>
<td>Sykes et al. (12)</td>
<td><em>Br J Anaesth</em></td>
<td>10–15</td>
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<td>1969</td>
<td>McIntyre et al. (13)</td>
<td><em>Can Anaesth Soc J</em></td>
<td>8–14</td>
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<td>1972</td>
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<td><em>J Clin Invest</em></td>
<td>9–24</td>
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<td>1972</td>
<td>Lutch and Murray (17)</td>
<td><em>Ann Intern Med</em></td>
<td>10–16</td>
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<td>1973</td>
<td>Kumar et al. (18)</td>
<td><em>Crit Care Med</em></td>
<td>12–18</td>
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<td>1974</td>
<td>Steier et al. (19)</td>
<td><em>J Thorac Cardiovasc Surg</em></td>
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<td>1975</td>
<td>Suter et al. (20)</td>
<td><em>N Engl J Med</em></td>
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<td>1979</td>
<td>Hemmer and Suter (21)</td>
<td><em>Anesthesiology</em></td>
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<td>1983</td>
<td>Mathru et al. (23)</td>
<td><em>Crit Care Med</em></td>
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</table>

Brochard and Lemaire
*Crit Care Med* 1999
Ventilator-Induced Lung Injury

High Volume
High Pressure
VILI
The New England Journal of Medicine

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VOLUME 342

MAY 4, 2000

NUMBER 18

VENTILATION WITH LOWER TIDAL VOLUMES AS COMPARED WITH TRADITIONAL TIDAL VOLUMES FOR ACUTE LUNG INJURY AND THE ACUTE RESPIRATORY DISTRESS SYNDROME

THE ACUTE RESPIRATORY DISTRESS SYNDROME NETWORK®
$V_T$ Recommendation

$V_T$ Goal = 6 mL/kg Predicted Body Weight

PBW based on gender, height
$V_T$ Recommendation

$V_T$ Goal = 6 mL/kg Predicted Body Weight

PBW based on gender, height

*Intended as a guide to lung size*
\( V_T \) Recommendation
ARDS Network

\( V_T \) Goal = 6 mL/kg Predicted Body Weight

PBW based on gender, height

*Intended as a guide to lung size*

**Male, 180 cm**

*Predicted FRC = 3.8 L*

*Measured FRC SD = 0.99 L*
Predicted Body Weight and Aerated Lung Volume in ARDS Patients

Chiumello et al. Crit Care 2016
Clinical Recommendation

\( V_T \) Goal = 6 mL/kg PBW
If \( P_{plat} > 30 \text{ cm } H_2O \), decrease \( V_T \) to 5 or 4 mL/kg PBW.
Pplat = \textit{Mean} distending pressure of \textit{respiratory system} (lungs and chest wall)
Pplat to Guide Tidal Volume?

Pplat = Distending pressure of the respiratory system

\[ P_{TP} = P_{\text{plat}} - P_{pl} = \text{Distending pressure of the lung} \]
Clinical Recommendation

$V_T$ Goal = 6 mL/kg PBW
If Pplat $> 30$ cm H$_2$O, decrease $V_T$ to 5 or 4 mL/kg PBW.

Are Pplats $< 30$ cm H$_2$O safe?
Safe Plateau Pressure?

Hager et al, AJRCCM 2005
Variable Consolidation, Edema, and Atelectasis

Terragni et al.
Am J Resp Crit Care Med 2007
Strain

\[ \text{Strain} = \frac{V_T}{\text{FRC}} \]
Strain Approach

• Measure FRC
  – Computerized Tomography
  – Helium Dilution
  – Nitrogen Wash-in-Wash-out

• Set $V_T$ to keep strain below a safe level
  – What is a safe level?
Stress

\[ \text{Stress} = \frac{\text{Force}}{\text{Area}} \]
Airway, Pleural, and Transpulmonary Pressures

\[ P_{\text{ao}} = 30 \text{ cm H}_2\text{O} \]

\[ P_{\text{pl}} = 5 \text{ cm H}_2\text{O} \]

\[ P_{\text{TP}} = 25 \text{ cm H}_2\text{O} \]

\[ P_{\text{pl}} = 15 \text{ cm H}_2\text{O} \]

\[ P_{\text{TP}} = 15 \text{ cm H}_2\text{O} \]
Potential sources of error in estimating pleural pressure by esophageal manometry

