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

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- Disclosures
  - Consulting fee Boerhinger Ingleheim
  - IPCE has mitigated all relevant financial relationships
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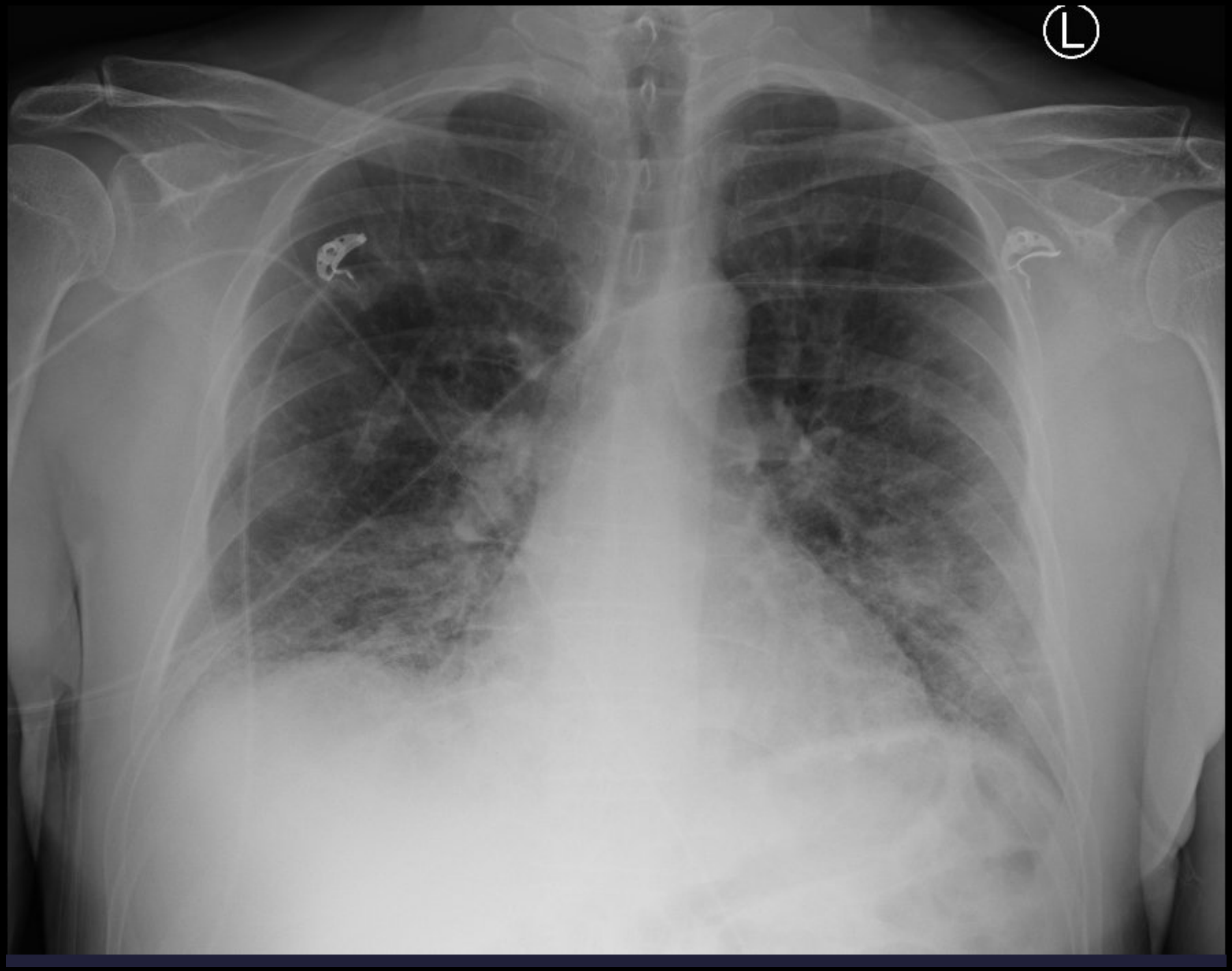
Case Presentation

