Respiratory physiology
– what you need to know from mechanical ventilation

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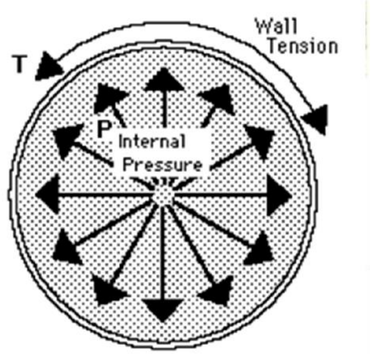
July 3, 2022

Basic concept

Basic concept

- **虎克定律(Hooke's law)**
  - ➢ 固體材料受力後，應力與應變（單位變形量）呈線性關係
  - ➢ 應用於肺臟
    - 應力Pressure (施加力量) vs.應變 Volume (肺部體積): 不呈現線性關係:
      - 肺部非固定材料
      - 深呼吸時增加肺泡打開數量不是單個肺泡體積增加, 參與的 alveoli 數目有變異
      - 不同體積下的 elastic recoil (肺回縮力)不同

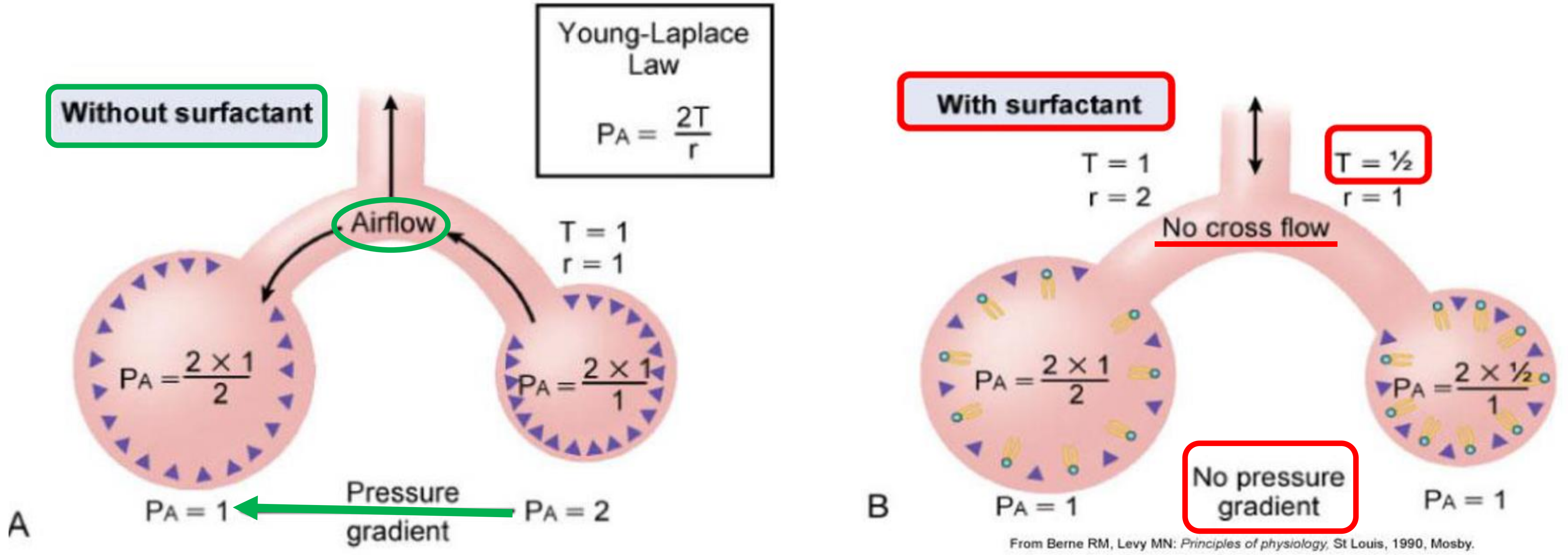


- **拉普拉斯定律(Laplace's law)**
  - ➢ P＝2T/r (P : 肺泡回縮力，T: 表面張力，r: 肺泡半徑)
  - ➢ 肺回縮力與表面張力成正比，與肺泡的半徑成反比
    - 如同把一顆氣球吹大，增加一定的氣體體積，所需的力量也要越多