Pleural Pressures Vary by Region

January 4

January 5
Problems with $P_{TP}$ Approach

- Requires esophageal catheter
- Pleural pressures not uniform in chest
  - Esophageal pressure not a good average
- $P_{TP}$ goal for setting Tidal Volume = ???
Driving Pressure and Survival in the Acute Respiratory Distress Syndrome

Marcelo B.P. Amato, M.D., Maureen O. Meade, M.D., Arthur S. Slutsky, M.D., Laurent Brochard, M.D., Eduardo L.V. Costa, M.D., David A. Schoenfeld, Ph.D., Thomas E. Stewart, M.D., Matthias Briel, M.D., Daniel Talmor, M.D., M.P.H., Alain Mercat, M.D., Jean-Christophe M. Richard, M.D., Carlos R.R. Carvalho, M.D., and Roy G. Brower, M.D.

New Eng J Med 2015
Driving Pressure

Airway Pressure

Pplat

Driving Pressure

Time

PEEP
Median $V_T$ (10th–90th percentile) — mg/kg of predicted body weight:

- $6.0$ (5.9–7.5)
- $6.1$ (5.8–9.2)
- $8.0$ (5.7–12.1)

$P<0.001$
Problems with Driving Pressure Approach

\[ P_{\text{plat}} = \text{Distending pressure of the respir system} \]

\[ P_{\text{TP}} = P_{\text{plat}} - P_{\text{pl}} = \text{Distending pressure of the lung} \]
Transpulmonary Driving Pressure

Transpulmonary Driving Pressure ($\Delta P_{TP}$)

$P_{TPei} - P_{Tpee}$

$\Delta P_{TP} = \frac{V_T}{C_L}$
Problems with $\Delta P_{TP}$ Approach

- Requires esophageal catheter
  - Many assumptions
- Safe upper limit?
  - Normal: $C_L = 200$, $V_T = 400$, then
    $\Delta P_{TP} = 400/200 = 2$ cm H$_2$O
  - ARDS: $C_L = 20 – 50$, $V_T = 400$
    $\Delta P_{TP} = 8 – 20$ cm H$_2$O
How to Set $V_T$ in ARDS

- Method must be acceptable to most clinicians
- Initial $V_T = 6$ mL/kg PBW (easiest)
- Reduce $V_T$ in decrements of $\sim 0.5$ ml/kg PBW over several hours until signs of intolerance.
PBW vs Strain vs Stress vs Driving Pressure vs Transpulmonary Driving Pressure?

Decrease $V_T$ until *signs of intolerance*:

- Tachycardia
- Hypertension or hypotension
- Agitation
- Tachypnea, dyssynchrony
- Acidosis
- Hypoxemia despite high $FiO_2$
Case Presentation

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  - Pplat = 34. ΔP = 24
- Chest volumes not large
- Tidal volume decreased to 5, 4 mL/kg PBW
  - Pplat = 28, ΔP = 18
- PaCO$_2$ = 55, pH = 7.28
Case Presentation

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- PaCO₂ = 55, pH = 7.28
- Tidal volume decreased to 2.8 mL/kg PBW. RR 40.
- Pplat = 24, ΔP = 14
Living on the Edge of the Evidence
PEEP?
<table>
<thead>
<tr>
<th><strong>ACUTE RESPIRATORY DISTRESS</strong></th>
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<td><strong>IN ADULTS</strong></td>
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</tbody>
</table>

Lancet 1967; 2:319-323
Setting PEEP

Traditional Approach
Adjust PEEP to allow acceptable arterial oxygenation on $\text{FiO}_2 \leq .70$

$\text{PEEP} = 5 -12 \text{ cm H}_2\text{O}$
How to Set PEEP

Table of fixed combinations of PEEP and FiO₂

<table>
<thead>
<tr>
<th>FiO₂</th>
<th>.3</th>
<th>.4</th>
<th>.4</th>
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<td>16</td>
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<td>18-24</td>
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Ventilator-Induced Lung Injury

Low Volume
Low Pressure
VILI
# How to Set PEEP

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<td>20</td>
<td>22</td>
<td>22</td>
<td>22-24</td>
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## 4 Higher PEEP Trials

