Mechanical Ventilation in the Brain-Injured Patient

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Outline

• Epidemiology of lung injury after brain injury

• Why is there reluctance in providing lung-protective ventilation in brain injury?

• Ventilation parameters to pay attention to:
  – $PCO_2$
  – PEEP

• Pragmatic approach to hypoxemic respiratory failure / ARDS in the brain-injured patient
Etiology of Respiratory Failure

- Aspiration
- Pneumonia
- Pulmonary Contusions
- ARDS
- Neurogenic Pulmonary Edema
- TRALI

This list is common to many MICU / SICU patients…
But are brain-injured patients really different?
ALI / ARDS is Common...

- In polytrauma with traumatic brain injury

But Also:
- Isolated traumatic brain injury $^{1,2}$
- Subarachnoid hemorrhage$^3$

ALI rates as high as 30% in severe brain injury
ALI/ARDS risk associated with severity of injury
Associated with worse outcomes

We are sometimes reluctant to implement this knowledge in brain-injured patients. WHY?
## Conflicting Paradigms

<table>
<thead>
<tr>
<th>Historical “brain-directed” strategy</th>
<th>Lung protective ventilation</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Optimize oxygen delivery</td>
<td>• Avoid overdistention</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>• Control of PCO2</td>
<td>• Open the lung</td>
</tr>
<tr>
<td>(higher $V_T$ and $V_E$)</td>
<td>• Avoid cyclical collapse</td>
</tr>
<tr>
<td>• Minimize potential effects of PEEP</td>
<td>(Atelectrauma)</td>
</tr>
</tbody>
</table>
What *Really* Matters to the Brain

- Avoid hypoxemia

- Protect cerebral perfusion
  - Avoid hypotension
  - Avoid high intracranial pressure
  - Avoid inadvertent hypocapnia

\[
CPP = MAP - ICP
\]
Two Parameters To Pay Attention To:

- $\text{PCO}_2$
- Positive End Expiratory Pressure (PEEP)
Concern Over Hypercapnia

- Concern that hypercapnia may worsen:
  - Hyperemia
  - ICP → cerebral herniation

*This is a concern in patients with very low intracranial compliance (little compensatory reserve)*
Intracranial Compliance

ICP (mmHg)

\[ \frac{\Delta P}{\Delta V} = \text{elastance} \]

\[ \frac{\Delta V}{\Delta P} = \text{compliance} \]

\[ \Delta V \]

\[ \Delta P \]

\[ \Delta P' \]

\[ \Delta V \]
Low Intracranial Compliance

Increase in intracranial blood from vasodilation / decreased venous drainage is critical.
CO$_2$ : Too Little of a Good Thing!

- Hypocapnia-related reduction in CBF causes:
  - Metabolic crisis $^{1,2}$
  - Increases ischemic brain volume$^1$
- Early, prophylactic hyperventilation in traumatic brain injury associated with worse outcomes $^3$

2 - Carrera E et al. *J Neurol Neurosurg Psychiatry.* 2010
CO₂: The Bottom Line

- **Eucapnia**
- Hypocapnia only if ICP emergency
- No ICP? Be wary of ↑PCO₂ if signs of low intracranial compliance
  - CT:
    - Sulcal effacement
    - Effaced basal cisterns
    - Small ventricles
    - Hydrocephalus
Two Parameters To Pay Attention To:

- $\text{PCO}_2$

- Positive End Expiratory Pressure (PEEP)
PEEP: Concern Over ICP

• High levels of PEEP may be bad in brain-injured patients:
  1. Decreased venous drainage
  2. Transmission of intrathoracic pressure ➔ Increased ICP
  2. Decreased Cardiac Output ➔ Decreased CBF
PEEP & ICP: Complex Relationship

- Intracranial Compliance
- Venous Drainage
- Head Elevation
- Pulmonary Compliance
- Starling Resistors
PEEP, Compliance and ICP

- Respiratory System Compliance ($C_{rs}$)
  - Hemodynamic and hydrostatic impact of PEEP is attenuated in patients with low $C_{rs}$

Patients in whom we want to use PEEP can often tolerate it

Why PEEP May Not Affect ICP...

- Cerebral circulation is a **Starling Resistor**
- Flow usually dependent on MAP-ICP

\[
\text{Hence CPP} = \text{MAP} - \text{ICP}
\]

- PEEP-related increases in CVP only relevant if CVP > ICP
Starling Resistors

The Starling Resistor Concept

P_A > P_a > P_v

P_a > P_A > P_v

P_a > P_v > P_A

Pulmonary Circulation
Head of Bed Elevation

MAP is relatively constant

ICP is relatively constant

Diminished effect of increased intrathoracic pressure due to decreased transmission of RAP to head

1 - Durward et al. J Neurosurg. 1983
PEEP is Usually Well-Tolerated

...in Patients Who Need It

• Moderate levels of PEEP associated with little change cerebral perfusion
  – As long as MAP maintained

• High PEEP may ↓ ICP reserve
• HOB at 30-45°
• Don’t forget about PCO₂!