Basic respiratory physiology

- **Elastic recoil**
  - The tendency of an object to return to its original shape after being stretched
  - Elastic and collagen fibers of the lung parenchyma (~1/3)
  - Surface-tension forces of the thin liquid film lining the alveoli (2/3)
- **Surfactant protein**
  - Pulmonary surfactant: **90% phospholipid and 10% protein**
  - Surfactant leads to a low surface tension
- Hysteresis

Surfactant and Laplace's law



在r=1狀況下以surfactant降低表面張力(T)，達到和r=2的壓力(P)一致
兩邊無壓力差就不會有cross flow

Basic respiratory physiology

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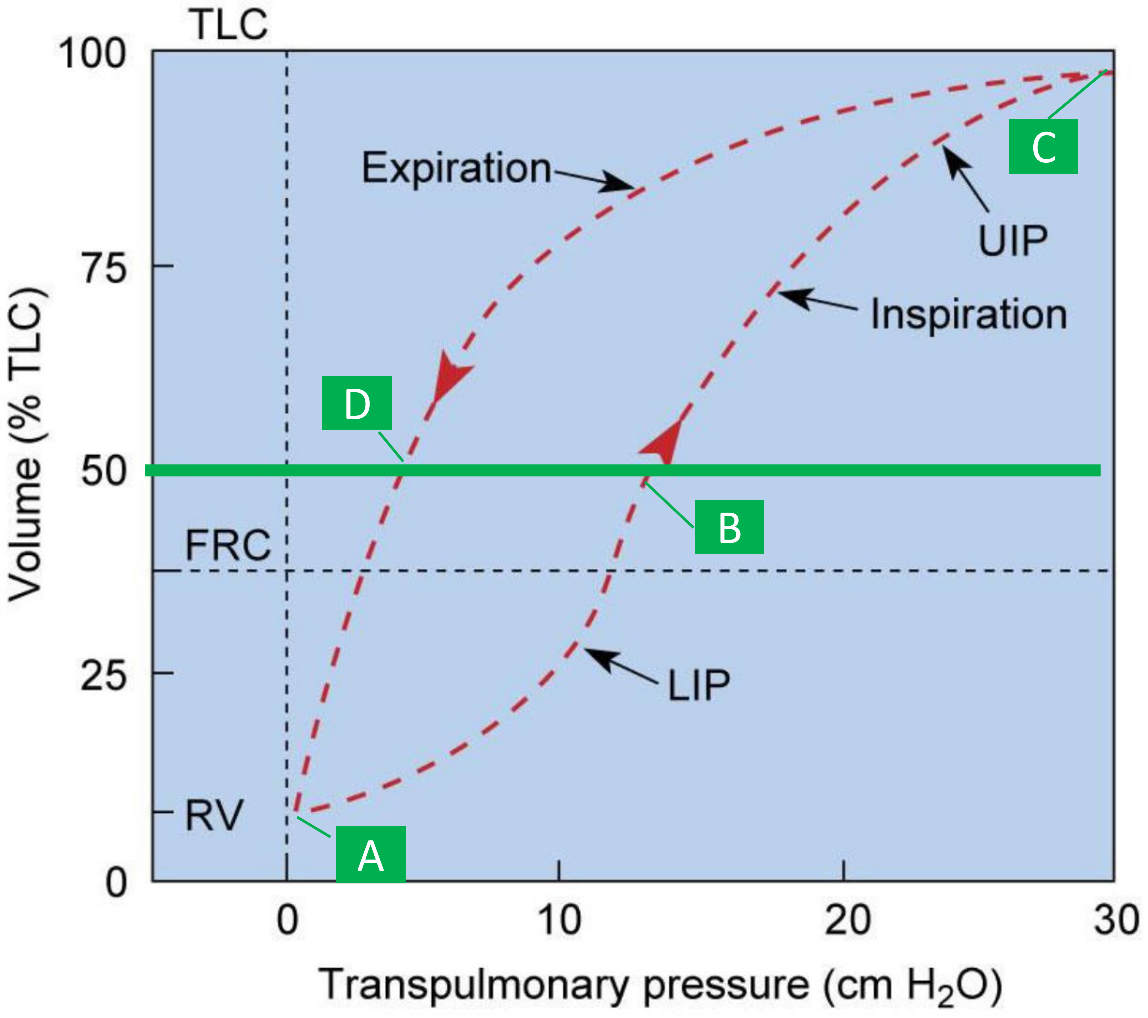
- Surfactant protein
  - Pulmonary surfactant: 90% phospholipid and 10% protein
  - Surfactant leads to a low surface tension
- Hysteresis (滯後現象)