- 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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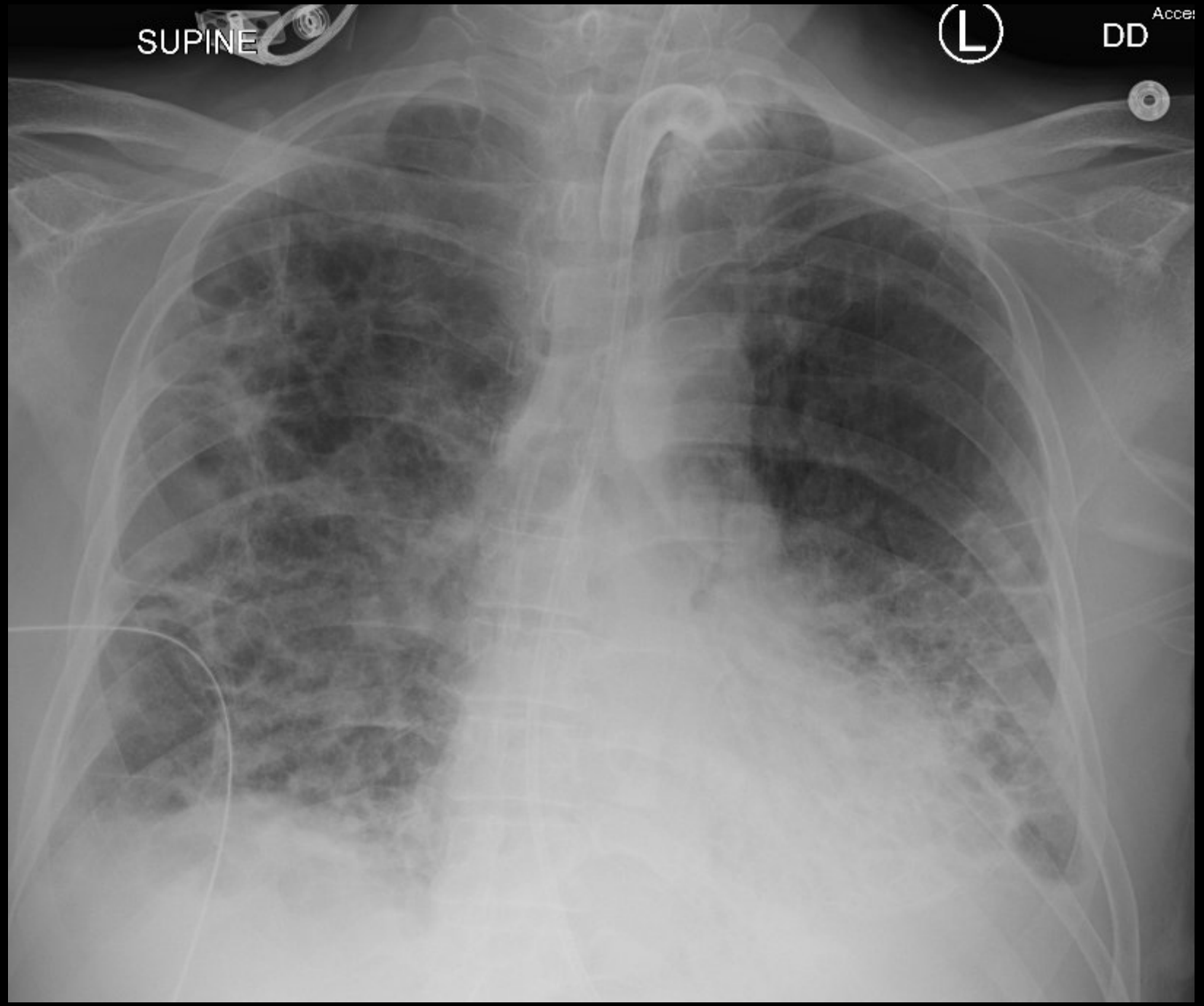
- Given hypoxia, early fears of aerosolization of SARS-CoV 2 virus, the patient was emergently intubated in the ED
  - Low VT protocol 6 ml/kg
  - PEEP 8 FiO2 60%
  - Prone ventilation initiated
- Despite deep sedation, RASS -4, the patient maintained a high WOB (*f* 28-38) with PEEP range 14-20 cm H20 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…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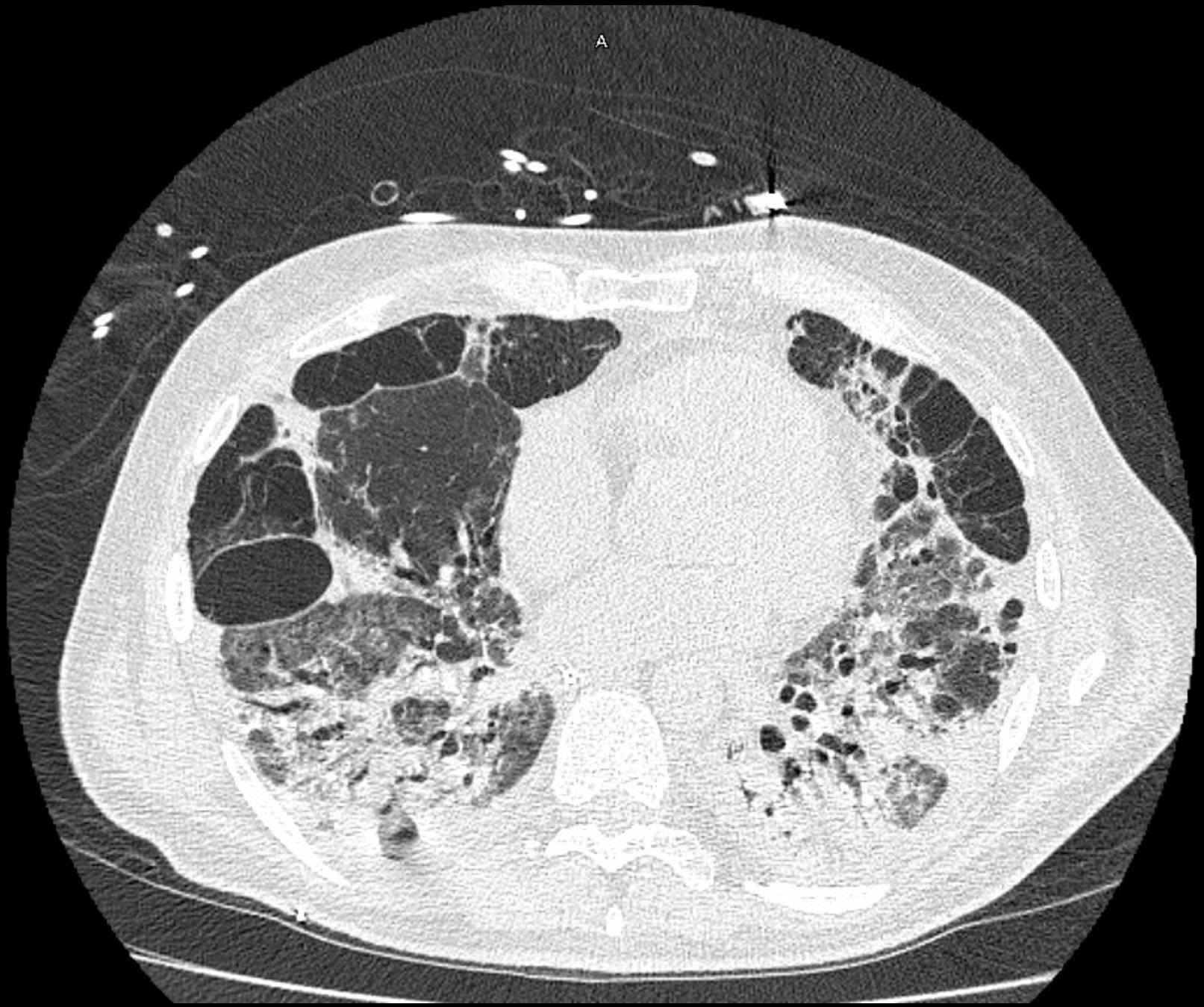
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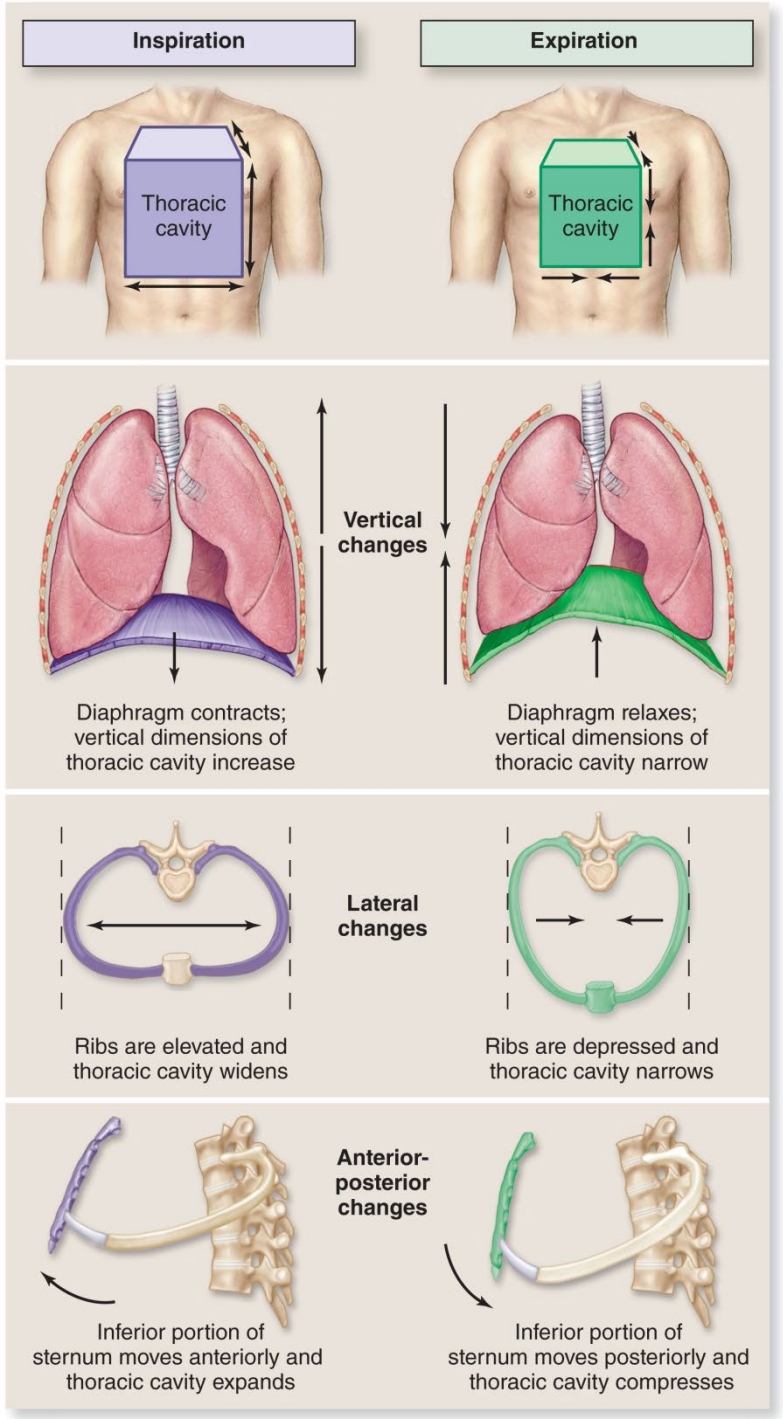
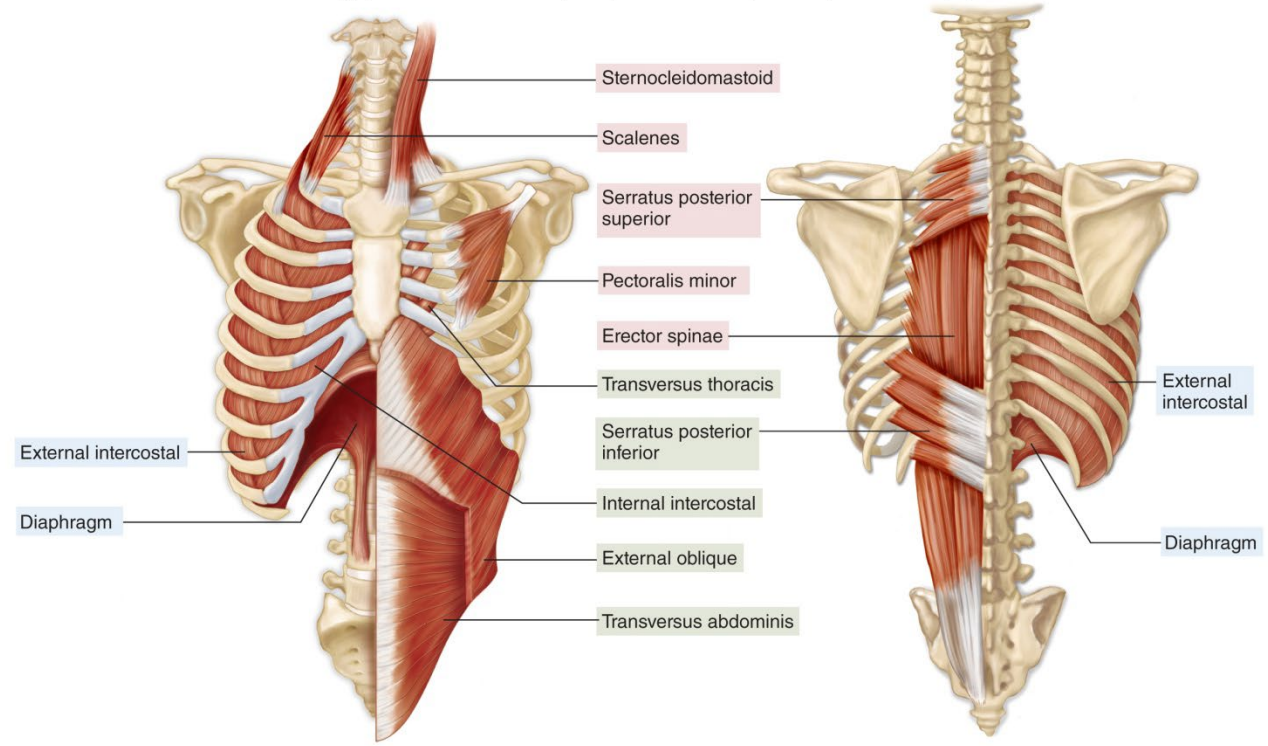
Objectives