Figure 1. Effects of positive end-expiratory pressure (PEEP) on intracranial pressure (ICP), brain tissue oxygen tension (Ptio₂), and regional cerebral blood flow (rCBF) in healthy pigs. Data are expressed as mean values ± sd.
Bottom Line: PEEP

- Can use PEEP as indicated, but:
  - Ensure no change in MAP
    - Adequate intravascular volume
  - Keep head elevated
  - Follow ICP
  - Consider maintaining PEEP < ICP
Putting It All Into Practice:
Lung Protection and Brain Injury

- Lung-protective ventilation saves lives
- High tidal volumes predict ALI/ARDS in TBI patients

"Can we afford to relax control of PCO₂ To achieve low tidal volumes?"
Not-so Permissive Hypercapnea

- Many large ARDS ventilation studies excluded patients with increased ICP

- But…PCO$_2$ levels in these studies were quite average, normal *(at least for first 72 hrs)*
ARMA: ARDSNet, *NEJM*, 2004

<table>
<thead>
<tr>
<th>VARIABLE</th>
<th>DAY 1</th>
<th>DAY 3</th>
<th>DAY 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GROUP RECEIVING LOWER TIDAL VOLUMES</td>
<td>GROUP RECEIVING TRADITIONAL TIDAL VOLUMES</td>
<td>GROUP RECEIVING LOWER TIDAL VOLUMES</td>
</tr>
<tr>
<td>PaCO₂ (mm Hg)</td>
<td>40±10</td>
<td>35±8</td>
<td>43±12</td>
</tr>
<tr>
<td>No. of patients</td>
<td>351</td>
<td>369</td>
<td>285</td>
</tr>
<tr>
<td>Arterial pH</td>
<td>7.38±0.08</td>
<td>7.41±0.07</td>
<td>7.38±0.08</td>
</tr>
<tr>
<td>No. of patients</td>
<td>351</td>
<td>369</td>
<td>285</td>
</tr>
</tbody>
</table>

ALVEOLI: ARDSNet, *NEJM*, 2004

Table 3. Respiratory Values during the First Seven Days of Treatment.*

<table>
<thead>
<tr>
<th>Variable</th>
<th>Day 1</th>
<th>Day 3</th>
<th>Day 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lower-PEEP Group</td>
<td>Higher-PEEP Group</td>
<td>Lower-PEEP Group</td>
</tr>
<tr>
<td>PaCO₂ (mm Hg)</td>
<td>41±11</td>
<td>41±11</td>
<td>43±13</td>
</tr>
<tr>
<td>No. of patients</td>
<td>230</td>
<td>244</td>
<td>159</td>
</tr>
</tbody>
</table>


Table 4. Respiratory Dataa

<table>
<thead>
<tr>
<th>Variables</th>
<th>Day 1</th>
<th>Day 3</th>
<th>Day 7</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lung Open Ventilation</td>
<td>Control</td>
<td>P Value</td>
</tr>
<tr>
<td>PaCO₂, mean (SD), mm Hg</td>
<td>45.5 (12.0)</td>
<td>44.6 (10.9)</td>
<td>.22</td>
</tr>
<tr>
<td>No. of patients</td>
<td>464</td>
<td>498</td>
<td></td>
</tr>
<tr>
<td>pH, mean (SD)</td>
<td>7.33 (0.10)</td>
<td>7.35 (0.09)</td>
<td>.17</td>
</tr>
<tr>
<td>No. of patients</td>
<td>464</td>
<td>498</td>
<td></td>
</tr>
</tbody>
</table>
ARDS and Brain Injury

1. **Start with what we know are best practices** \((low \ V_T, \ P_{plat})\)
2. Monitor PCO\(_2\) and ICP
3. Carefully consider anything to improve CO\(_2\) clearance and minimize pressures
   - Dead space in circuit
   - Synchrony
   - Draining effusions or ascites

You may have to decide which is more important to you – \(V_T\) or PCO\(_2\)
# Rational Approach to ALI / ARDS in Brain Injury

## Table: Rational Approach to ALI / ARDS in Brain Injury

<table>
<thead>
<tr>
<th></th>
<th>Normal ICP</th>
<th>Higher ICP</th>
</tr>
</thead>
</table>
| **Start with…**  | Normocapnia  
                       Low $V_T$ (6 ml/kg)  
                       Limit $P_{plat}$                                                   | Normocapnia  
                       Low $V_T$ (6 ml/kg)  
                       Limit $P_{plat}$                                                   |
| **If respiratory acidosis**  
                       (CO$_2$ rising)... | Moderate Hypercarbia  
                       Follow ICP                                                              | Consider increasing $V_T$  
                       Normocarbia  
                       Follow ICP                                                              |
|                   | Remove excess dead space  
                       Sedation / Ensure synchrony  
                       Drain large effusions / ascites                                         | Remove excess dead space  
                       Sedation / Ensure synchrony  
                       Drain large effusions / ascites                                         |
| **Then…**         | Alternative modes, prioritizing lung protection  
                       (but following ICP)                                                     | Alternative modes, prioritizing CO$_2$ elimination                        |
Summary

• Acute Lung Injury is common in patients with brain injury

• Be vigilant about PCO$_2$ – hypopcapnia can be harmful!