<table>
<thead>
<tr>
<th></th>
<th>Higher PEEP</th>
<th>Lower PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARDSNet (549)</td>
<td>27.5</td>
<td>24.9</td>
</tr>
<tr>
<td>Canadian (983)</td>
<td>36.4</td>
<td>40.4</td>
</tr>
<tr>
<td>French (767)</td>
<td>35.4</td>
<td>39.4</td>
</tr>
<tr>
<td>ART (1010)</td>
<td>55.3*</td>
<td>49.3</td>
</tr>
<tr>
<td>Combined (3309)</td>
<td>40.4</td>
<td>40.2</td>
</tr>
</tbody>
</table>

ARDSnet NEJM 2004  Meade JAMA 2008
Mercat JAMA 2008   Cavalcanti JAMA 2017
Why Mortality Not Lower with Higher PEEP?

Effects of Higher PEEP in each patient
- Reduce VILI from Low volume/Low pressure
- Increase VILI from Overdistention
Effects of PEEP are Variable Among Patients

Diffuse

Recruitment

Overdistention

Lobar

Recruitment

Overdistention
- Who are the PEEP responders?
- How much PEEP in responders?
- When to decrease PEEP in responders?
- How much PEEP in nonresponders?
Effects of PEEP

<table>
<thead>
<tr>
<th></th>
<th>Responders</th>
<th>Nonresponders</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaO₂/FiO₂ (SD)</td>
<td>150 (36)</td>
<td>149 (38)</td>
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<tr>
<td>PEEP</td>
<td>9</td>
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</tbody>
</table>

Lower PEEP $\rightarrow$ Higher PEEP

Tables

- Easy to identify PEEP responders
- No special equipment
- Optimal PEEP?
- Some patients may need lower PEEP than they receive on the lower PEEP table
EXPRESS PEEP

• Raise PEEP until inspiratory Pplat approaches 30 cm H$_2$O
  – Greater Ventilator-free days
  – Mortality NS but favorable trend

Mercat et al
JAMA 2008
Stress Index

\[ Pao = a \cdot \text{inspiratory time}^b + c \]

Stress Index

- Special monitoring equipment needed
- Must be relaxed during inspiration
Driving Pressure ($\Delta P$)

Volume

Airway Pressure

Determinants of $\Delta P$

- Tidal Volume ($V_T$)
- Compliance $RS$

$\Delta P$
Driving Pressure and Survival in the Acute Respiratory Distress Syndrome

Marcelo B.P. Amato, M.D., Maureen O. Meade, M.D., Arthur S. Slutsky, M.D., Laurent Brochard, M.D., Eduardo L.V. Costa, M.D., David A. Schoenfeld, Ph.D., Thomas E. Stewart, M.D., Matthias Briel, M.D., Daniel Talmor, M.D., M.P.H., Alain Mercat, M.D., Jean-Christophe M. Richard, M.D., Carlos R.R. Carvalho, M.D., and Roy G. Brower, M.D.
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- 6.0 (5.9–7.5)
- 6.1 (5.8–9.2)
- 8.0 (5.7–12.1)
\[ \Delta P \text{-Guided PEEP} \]

Volume

\[ V_T = 6 \text{ ml/kg} \]

\[ \Delta P = 18 \]
\[\Delta P\text{-Guided PEEP}\]

\[V_T = 6 \text{ ml/kg}\]
\[\Delta P = 14\]
$\Delta P$-Guided PEEP

Volume

Paw

$V_T = 6$ ml/kg

$\Delta P = 18$
Driving Pressure

- Special monitoring equipment not needed
- Inspiratory efforts OK
- Patient must be relaxed during exhalation
Higher PEEP to More Recruitable Lung and Lower PEEP to Less Recruitable Lung

- Table of fixed combinations of PEEP and FiO$_2$  YES
- Raise PEEP until Pplat approaches 30 cm H$_2$O  No
- Raise PEEP until transpulmonary pressure > 0  No
- Adjust PEEP to Stress Index = 1.0  No
- Adjust PEEP to minimize Driving Pressure  ?