- 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



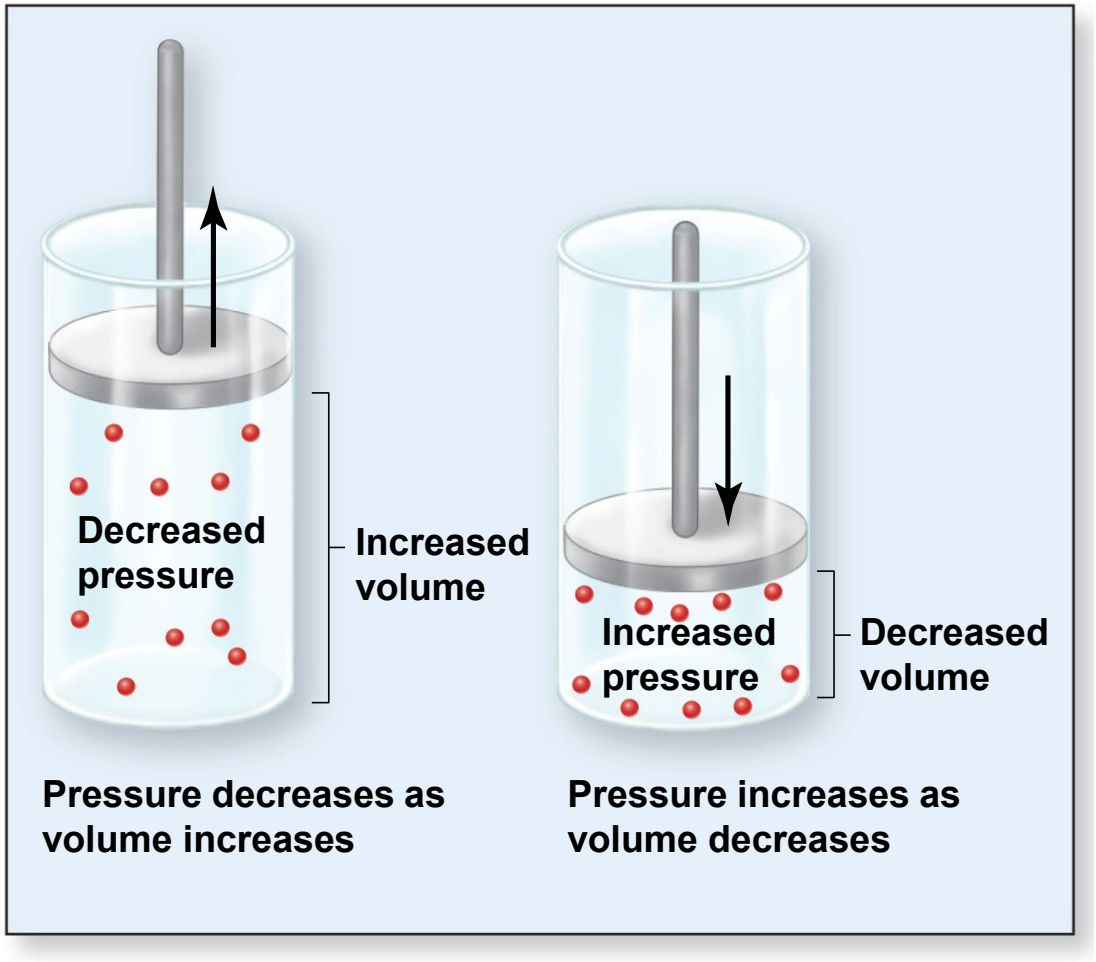


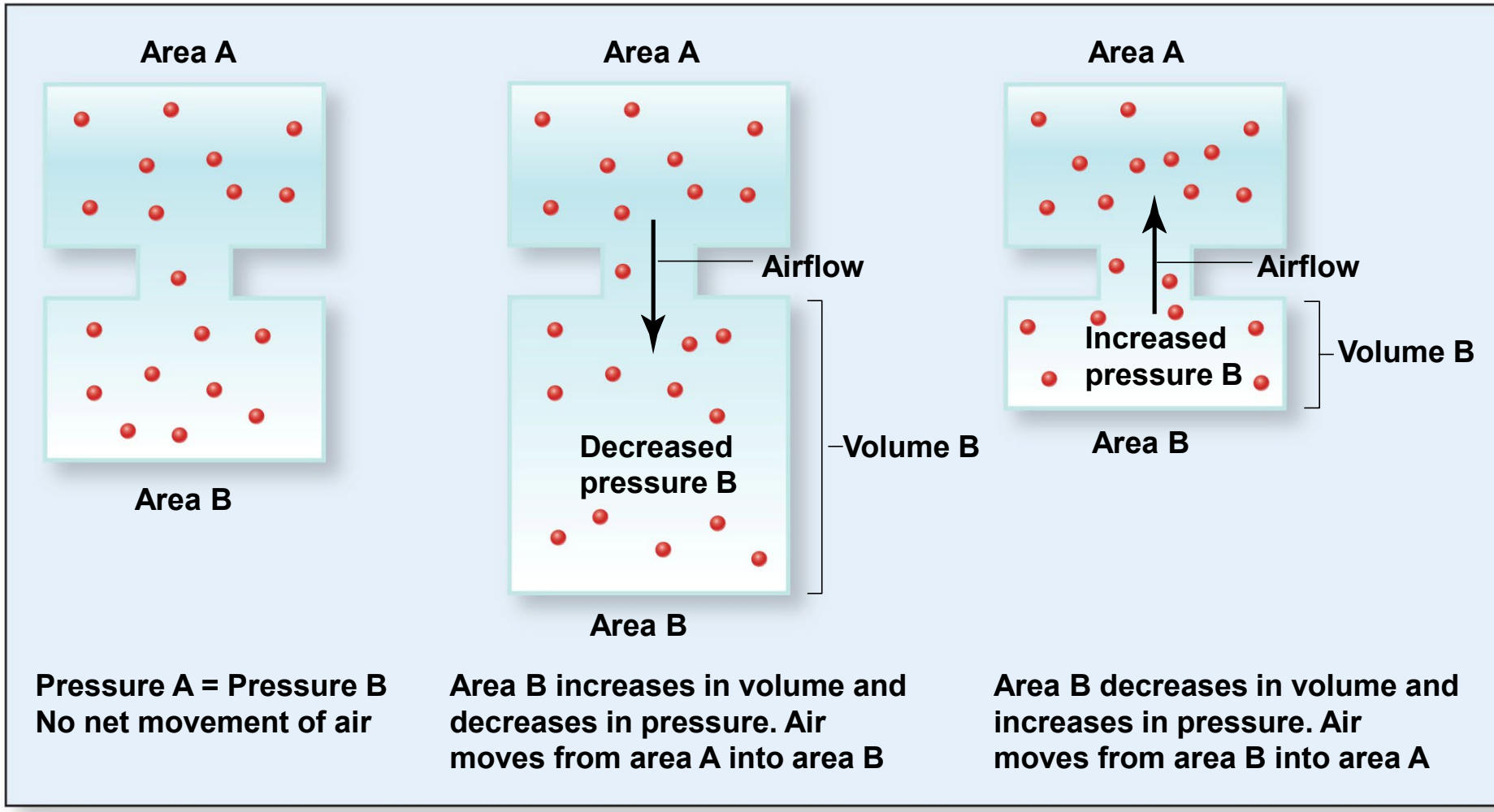
Anterior view **Posterior view**

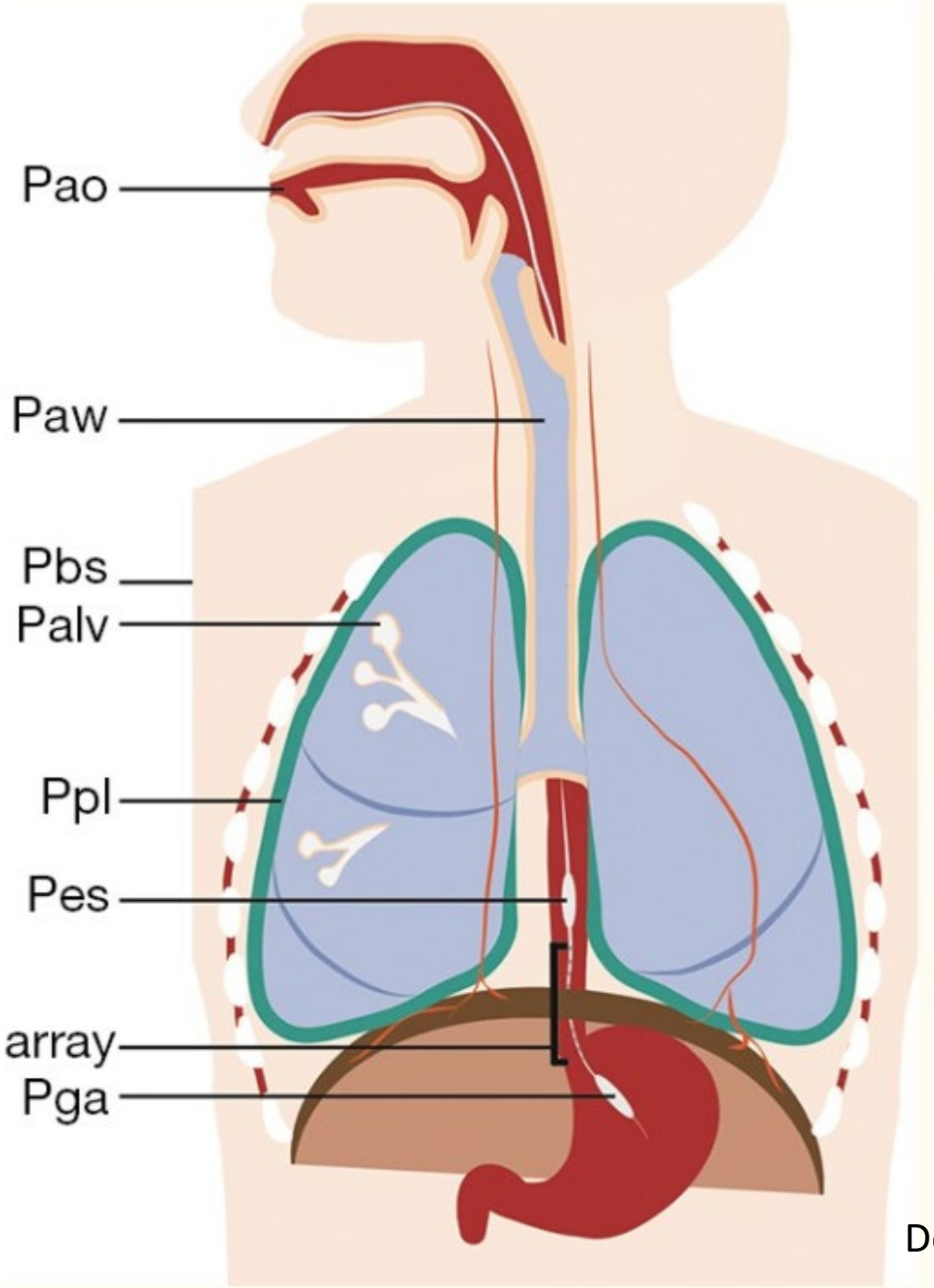
Muscles of Breathing	
Muscles of quiet breathing	The **diaphragm** forms the rounded "floor" of the thoracic cavity and is dome-shaped when relaxed. It alternates between the relaxed domed position and the contracted flattened position and changes the vertical dimensions of the thoracic cavity. The **external intercostals** extend from a superior rib inferiomedially 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 **scalenes** attach to ribs 1 and 2; elevates ribs 1 and 2. The **pectoralis minor** attaches to ribs 3–5; elevates ribs 3–5. The **serratus posterior superior** attaches to ribs 2–5 on its anterior surface; lifts ribs 2–5. The **erector spinae** 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 **transversus thoracis** extends across the inner surface of the thoracic cage and attaches to ribs 2–6; depresses ribs 2–6 . The **serratus posterior inferior** extends between the ligamentum nuchae and the lower border of ribs 9–12; depresses ribs 9–12.

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 A