• PEEP appears safe in patients who need it

• Protect the lungs, but prioritize CO$_2$ control and cerebral perfusion
Questions? Slides?

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Extra Slides
Mechanical Ventilation In Brain Injury

- Brain injury may be main indication for mechanical ventilation in up to 20% of cases
- Major contributor to prolongation of mechanical ventilation in over a third of patients
- Associated with 3-fold risk of dying or unfavourable outcome

Kelly BJ et al. *Chest.* 1993
Holland MC et al. *J Trauma.* 2003
Cerebral Perfusion

- Adult brain is only 2% of body weight
  - 15% of the resting cardiac output
  - 20% of the total body oxygen consumption
- Blood flow regulated by three primary factors
  1. Metabolic stimuli
  2. Chemical stimuli
  3. Perfusion pressure
Cerebral Perfusion Pressure

- Cerebral Perfusion Pressure

\[
CPP = MAP - ICP
\]

Mechanical Ventilation may affect MAP and ICP through multiple mechanisms
3 Key Concepts

1. Intracranial Pressure

2. CO$_2$ and the Brain

3. Intracranial Compliance
   (ICP compensatory reserve)
Key Concept 1: ICP

Monro-Kellie Doctrine

Skull has fixed volume

1. Brain parenchyma (80%)
2. CSF (10%)
3. Intravascular blood (10%)
Key Concept 2: \( \text{CO}_2 \) and the Brain

- \( \text{CO}_2 \) is a potent cerebral vasodilator
  - \( \sim 2\% \) increase in CBF / mmHg increase PaCO\( _2 \)
  - Hyperventilation for emergent ICP control
  - Buffering of perivascular space restores CBF towards normal within hours
Key Concept 3: Intracranial Compliance

- Low intracranial compliance

*Increase in intracranial blood from vasodilation / decreased drainage is critical*
High Frequency Oscillation

- Existing case series suggest **safe**:
  - Most patients had little / no ICP increase attributable to HFO $^{1,2}$
  - Volume loading important to avoid drops in MAP / CPP on initiation $^1$
  - Infrequent, but clinically important rapid changes in PCO$_2$ on initiation

Careful monitoring of PCO$_2$ at start
Initial use of aggressive CO$_2$ settings

Prone Positioning

• 16 Patients with SAH
  – Improved brain tissue oxygenation
    • 2° improved arterial oxygenation
  – BUT:
    • Can’t maintain head elevation
    • Increased transmission of intrathoracic pressure

→ increase in ICP and reduction in CPP with prone position

Low-Tidal Volume Ventilation

- Only 30% of SAH patients with ALI received low $V_T$ ventilation
  - Patients who did had
    - Higher applied PEEP
    - Similar arterial pH
    - Similar $PCO_2$
    - *Worse oxygenation*

<table>
<thead>
<tr>
<th>Arterial $Pco_2$, mm Hg</th>
<th>Received Lung-Protective Ventilation (n = 51)</th>
<th>Did Not Receive Lung-Protective Ventilation (n = 119)</th>
<th>$p$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Day 1</td>
<td>38 ± 8</td>
<td>36 ± 6</td>
<td>.08</td>
</tr>
<tr>
<td>No. of patients</td>
<td>51</td>
<td>112</td>
<td></td>
</tr>
<tr>
<td>Day 3</td>
<td>37 ± 7</td>
<td>36 ± 7</td>
<td>.43</td>
</tr>
<tr>
<td>No. of patients</td>
<td>46</td>
<td>79</td>
<td></td>
</tr>
<tr>
<td>Day 7</td>
<td>40 ± 8</td>
<td>39 ± 7</td>
<td>.74</td>
</tr>
<tr>
<td>No. of patients</td>
<td>27</td>
<td>52</td>
<td></td>
</tr>
</tbody>
</table>

**V_T in Brain-Injured Patients?**

- Mascia et al.
  - Retrospective review: 86 pts with severe brain injuries who developed ALI/ARDS within 8 days
  - Most ventilated to PaCO_2 \approx 35 \text{ mmHg}
  - Baseline Vt \((\text{ml/kg}_{\text{PBW}})\) associated with 5.4x odds of development of subsequent ALI/ARDS

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*High tidal volume is associated with the development of acute lung injury after severe brain injury: An international observational study*

Luciana Mascia, MD, PhD; Elisabeth Zavala, MD; Karen Bosma, MD; Daniela Pasero, MD; Daniela Decaroli, MD; Peter Andrews, MD; Donatella Isnardi, MD; Alessandra Davi, MD; Maria Jose Arguis, MD; Maurizio Berardino, MD; Alessandro Ducati, MD; on behalf of the Brain IT group