Chiumello D
Crit Care Med 2014
How to Set PEEP

Table of fixed combinations of PEEP and FiO₂

<table>
<thead>
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<td>16</td>
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</tbody>
</table>
Thank You
Thank You
Trials of Lung-protective Mechanical Ventilation

Clinical Trials (3562 Patients)
1. Amato NEJM 1998 – Lower $V_T$ + Higher PEEP
2. Stewart NEJM 1998 – Lower $V_T$
3. Brochard AJRCCM 1998 – Lower $V_T$
4. Brower CCM 1999 – Lower $V_T$
5. ARDS Network NEJM 2000 – Lower $V_T$
6. ARDS Network NEJM 2004 – Higher PEEP
7. Mercat JAMA 2008 – Higher PEEP
8. Meade JAMA 2008 – Higher PEEP
9. Talmor NEJM 2008 – Pes guided higher PEEP
Model Variables

Patient variables
- Days on mech vent
- Age
- APACHE III (1.31)
- # Organ failures
- Arterial pH (0.64)
- PaCO₂
- PaO₂/FIO₂
- Tidal-compliance

Mech Vent Variables
- Tidal volume
- Plateau pressure
- PEEP
- FiO₂ (1.32)
- Respiratory rate
- Mean airway pressure
- ΔP (Pplat – PEEP) (1.47)
Effect of ventilation on surface forces in excised dogs’ lungs\textsuperscript{1,2}

EDMUND E. FARIDY,\textsuperscript{3} SOLBERT PERMUTT, AND RICHARD L. RILEY
Department of Environmental Medicine, Johns Hopkins University,
Baltimore, Maryland

Sol Permutt
Mechanical Ventilation and ARDS

- Critical for survival
  - ensure gas exchange
  - buy time …
- Can cause lung injury
  - may prevent recovery
Effects of Lower PEEP on Inflammatory Mediators

Grasso S et al.
Am J Resp Crit Care Med 2007;
176:761-767
Pao = a \cdot \text{inspiratory time}^b + c

Stress Index in “Lobar” ARDS
PEEP, Pplat, and Lung Volume

Effects of Lowering PEEP on Gas Exchange in Lobar ARDS

<table>
<thead>
<tr>
<th></th>
<th>ARDSNet Table</th>
<th>Stress Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>PaO$_2$/FiO$_2$</td>
<td>122 ± 44</td>
<td>110 ± 32 (NS)</td>
</tr>
<tr>
<td>PaCO$_2$ (mm Hg)</td>
<td>46 ± 6</td>
<td>42 ± 6 (&lt;0.01)</td>
</tr>
</tbody>
</table>

Stress Index Predicts Lung Injury

Air Flow

Airway Pressure

Decrease PEEP

ΔP
Air Flow

Airway Pressure

Raise PEEP

## Driving Pressures in Higher PEEP Trials

<table>
<thead>
<tr>
<th></th>
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<th>PEEP</th>
<th>ΔP</th>
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<td>Higher</td>
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<td>12.3</td>
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<tr>
<td>Higher</td>
<td>27.5</td>
<td>14.6</td>
<td>12.9</td>
<td>+0.2</td>
</tr>
</tbody>
</table>
# Model Variables

<table>
<thead>
<tr>
<th>Patient variables</th>
<th>Mech Vent Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days on mech vent</td>
<td>Tidal volume</td>
</tr>
<tr>
<td>Age</td>
<td>Plateau pressure</td>
</tr>
<tr>
<td>APACHE III</td>
<td>PEEP</td>
</tr>
<tr>
<td># Organ failures</td>
<td>FiO₂</td>
</tr>
<tr>
<td>Arterial pH</td>
<td>Respiratory rate</td>
</tr>
<tr>
<td>PaCO₂</td>
<td>Mean airway pressure</td>
</tr>
<tr>
<td>PaO₂/FIO₂</td>
<td>ΔP (Pplat – PEEP)</td>
</tr>
<tr>
<td>Tidal-compliance</td>
<td></td>
</tr>
</tbody>
</table>
Driving Pressure (Pplat – PEEP) = $\frac{V_T}{C_{RS}}$

E.g., $V_T = 600$, $C_{RS} = 25$ ml/cm H$_2$O

Driving Pressure = $\frac{600}{25} = 24$ cm H$_2$O
Alveolar Type II Epithelial Cells

Tschumperlin et al. Am J Respir Crit Care Med 2000
Figure 1:

Resampling A:  
- matched PEEP

Resampling B:  
- matched \( \Delta P \)

Resampling C:  
- matched \( P_{PLAT} \)

Airway Pressure (cmH\(_2\)O)

Relative risk (adjusted mortality rate*)

