Don’t be “SILI”: Understanding Patient Self-Induced Lung Injury (P-SILI)

Peter Crossno MD
Medical Director- Schmidt Chest Clinic and Respiratory Care
Intermountain Medical Center
• Disclosures
  • Consulting fee Boehringer Ingleheim
  • IPCE has mitigated all relevant financial relationships

• Slides and figures used for presentation are available from the public domain.
Case Presentation

• 61 yo previously healthy man, who is an active runner and recently returned from a trip to Florida, presented to IMC with 4 days of fevers and progressive shortness of breath.

• ED visit documented initial SaO2 70% on RA, Tm 39.9 degrees C, HR 86 BP 85/49, f 25 normal WBC and an elevated CRP of 26.7

• 3rd COVID test was reported positive.

• CXR performed in ED
• Given hypoxia, early fears of aerosolization of SARS-CoV 2 virus, the patient was emergently intubated in the ED
  • Low VT protocol 6 ml/kg
  • PEEP 8 FiO2 60%
  • Prone ventilation initiated

• Despite deep sedation, RASS -4, the patient maintained a high WOB ($f$ 28-38) with PEEP range 14-20 cm H20 with FiO2 60-100%. Over following 10 days
  • Pplat ~ 24-33 cm H20
  • Ppeak ~25-49 cm H20

• Rocuronium pushes employed intermittently during 1st ten days for refractory hypoxemia

• iNO initiated at day 10 w/ improvement in oxygenation
• Day 0-21 The patient remained intubated
• Day 22 extubation
• Day 25 required reintubation, resumed LVT protocol
• Day 28 Tracheostomy tube placement
• Day 29 A CXR then HRCT were performed...
Objectives

• Understanding the mechanics of breathing
  • Relationship of intrapleural pressure and airway pressures
    • During spontaneous breathing
    • During mechanical ventilation

• Understanding Volume and pressure changes in the lung (Boyle’s gas law)

• Understanding the mechanics of breathing in the injured lung
  • ARDS
  • Pendelluft Effect

• Analyzing P-SILI and where it may fit in our understanding of lung injury

• Understanding how P-SILI and VILI differ

• Understand how to recognize and hopefully avoid P-SILI
Understanding the Mechanics of Breathing

- Movement of gas in and out of the lung is a function of a biomechanical system and simple physics
  - Quiet Inhalation
    - Active – diaphragm and external intercostal muscles
  - Quiet Exhalation
    - Passive (allow muscle groups to relax)
  - Forced inhalation (active)
    - the diaphragm
    - external intercostal muscles
    - **accessory respiratory muscles:**
      - activated when respiration increases significantly
  - Forced exhalation (active)
    - **accessory respiratory muscles:**
      - activated when respiration increases significantly
Muscles of Breathing

Muscles of quiet breathing
The **diaphragm** forms the rounded “floor” of the thoracic cavity and is dome-shaped when relaxed. It alternates between the relaxed dome position and the contracted flattened position and changes the vertical dimensions of the thoracic cavity.

The **external intercostals** extend from a superior rib inferomedially to the adjacent inferior rib. These elevate the ribs and increase the transverse dimensions of the thoracic cavity.

Muscles of forced inspiration
The **sternocleidomastoid** attaches to sternum and clavicle; lifts rib cage.
The **serratus posterior superior** attaches to ribs 2–5 on its anterior surface; lifts ribs 2–5.

The **pectoralis minor** attaches to ribs 3–5; elevates ribs 3–5.

The **transversus thoracis** extends across the inner surface of the thoracic cage and attaches to ribs 2–6; depresses ribs 2–6.

The **transversus abdominis** extends between the ligamentum nuchae and the lower border of ribs 9–12; depresses ribs 9–12.

The **diaphragm** is a group of deep muscles along the length of the vertebral column; extends the vertebral column.

Muscles of forced expiration
The **internal intercostals** lie deep and at right angles to the external intercostals; depress the ribs and decrease the transverse dimensions of the thoracic cavity.

The **abdominal muscles** (primarily the external obliques and transversus abdominis) compress the abdominal contents, forcing the diaphragm into a higher domed position and the rectus abdominus pulls the sternum and rib cage inferiorly.

The **external intercostals** inferomedially to the adjacent inferior rib. These elevate the ribs and increase the transverse dimensions of the thoracic cavity.
Movement of Gas in/out of the lungs is a function of Volume and Pressure

• Boyle’s Law
  • At a constant temperature, the pressure ($P$) of a gas decreases if the volume ($V$) of the container increases, and vice versa
  • $P_1$ and $V_1$ represent the initial conditions and $P_2$ and $V_2$ the changed conditions
  • $P_1V_1 = P_2V_2$
  • Inverse relationship between gas pressure and volume
Area B decreases in volume and increases in pressure. Air moves from area B into area A.

Area B increases in volume and decreases in pressure. Air moves from area A into area B.

Pressure A = Pressure B
No net movement of air

Area B increases in volume and decreases in pressure. Air moves from area A into area B.