Area B
Pressure A = Pressure B
No net movement of air
Area A
Airflow
Decreased
pressure B
Volume B
Area B
Area B increases in volume and
decreases in pressure. Air
moves from area A into area B
Area A
Airflow
Increased
pressure B
Volume B
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

Gradient name	Abbreviation	Formula	Clinical assessment
Transpulmonary pressure	P_L	Pao – Ppl	Paw – Pes
Transalveolar pressure/elastic recoil pressure of the lung	Pel(L)	Palv – Ppl	Paw (zero flow) – Pes
Transdiaphragmatic pressure	Pdi	Pab – Ppl	Pga – Pes
Pressure gradient over the chest wall	Pcw	Ppl – Pbs	Pes (as Pbs is conventionally 0)
Pressure gradient over the respiratory system	Prs	Pao – Pbs	Paw (as Pbs is conventionally 0)

Pab, abdominal pressure; Pao, pressure at airway opening; Palv, alveolar pressure; Pbs, pressure at body surface; Ppl, pleural pressure; Paw, airway pressure; Pes, esophageal pressure; Pga, gastric pressure.

De Vries H *et al* Ann Transl Med 2018

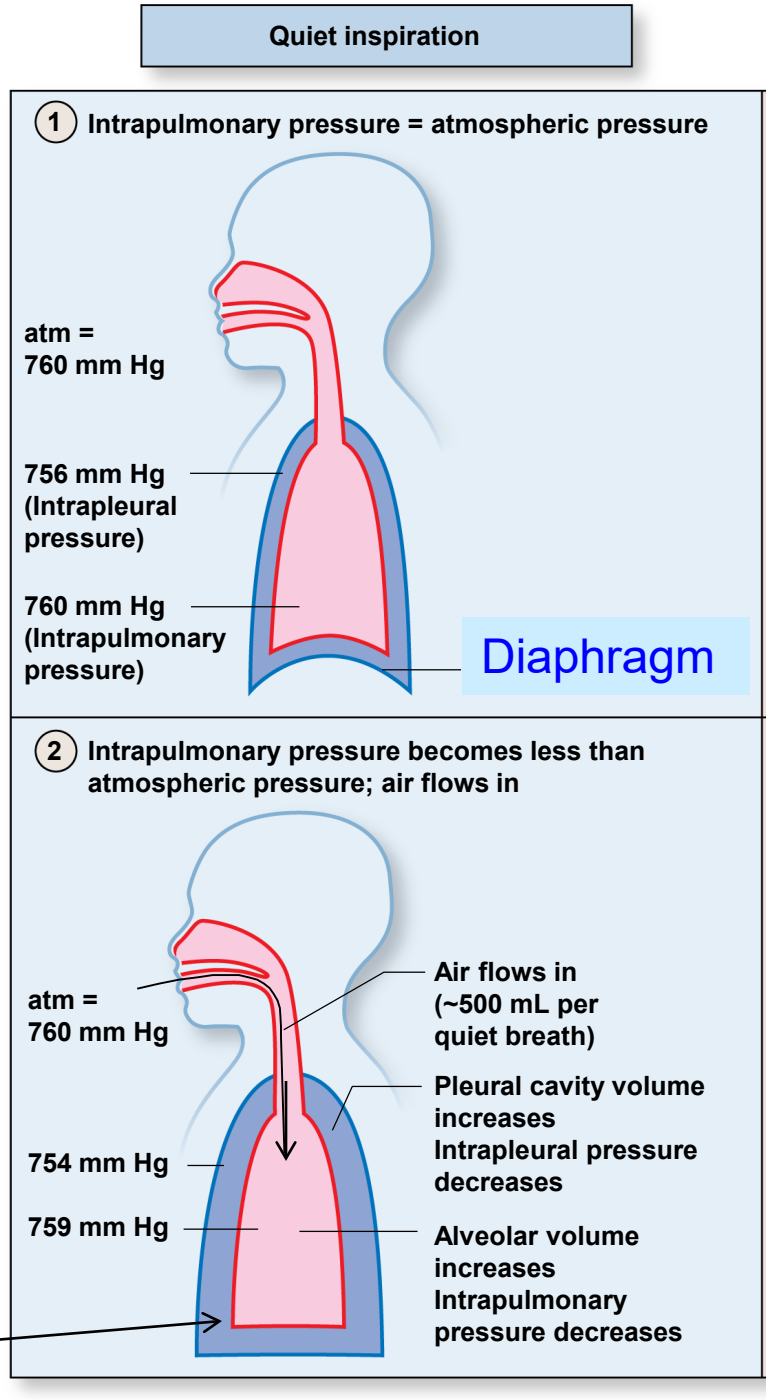
No breathing:

- atmospheric pressure equals intrapulmonary pressure ie 760mm Hg
- intrapleural pressure is below 760mm Hg
- **Patm=Paw>Ppl**

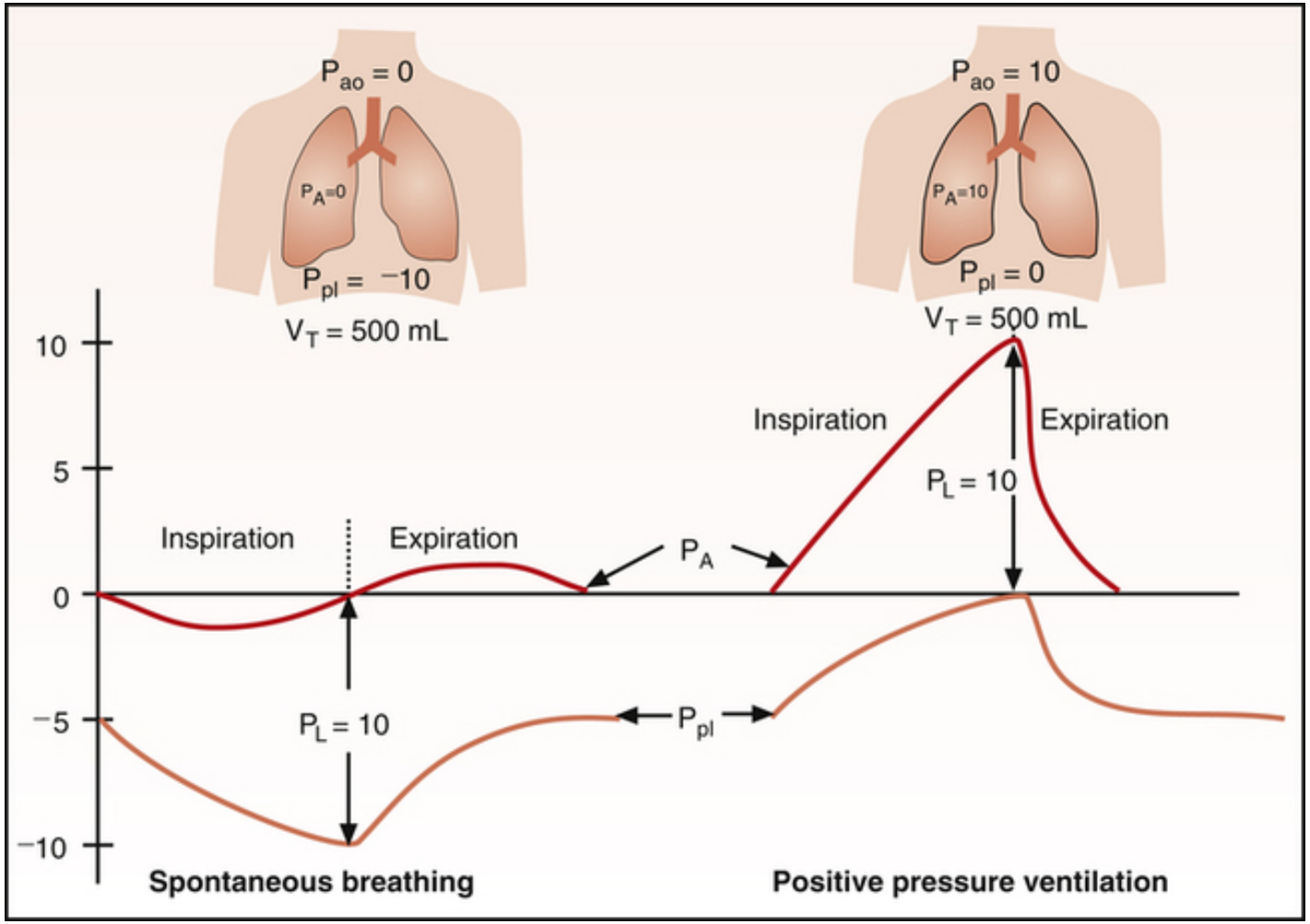
with Inhalation:

- Alveolar volume increases
- Alveolar pressure decreases
- intrapulmonary pressure drops to 759mm Hg
- intrapleural pressure drops to 754mm Hg
- **Patm>Paw>Ppl**

Diaphragm contracted

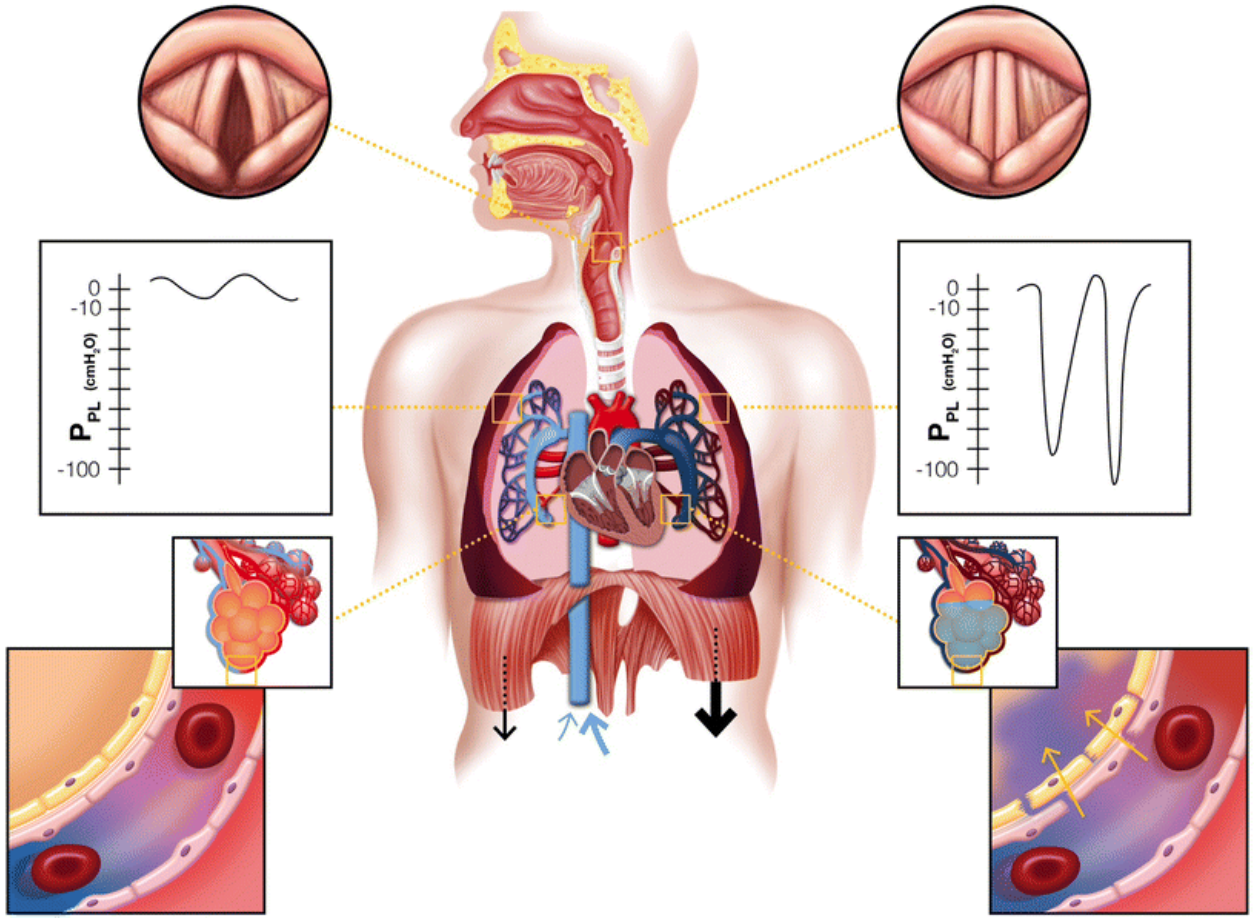


Spontaneous (Negative pressure) Ventilation vs Positive Pressure Ventilation



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 P_L 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

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

$$C_{stat} = \frac{V_T}{P_{plat} - PEEP}$$

$$C_{dyn} = \frac{V_T}{PIP - PEEP}$$

ARDS

Berlin Criteria for Acute Respiratory Distress Syndrome (ARDS)

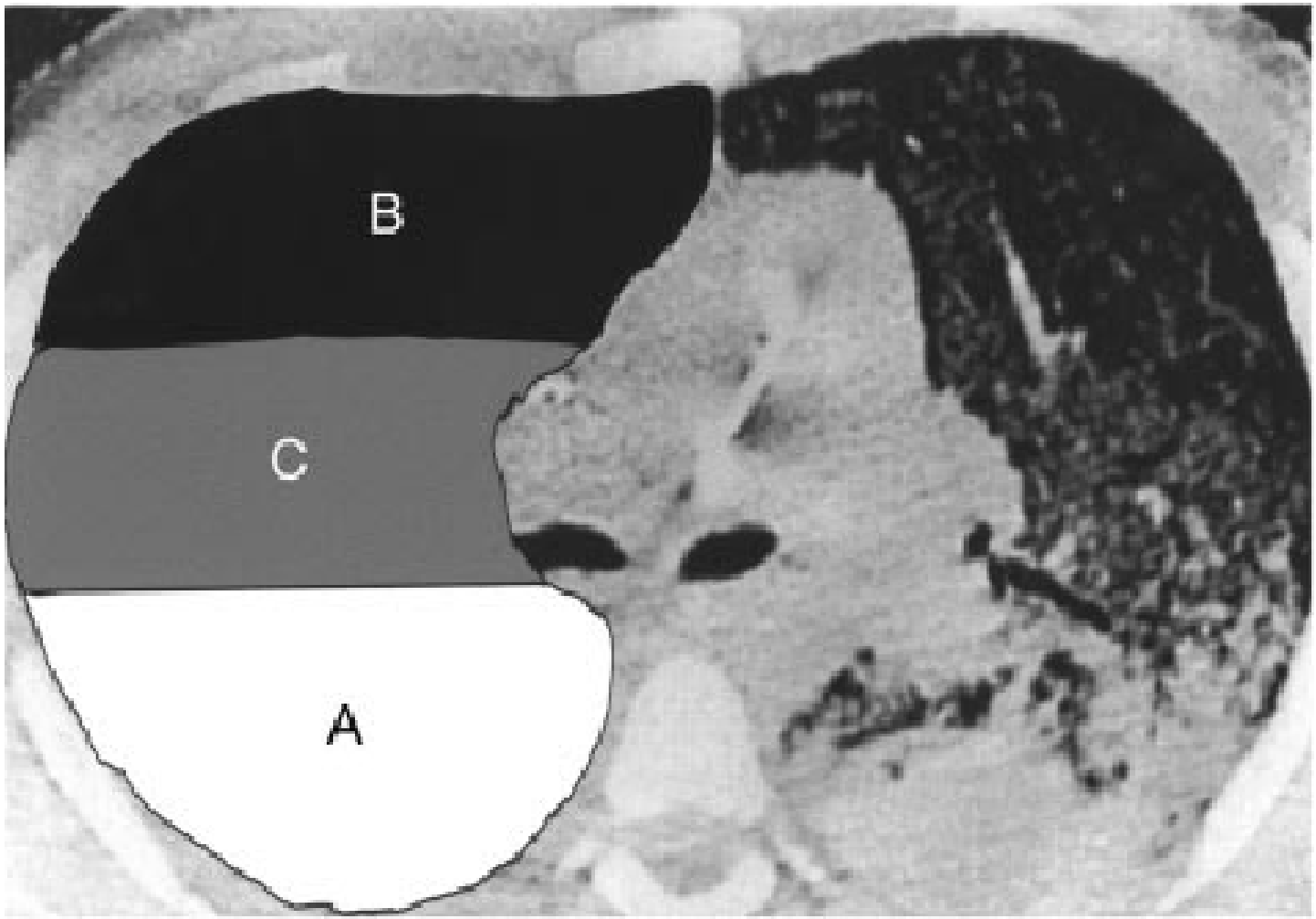
Respiratory symptoms must have begun within one week of a known clinical insult OR the patient must have new or worsening symptoms during the past week.