Modified from Berne RM, Levy MN: *Physiology*, ed 3, St Louis, 1993, Mosby.

Fig. 3-7. Pressure-volume curve of the lung during inspiration and expiration. The phenomenon of surface tension at the alveolar air-liquid interface creates hysteresis or different inspiration and expiration pathways. *TLC*, Total lung capacity; *FRC*, functional residual capacity; *RV*, residual volume; *UIP*, upper inflection point; *LIP*, lower inflection point.

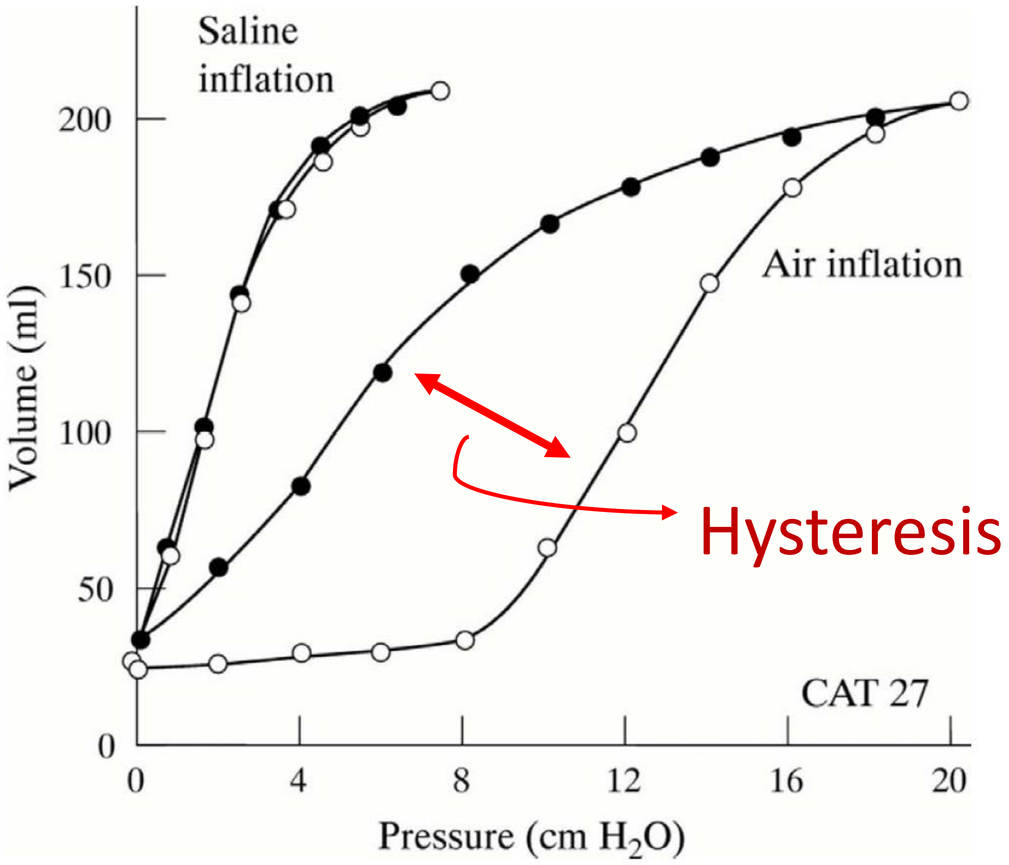
Pressure-Volume loop

B(在吸氣過程) ， D(在吐氣過程)

B, D 體積(volume)完全相等，但測量到的壓力(pressure)卻不相同

B(在吸氣過程)需額外壓力克服原本的elastic recoil才能將volume脹到跟D(在吐氣過程)一樣大

Hysteresis的原因可能是Surface tension



- **Air-filled lungs**
  - High surface tension
  - High elastance recoil
  - High hysteresis
- **Saline-filled lungs**
  - Less surface tension
  - Low elastance recoil
  - Low hysteresis

Physical parameters in lung mechanics

Physical parameters in lung mechanics

- **Basic parameters**
  - Pressure
  - Flow / Volume
- **Derived indices**
  - Compliance
  - Resistance
  - Work of breath (WOB) (呼吸功)
  - Time constant (τ)