Area B decreases in volume and increases in pressure. Air moves from area B into area A.
Pressure gradients of the respiratory system

<table>
<thead>
<tr>
<th>Gradient name</th>
<th>Abbreviation</th>
<th>Formula</th>
<th>Clinical assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transpulmonary pressure</td>
<td>P_{t}</td>
<td>Pao − Ppl</td>
<td>Paw − Pes</td>
</tr>
<tr>
<td>Transalveolar pressure/elastic recoil pressure of the</td>
<td>P_{el}(L)</td>
<td>P_lv − Ppl</td>
<td>Paw (zero flow) − Pes</td>
</tr>
<tr>
<td>lung</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transdiaphragmatic pressure</td>
<td>P_{di}</td>
<td>Pab − Ppl</td>
<td>Pga − Pes</td>
</tr>
<tr>
<td>Pressure gradient over the chest wall</td>
<td>P_{cw}</td>
<td>Ppl − Pbs</td>
<td>Pes (as Pbs is conventionally 0)</td>
</tr>
<tr>
<td>Pressure gradient over the respiratory system</td>
<td>P_{rs}</td>
<td>Pao − Pbs</td>
<td>Paw (as Pbs is conventionally 0)</td>
</tr>
</tbody>
</table>

Pab, abdominal pressure; Pao, pressure at airway opening; P_{l}v, alveolar pressure; Pbs, pressure at body surface; Ppl, pleural pressure; Paw, airway pressure; Pes, esophageal pressure; Pga, gastric pressure.
No breathing:
- atmospheric pressure equals intrapulmonary pressure ie 760mm Hg
- intrapleural pressure is below 760mm Hg
- $P_{\text{atm}} = P_{\text{aw}} > P_{\text{pl}}$

with Inhalation:
- Alveolar volume increases
- Alveolar pressure decreases
- intrapulmonary pressure drops to 759mm Hg
- intrapleural pressure drops to 754mm Hg
- $P_{\text{atm}} > P_{\text{aw}} > P_{\text{pl}}$
Spontaneous (Negative pressure) Ventilation vs Positive Pressure Ventilation
Consequences of “too much” negative Pleural Pressure in spontaneous breathing

• Good Example
  • Negative pressure pulmonary edema
  • Generation of large amount of negative Ppl results in dramatic shift in PL resulting alveolar epithelial injury and capillary leak (from large increase in transvascular pressure)

Lemzye M Intensive Care Med 2014
Important factors impacting ventilation

• Lung Compliance
  • a measure of the lung's ability to stretch and expand (distensibility of elastic tissue).

• Static and dynamic pressures are reflections of static and dynamic lung compliance

• Measured lung compliance is an “average”

• Lungs are heterogeneous, thus regional lung compliance varies, especially in ARDS

Compliance = \frac{\Delta V}{\Delta P}

\begin{align*}
C_{stat} & = \frac{V_T}{P_{plat} - PEEP} \\
C_{dyn} & = \frac{V_T}{PIP - PEEP}
\end{align*}
ARDS

Berlin Criteria for Acute Respiratory Distress Syndrome (ARDS)

Respiratory symptoms must have begun within one week of a known clinical insult OR the patient must have new or worsening symptoms during the past week.

Bilateral opacities consistent with pulmonary edema must be present on a chest radiograph or computed tomographic (CT) scan. These opacities must not be fully explained by pleural effusions, lobar collapse, lung collapse, or pulmonary nodules.

A moderate to severe impairment of oxygenation must be present, as defined by the ratio of arterial oxygen tension to fraction of inspired oxygen (PaO₂/FiO₂). The severity of the hypoxemia defines the severity of the ARDS:

- Mild ARDS – The PaO₂/FiO₂ is > 200 mm Hg, but ≤ 300 mm Hg, on ventilator settings that include positive end-expiratory pressure (PEEP) or continuous positive airway pressure (CPAP) ≥ 5 cm H₂O.
- Moderate ARDS – The PaO₂/FiO₂ is > 100 mm Hg, but ≤ 200 mm Hg, on ventilator settings that include PEEP ≥ 5 cm H₂O.
- Severe ARDS – The PaO₂/FiO₂ is ≤ 100 mm Hg on ventilators setting that include PEEP ≥ 5 cm H₂O.
ARDS as a disease of heterogeneous lung compliance

Griffiths M *British Journal of Anaesthesia* 2004
Zone of over-distension

Zone of atelectasis
Prone Positioning

• Improves perfusion to the lungs → better VQ matching
• Heart shifts forward → improved compliance
• Improved lung recruitment
• Lung protective


**Pendelluft Effect in ARDS**

- Inhomogeneous inflation or deflation of the lungs causing dynamic pressure difference between lung regions leading to interregional airflow.

- Occurs when regions of the lung have different dynamics of regional inflation and deflation.