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

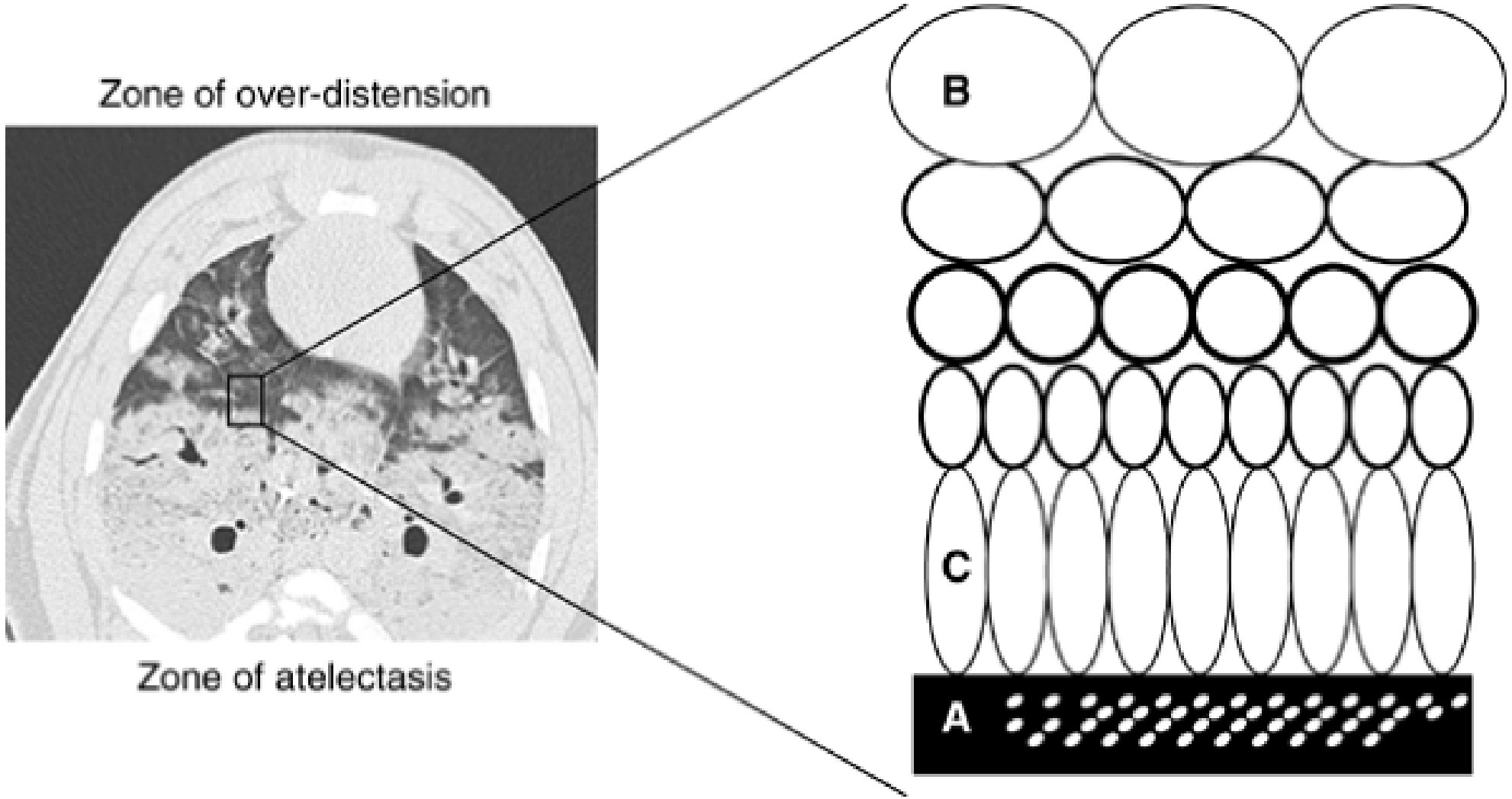
A moderate to severe impairment of oxygenation must be present, as defined by the ratio of arterial oxygen tension to fraction of inspired oxygen (PaO_2/FiO_2). The severity of the hypoxemia defines the severity of the ARDS:

- Mild ARDS – The PaO_2/FiO_2 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 H_2O.
- Moderate ARDS – The $PaO_2/FiO2$ is > 100 mm Hg, but ≤ 200 mm Hg, on ventilator settings that include PEEP ≥ 5 cm H_2O.
- Severe ARDS – The $PaO_2/FiO2$ is ≤ 100 mm Hg on ventilators setting that include PEEP ≥ 5 cm H_2O.

ARDS as a disease of heterogenous lung compliance



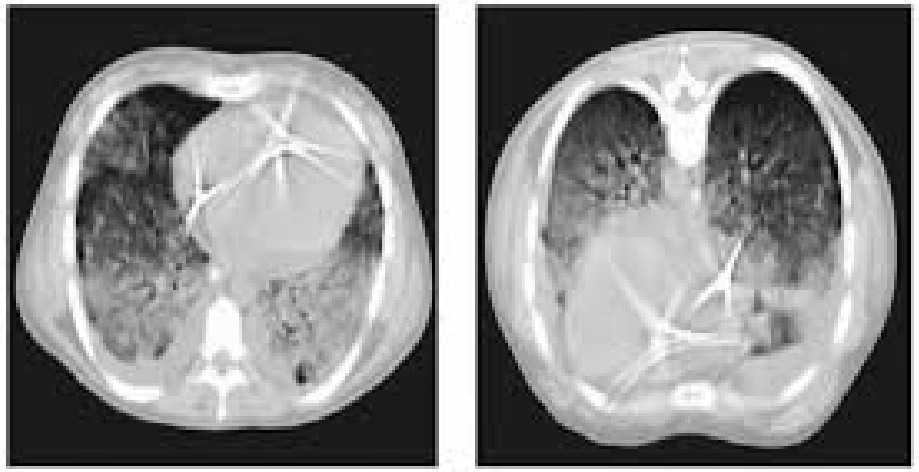
Griffiths M *British Journal of Anaesthesia* 2004

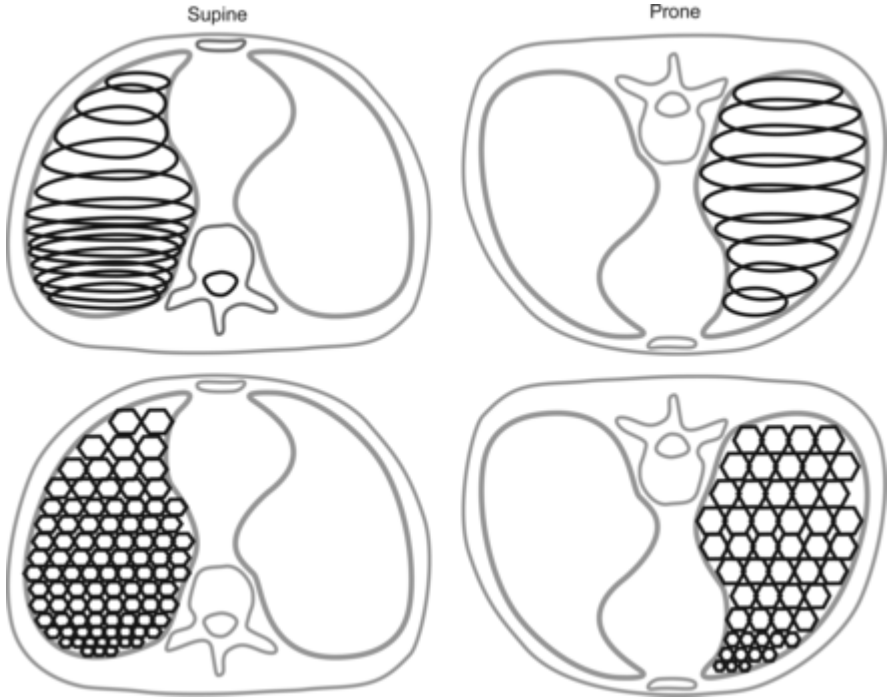


Griffiths M *British Journal of Anaesthesia* 2004

Prone Positioning

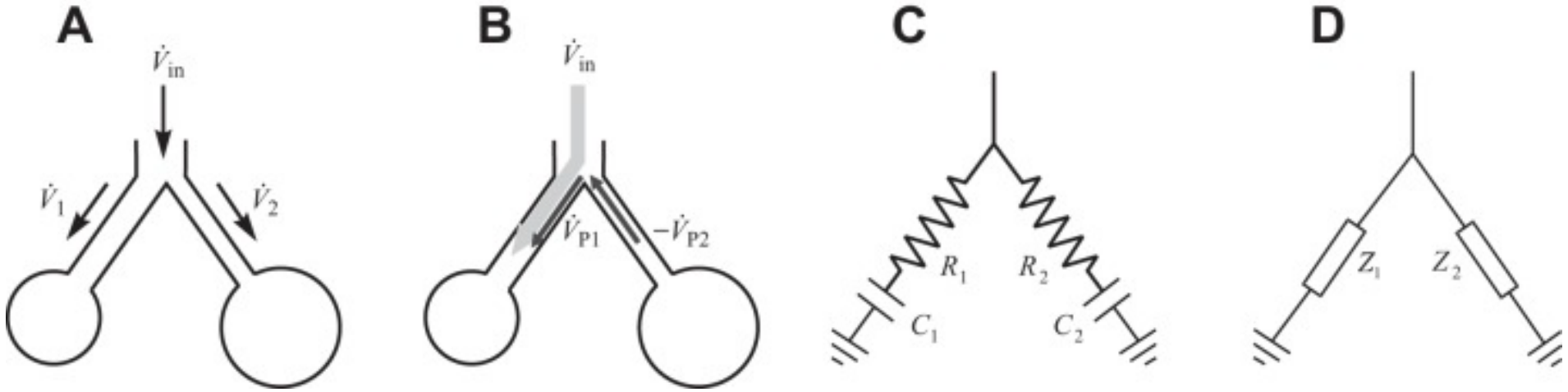
- Improves perfusion to the lungs → better VQ matching
- Heart shifts forward → improved compliance
- Improved lung recruitment
- Lung protective