Spontaneous ventilation

Volume change

↓

Pressure difference

↓

Gas flow

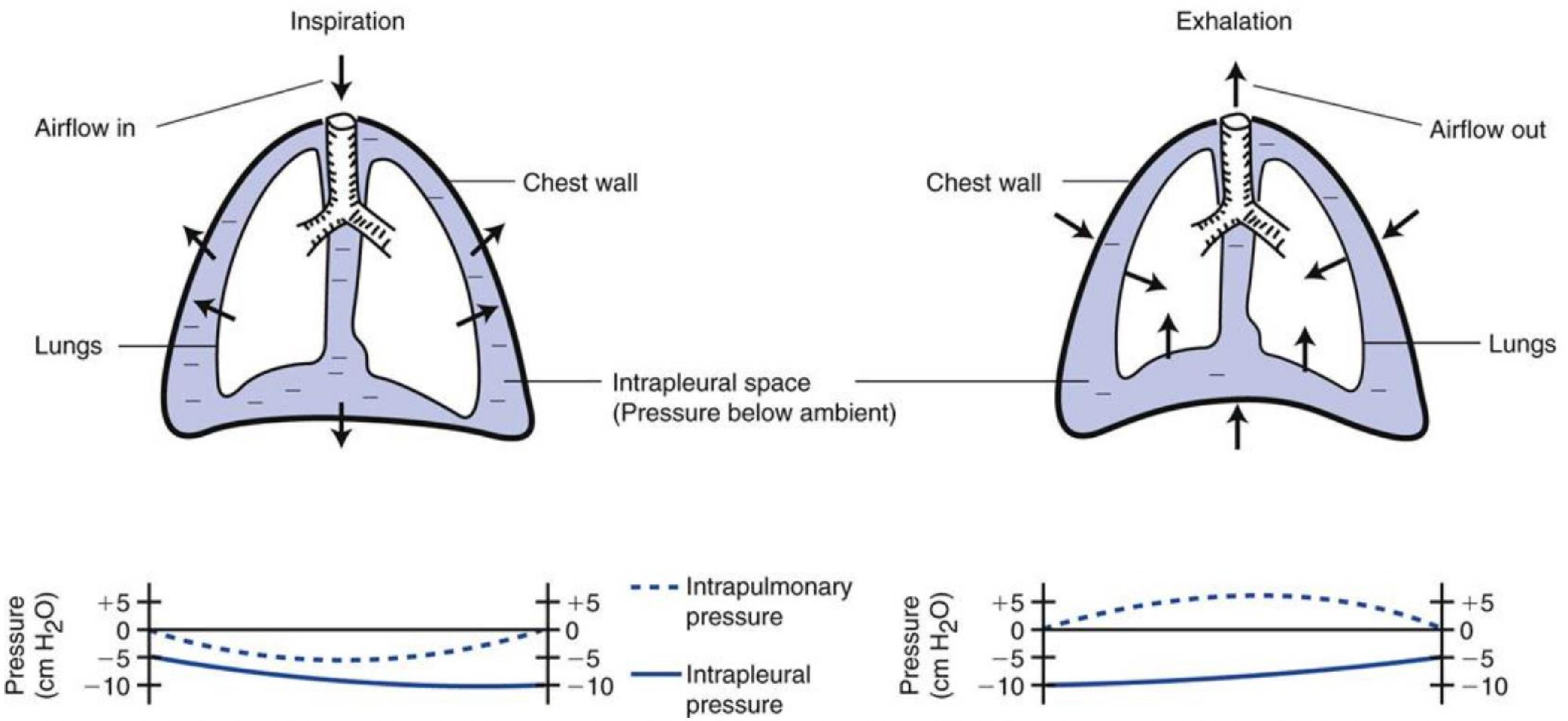


FIG. 1-2 The mechanics of spontaneous ventilation and the resulting pressure waves (approximately normal values). During inspiration, intrapleural pressure (Ppl) decreases to −10 cm H2O. During exhalation, Ppl increases from ×10 to −5 cm H2O. (See the text for further description.)