---

Greenblatt EE et al J Appl Physiol 1985
Spontaneous Breathing during Mechanical Ventilation

• Normal lungs can tolerate short periods of large volume swings
  • Transpulmonary pressure (PL) swings are distributed throughout the lung
  • Homogeneous ventilation can be achieved

• Injured lung does not tolerate large volume swings
  • Regional increases in PL can result or perpetuate lung injury
  • Ventilation in injured lung is heterogeneous
So, what is P-SILI and why are we talking about it now?

- P-SILI is a hypothetical, somewhat controversial mechanism by which intense, patient triggered inspiratory effort results in large swings in transpulmonary pressures.
- Regional shift in transpulmonary pressure may aggravate lung injury.
- The peculiar phenotypes of COVID 19 associated respiratory failure/ARDS has offered increased insight into the evolution of lung injury.
- P-SILI, in tandem with VILI (via mechanical ventilator induced volutrauma and barotrauma) may accentuate lung injury.
COVID 19 and P-SILI

- Phenotypic differences in ARDS from COVID 19 are distinct

Tonelli R et al J Clin Med 2021
Initial Lung Injury → Capillary Leak → Lung Edema → Impaired Gas Exchange Mechanics → Increased Respiratory Drive → Increased Pes swings → P-SILI → ↓Paw, ↑Vt, Pendelluft → Increased Pes swings →...

Brochard L et al Am J Resp Crit Care Med 2017
**Fig. 1** Principles of lung and diaphragm-protective ventilation. $\Delta P$: change in airway pressure during inspiration; PEEP: positive end-expiratory pressure; P-SILI: patient self-inflicted lung injury; VILI: ventilator-induced lung injury; $V_t$: tidal volume.
Physiologic effects of P-SILI

• Large swings in transpulmonary pressures (increased lung stress)
• Abnormal increase in transvascular pressures
• *Pendelluft*
• Diaphragmatic injury→weakness
• Increased lung inflammation
Ventilator Induced Lung Injury (VILI) vs P-SILI

- **VILI**
  - Composite lung injury consisting of pulmonary barotrauma, volutrauma, atelectrauma and biotrauma occurring during applied mechanical ventilation
    - Excessive tidal volumes
    - Excessive driving pressures (Pplat - PEEP)
    - Mechanical shear (atelectrauma) or recurrent “derecruitment”
    - Mechanical cellular injury leading to or propagating a systemic inflammatory response

- **P-SILI**
  - May occur in spontaneous breathing or mechanical ventilation (invasive and noninvasive)
  - Injury is a result of increase transpulmonary pressures
  - Transcapillary and transpulmonary pressures increase capillary leak and ultimately contribute to further “biotrauma”
Recognizing P-SILI

• As a consequence of patient effort/respiratory drive
  • Inspiratory effort is proportional to CO2 and negatively proportional to pH
  • Objective assessment of respiratory effort

• As a consequence of ventilator dysynchrony
  • Breath stacking
  • Double triggering
  • Excessive inspiratory times
Assessing Respiratory Effort

• Physical Exam
  • Increased respiratory rate
  • Anterior scalenus, Platysmus retractions
  • Intercostal muscle retractions
  • Paradoxical abdominal contractions
  • Grimacing

• Objective measures
  • Difficult to quantify without specific pressure measurements
    • Pressure amplitudes
    • Lower esophageal and gastric pressure measurement
    • Electromyelographic method
    • Ultrasound assessment
Preventing P-SILI

• The RT has a critical role to play
  • For spontaneous breathing patients
    • Appropriate timing of respiratory assist
      • Recognize with patient effort is high
      • Avoid Auto-PEEP
  • For magnitude of assist
    • Avoid unnecessary Pressure support/IPAP
      • Target low VT goals (6 ml/kg)
    • Avoid breath stacking and double triggering during assisted modes (PRVC, VC, PC)
  • Favor HFNC where appropriate
  • Avoid overuse of BiLevel NIPPV for hypoxemia
  • Understand Airway Occlusion Pressure (P0.1) and how it can help you in mechanically ventilated patients
Airway Occlusion Pressure (P0.1)

- P0.1 is the pressure generated at the airways during the first 100 msec of an inspiratory effort against an occluded airway
- P0.1 vent correlates with inspiratory effort as suggested by Pes.
- P0.1 3.5-4.0 cm H2O suggests excessive insp. Effort
- P0.1 ~1 cm H2O is considered low
- P0.1 can be variable and multiple (~5 sequential) measurements are recommended
- P0.1 is not necessarily tied to clinical outcomes
- Measurement of P0.1 may be a “bellwether” as to excessive inspiratory effort during mechanical ventilation.

Telia I et al AJRCCM 2020
Summary

• Patient self-induced lung injury (P-SILI) is a plausible mechanism for possible development and perpetuation lung injury.

• Understanding of the mechanics of breathing are fundamental to understanding the P-SILI concept.

• ARDS and specifically COVID19-associated ARDS have offered interesting insights into the role of P-SILI.

• Objective measurement of respiratory effort is technically challenging.

• Measurement and understanding of Airway Occlusion Pressure (P0.1) may be a tool to aid in evaluating for excessive inspiratory effort and risk of P-SILI in our mechanically ventilated patients.