Pendelluft Effect in ARDS

- Inhomogeneous inflation or deflation of the lungs causing dynamic pressure difference between lung regions leading to interregional airflows
- 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 (P_L) swings are distributed throughout the lung
  - Homogeneous ventilation can be achieved
- Injured lung does not tolerate large volume swings
  - Regional increases in P_L can result or perpetuate lung injury
  - Ventilation in injured lung is heterogeneous

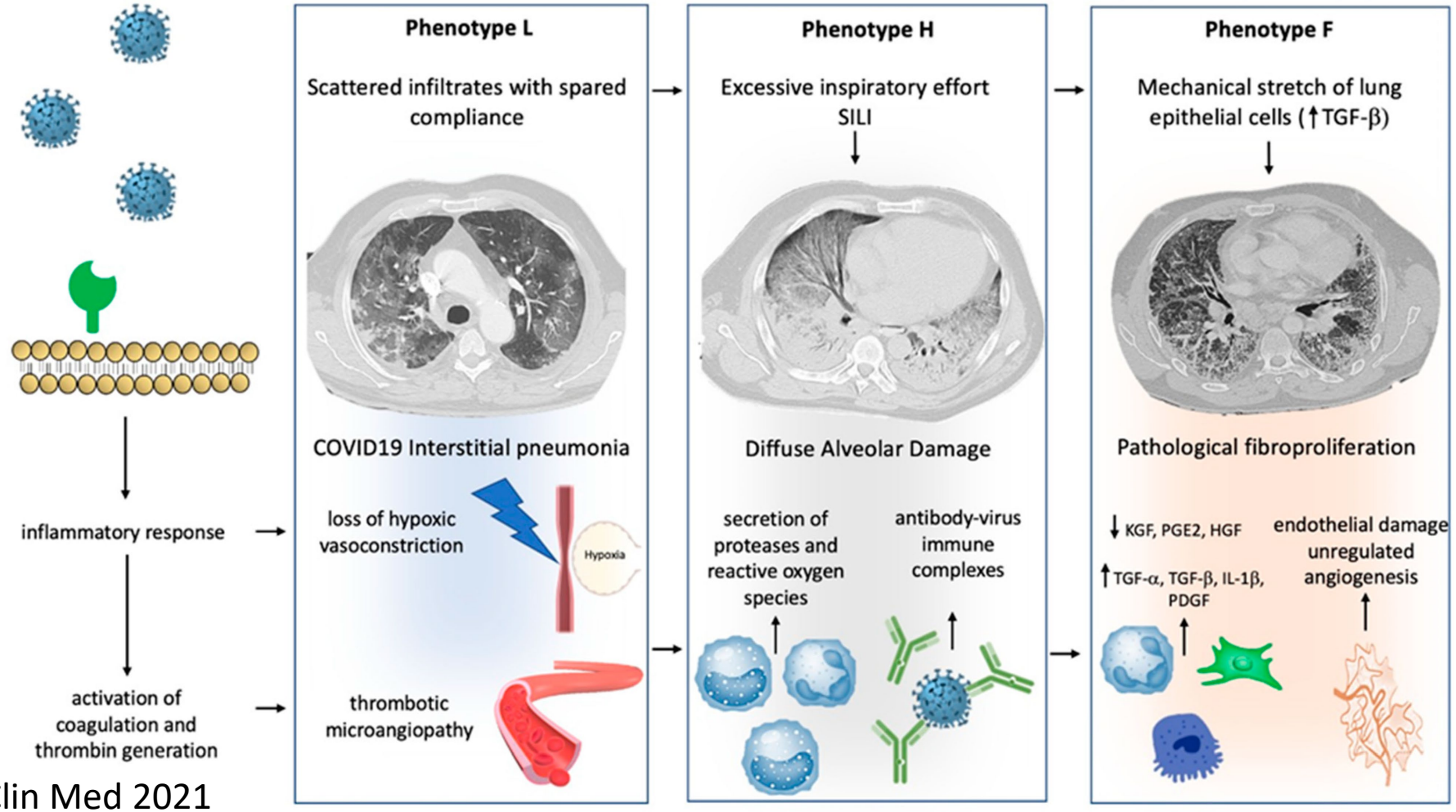
Brochard L *et al* Am J Resp Crit Care Med 2017

So, what is P-SILI and why are we talking about it now?

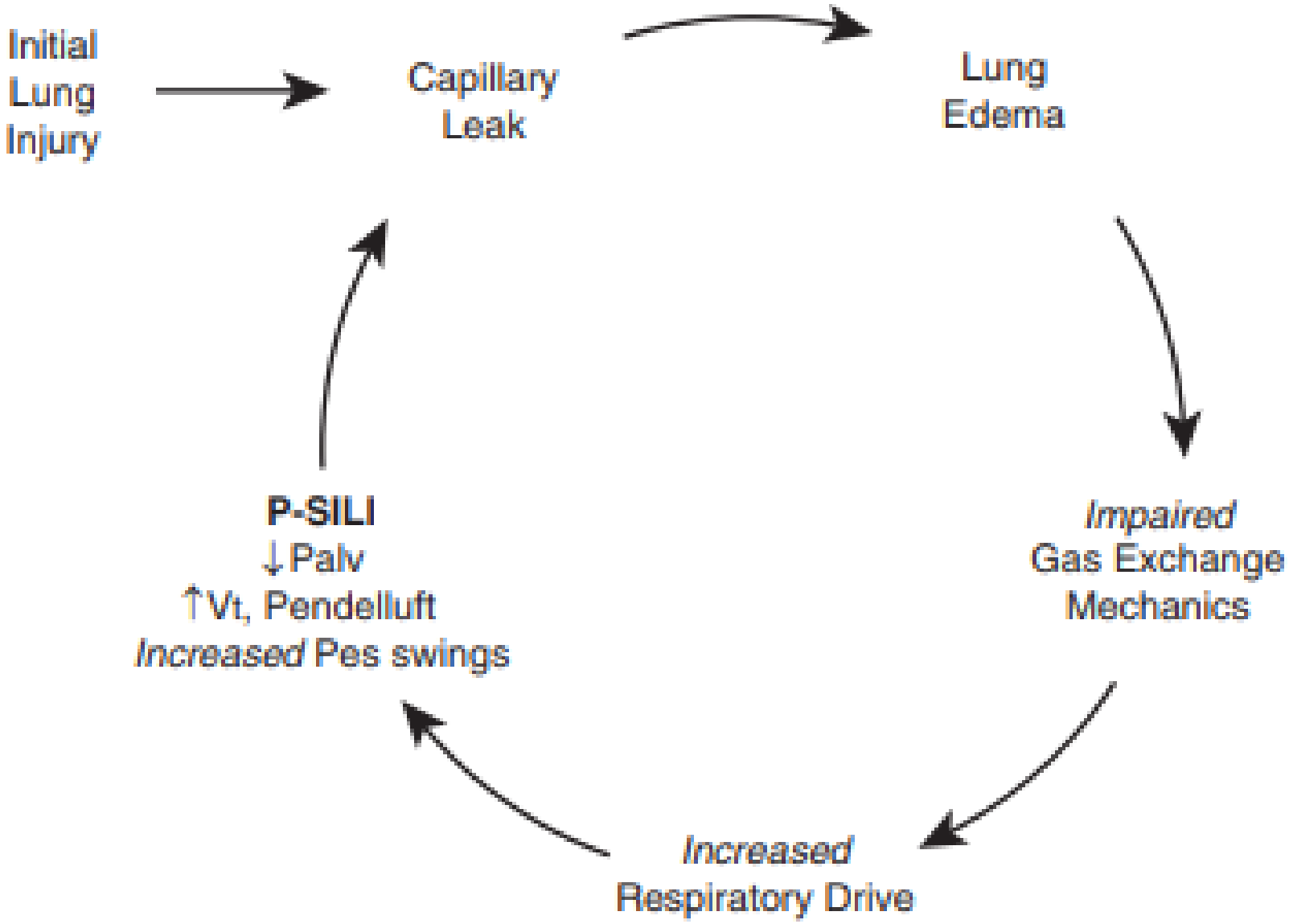
- P-SILI is a hypothetical, somewhat controversial mechanism by which intense, patient triggered inspiratory effort results in large swings in transpulmonary pressures
- Regional shift in transpulmonary pressure may aggravate lung injury
- The peculiar phenotypes of COVID 19 associated respiratory failure/ARDS 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