A: contrast  
higher \( P_{PLAT} \): not always risky

B: contrast  
higher PEEP: not always protective

* adjusted for age, APACHE/SAPS risk, arterial-pH, P/F ratio, and study-trial
Figure 4: \( \Delta P \)-changes driven by randomization mediate survival in the higher-PEEP arms

\[ \begin{align*}
P &= 0.002 \text{ (survival difference across terciles)} \\
\text{Adjusted Survival} * (%) \\
\text{Days after randomization} \\
\text{Low-PEEP arm; } N = 794 \\
\text{(mean } \Delta P\text{-change } = +1.3) \\
\text{mean } \Delta P\text{-change } &= -3.7 \text{ cmH}_2\text{O} \\
\text{mean } \Delta P\text{-change } &= +0.4 \text{ cmH}_2\text{O} \\
\text{mean } \Delta P\text{-change } &= +4.1 \text{ cmH}_2\text{O} \\
\end{align*} \]

*: Adjusted for: age, APACHE/SAPS risk, arterial-pH, P/F ratio, study-trial, and Disease-\( \Delta P \)
Figure 2a: Subsample of patients under “protective settings”

( N = 1745 )

All with Plateau-pressure ≤ 30 cmH₂O & Vₜ ≤ 7 mL/ibw

<table>
<thead>
<tr>
<th>Cumm. Survival (%) (adjusted*)</th>
<th>P &lt; 0.001 stratification: ( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>∆P ≤ 14 cmH₂O (989)</td>
<td></td>
</tr>
<tr>
<td>∆P &gt; 14 cmH₂O (756)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cumm. Survival (%) (adjusted*)</th>
<th>P = 0.98</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pₚ₁₅ ≤ 25 cmH₂O (955)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pₚ₁₅ &gt; 25 cmH₂O (790)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cumm. Survival (%) (adjusted*)</th>
<th>P = 0.30</th>
<th>( N )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vₜ ≥ 6 mL/kg (867)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vₜ &lt; 6 mL/kg (878)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*: adjusted for age, APACHE/SAPS risk, arterial-pH, P/F ratio, and study-trial
Strain

Ratio of total deformation to the initial dimension of the material body in which the forces are being applied.

\[ \varepsilon = \frac{\Delta L}{L} \]
they are compressed. Thus, we have

\[
\varepsilon = \frac{\Delta L}{L} = \frac{L - L_0}{L_0} = \frac{L_3 - L_0}{L_0} = \frac{L_3}{L_0} - 1
\]

**Strain**

Ratio of total deformation to the initial dimension of the material body in which the forces are being applied.

\[
\text{Strain} = \frac{\Delta L}{L}
\]
Figure 2b: Combined population of ARDS (N = 3080)

- **P < 0.001**
- **P < 0.01**

* Adjusted for age, APACHE/SAPS risk, arterial-pH, P/F ratio, and study-trial
<table>
<thead>
<tr>
<th></th>
<th>Pplat</th>
<th>PEEP</th>
<th>ΔP</th>
<th>Δ-ΔP</th>
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<tbody>
<tr>
<td><strong>ARDSnet</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>24.0</td>
<td>8.9</td>
<td>15.1</td>
<td></td>
</tr>
<tr>
<td>Higher</td>
<td>27.0</td>
<td>14.7</td>
<td>12.3</td>
<td>-2.8</td>
</tr>
<tr>
<td><strong>Canadian</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>24.9</td>
<td>10.1</td>
<td>14.8</td>
<td></td>
</tr>
<tr>
<td>Higher</td>
<td>30.2</td>
<td>15.6</td>
<td>14.6</td>
<td>-0.2</td>
</tr>
<tr>
<td><strong>French</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>21.1</td>
<td>8.4</td>
<td>12.7</td>
<td></td>
</tr>
<tr>
<td>Higher</td>
<td>27.5</td>
<td>14.6</td>
<td>12.9</td>
<td>+0.2</td>
</tr>
<tr>
<td><strong>ARDSnet Tidal Volume</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower</td>
<td>25</td>
<td>9.4</td>
<td>15.6</td>
<td>-8.8</td>
</tr>
<tr>
<td>Higher</td>
<td>33</td>
<td>8.6</td>
<td>24.4</td>
<td></td>
</tr>
</tbody>
</table>
Lower $V_T$/Pressure Ventilation