Brochard L *et al* Am J Resp Crit Care Med 2017

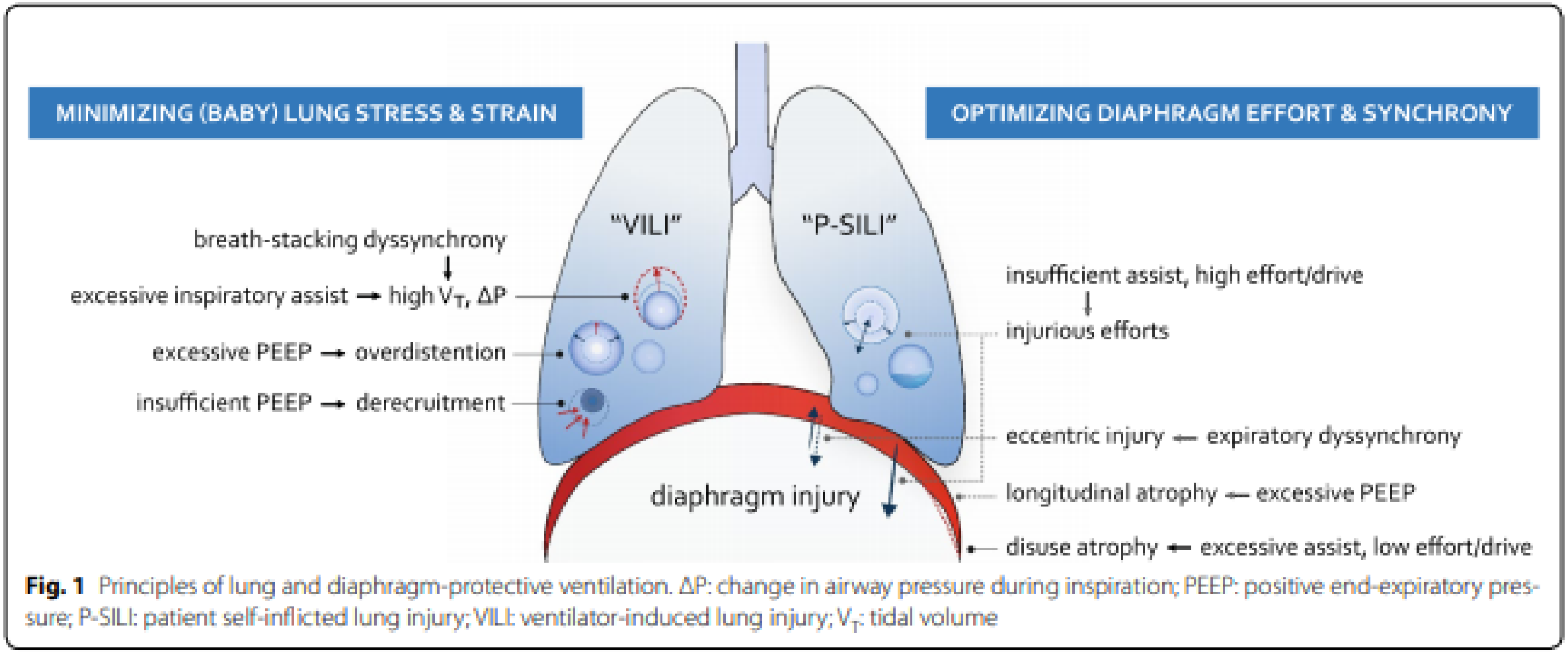
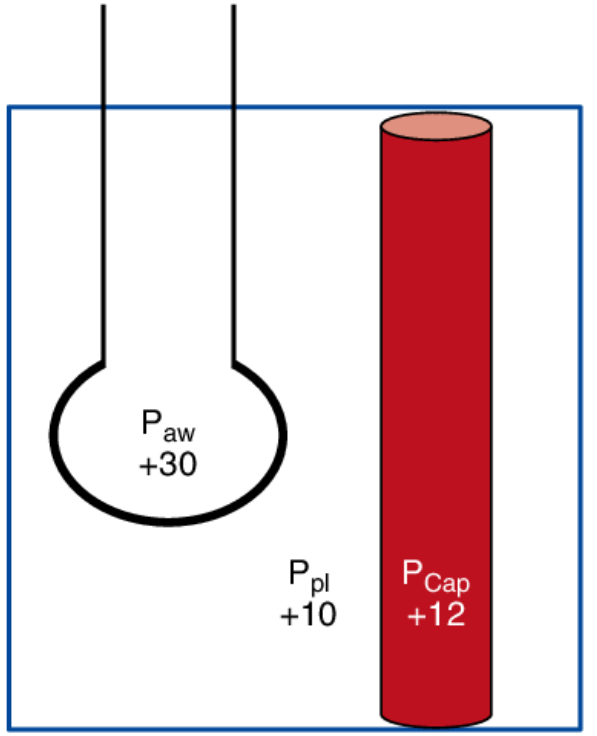


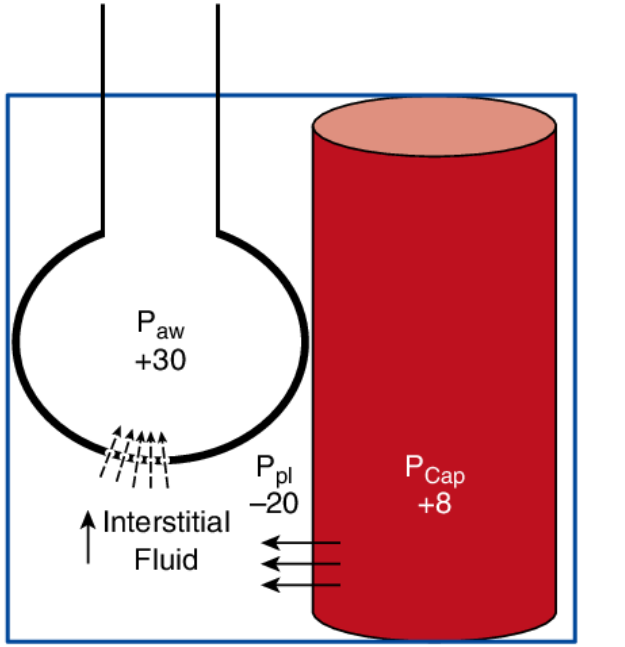
Fig. 1 Principles of lung and diaphragm-protective ventilation. ΔP: change in airway pressure during inspiration; PEEP: positive end-expiratory pressure; P-SILI: patient self-inflicted lung injury; VILI: ventilator-induced lung injury; V_T: tidal volume

Goligher EC *et al* Intensive Care Med 2020

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

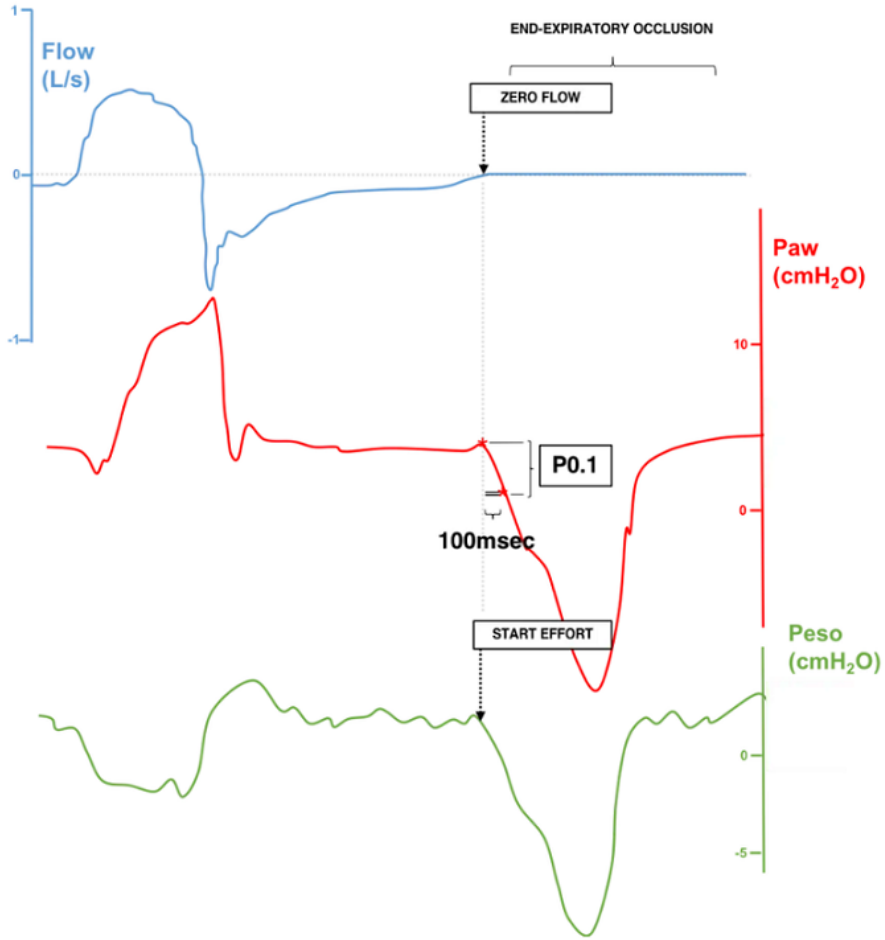
De Vries H *et al* Ann Transl Med 2018

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
- P0.1vent correlates with inspiratory effort as suggested by Pes.
- P0.1 3.5-4.0 cm H20 suggests excessive insp. Effort
- P0.1 ~1 cm H20 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.