- VILI from Overdistension
- VILI from Opening-Closing
- Lower $V_T$
ARDS Network Tidal Volume Trial
Mortality Before Hospital Discharge

Mortality (Percent)

P = 0.007

6 ml/kg
12 ml/kg

ARDSnet. NEJM 2000
ARDS Network Tidal Volume Trial

Tidal Volume goal = 6 ml/kg PBW

Plateau Pressure limit = 30 cm H₂O
Mechanical Ventilation
Traditional Approach
PEEP 0-12 cm H₂O

Low Volume/Low Pressure at End-expiration
Lower $V_T$/Pressure Ventilation

- VILI from Overdistension
- VILI from Opening-Closing
- Lower $V_T$
Lower $V_T$ and Higher PEEP

Lung Volume

Time

VILI from Overdistension

VILI from Opening-Closing
Ventilator-Induced Lung Injury

14/0  45/10  45/0

PIP/PEEP

Webb and Tierney
Am Rev Resp Dis
110:556-565, 1974
## 3 Higher PEEP Trials

<table>
<thead>
<tr>
<th></th>
<th>Higher PEEP</th>
<th>Lower PEEP</th>
</tr>
</thead>
<tbody>
<tr>
<td>ARDSnet (549)&lt;sup&gt;1&lt;/sup&gt;</td>
<td>27.5</td>
<td>24.9</td>
</tr>
<tr>
<td>Canadian (983)&lt;sup&gt;2&lt;/sup&gt;</td>
<td>36.4</td>
<td>40.4</td>
</tr>
<tr>
<td>French (767)&lt;sup&gt;3&lt;/sup&gt;</td>
<td>35.4</td>
<td>39.4</td>
</tr>
<tr>
<td>Combined (2299)</td>
<td>33.9</td>
<td>36.2</td>
</tr>
</tbody>
</table>

1 ARDSnet NEJM 2004  
2 Meade JAMA 2008  
3 Mercat JAMA 2008
Effects of PEEP are Variable

- Diffuse Recruitment
- Overdistention
- Lobar Recruitment
- Overdistention
ARDS Network Trial – Tidal Volumes

\( V_T \) (ml/kg PBW)

6 ml/kg

12 ml/kg

Study Day
ARDS Network Trial - Plateau Pressures

- **6 ml/kg**
- **12 ml/kg**

<table>
<thead>
<tr>
<th>Study Day</th>
<th>cm water</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>
ARDS Network Trial of Lower Tidal Volume Ventilation in ALI/ARDS

Subset analysis

*No “safe” level of $P_{plat}$ identified*
Mortality by Day 1 Pplat Quartiles (n=822)

- Highest: >37, 29%
- Third: >29, 37%
- Second: 25, 25%
- Lowest: 20, 26%

Mortality (%) vs. Day 1 Pplat Quartiles
Lower $V_T$/Pressure Ventilation and Higher PEEP

- VILI from Overdistension
- Higher PEEP and Lower $V_T$
- VILI from Opening-Closing

Lung Volume

Time
Stress Index

Lung-protective Mechanical Ventilation in ALI and ARDS

PEEP Questions

– Who are the responders?
– How much PEEP in responders?
– How much PEEP in nonresponders?
– When to decrease PEEP in responders?
Ventilator-Induced Lung Injury

High Volume
High Pressure
VILI

Low Volume
Low Pressure
VILI
Effects of PEEP on Elastance
Recruiters and Nonrecruiters

Lower $V_T$ and Inspiratory Pressure Reduced Overdistention AND Opening-Closing

Volume

Pressure

Higher $V_T$

Lower $V_T$
Higher $V_T$ and Inspiratory Pressure

![Graph showing the relationship between volume and pressure with higher $V_T$ indicated on the curve.](image-url)
Ventilator-induced Lung Injury

*Effect of Positive Pressure Ventilation on Surface Tension Properties of Lung Extracts*

Lazar J. Greenfield, M.D., Paul A. Ebert, M.D., Donald W. Benson, M.D., Ph.D.

Anesthesiology 1964; 312-316
Effects of PEEP

Responders  Nonresponders

Pressure Volume Curve

Stress Index

Volume

Pao

Stress Index = 1
Pressure Volume Curve
Stress Index

Volume
Pao

Stress Index >1