(Positive pressure) Mechanical ventilation

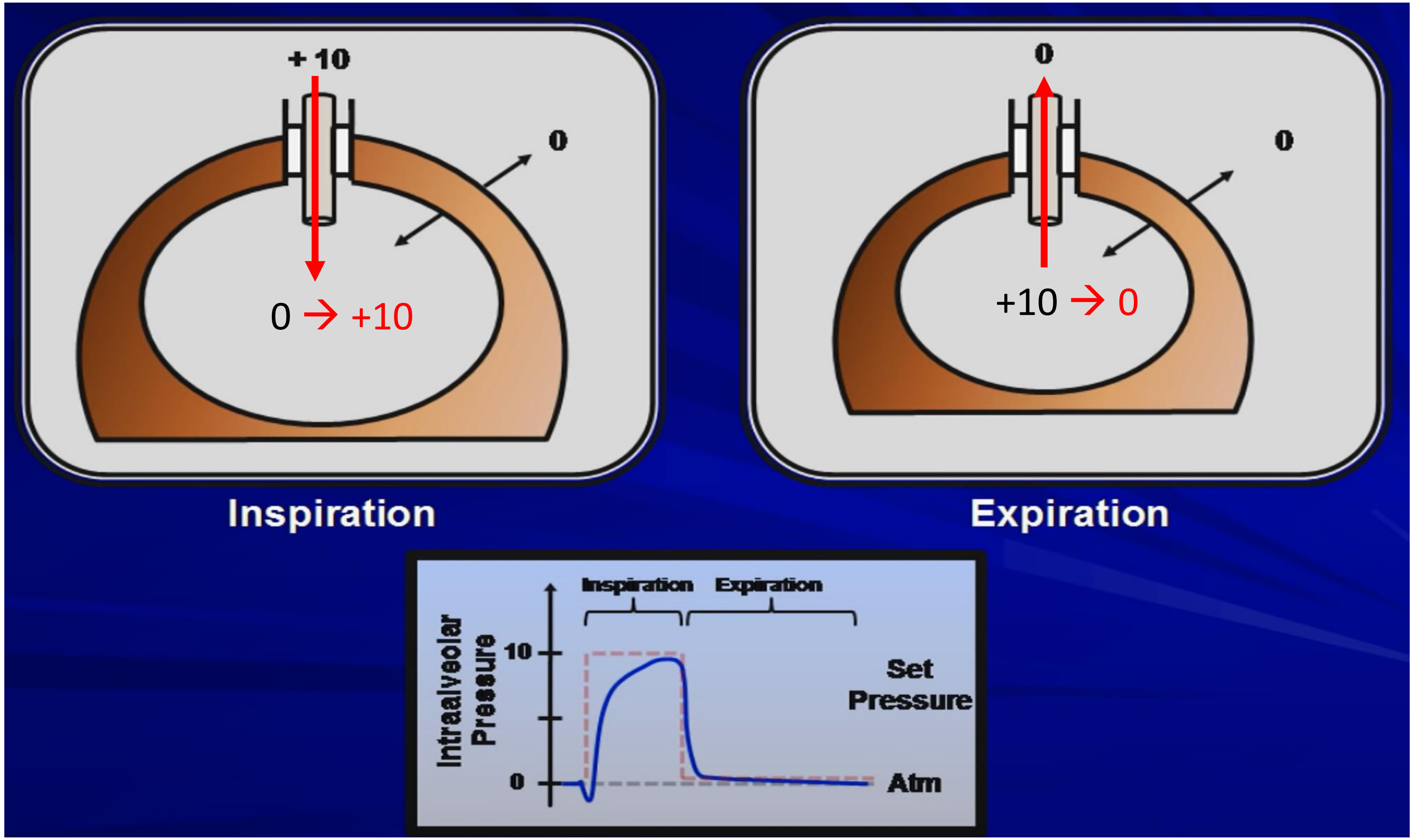
Pressure difference

↓

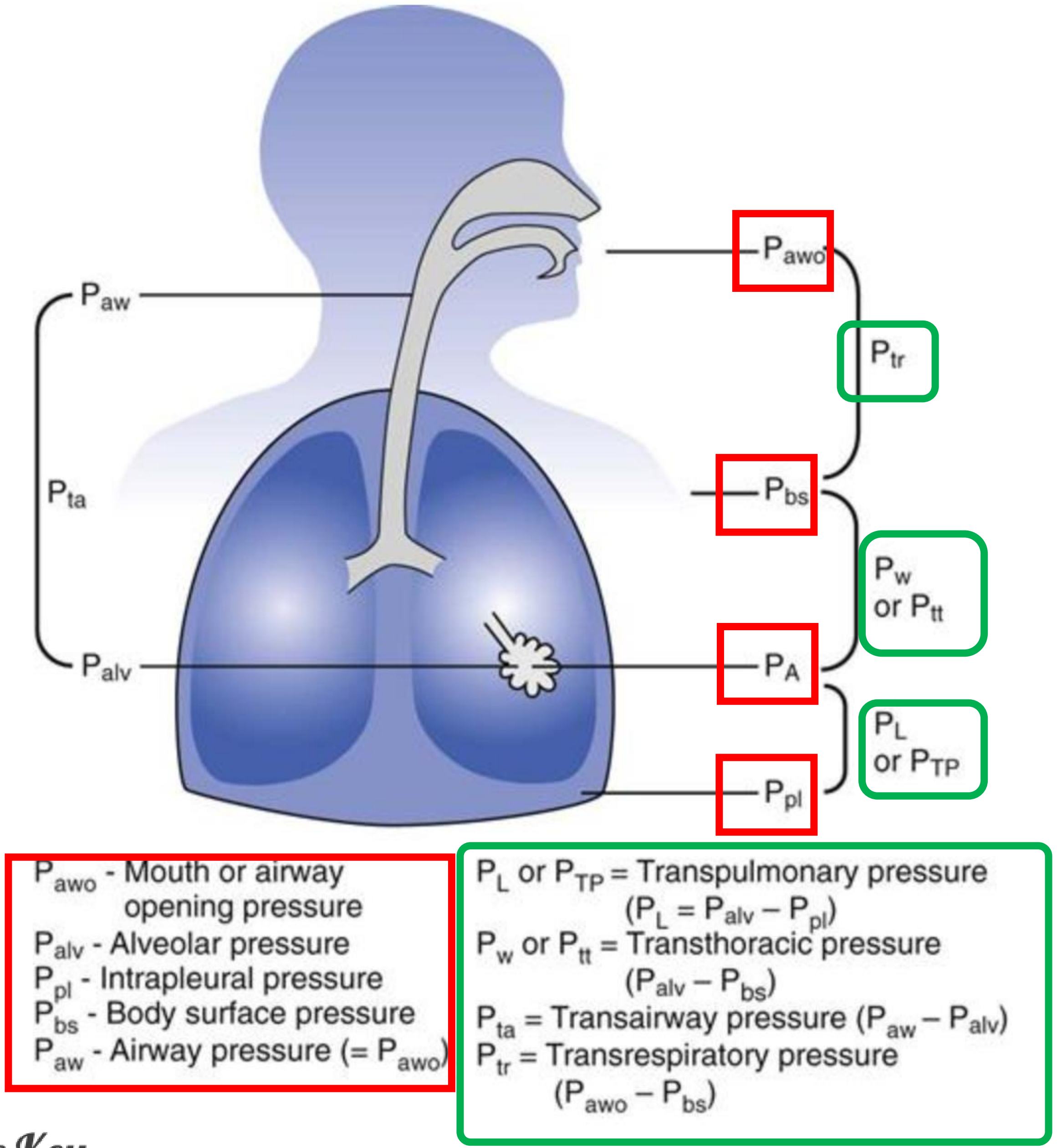
Gas flow

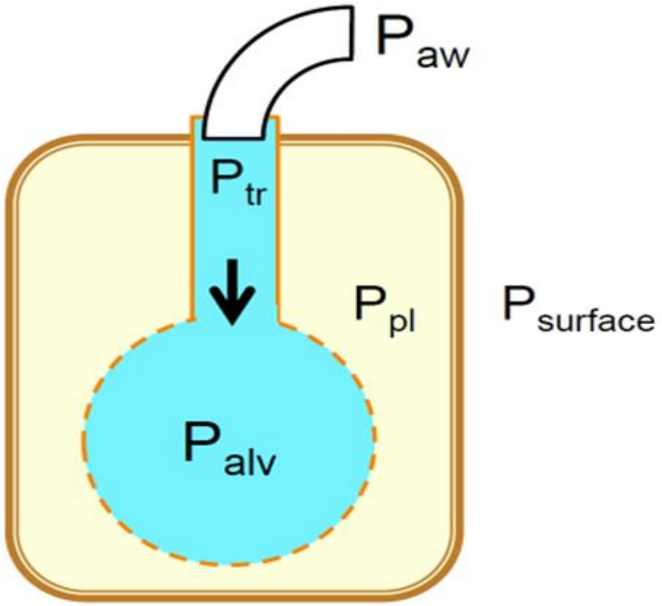
↓

Volume change



Pressure of respiratory system





Pilbeam's mechanical ventilation

Pressure differences determine lung distension

- Pao: airway opening
- P_A (P_{alv}) : alveolar
  - 正壓呼吸時static phase之肺泡壓力
- Ppl (Pes): intra-pleural pressure
  - 一般用食道球量測esophageal pressure
- Pbs: body surface pressure

- Transrespiratory pressure (Prs) or P_{tr}
  - $P_{rs} = P_A – P_{ao} = P_L + P_W = P_A - P_{bs}$
  - 整個呼吸系統(包含呼吸道與肺實質)所承受到的壓力
- Transpulmonary pressure (P_L) or P_{tp}
  - $P_L = P_A – P_{pl}$
  - 肺實質承受到的壓力（與ARDS最相關）
- Transthoracic pressure (P_W) or P_{tt}
  - $P_W = P_{pl} – P_{bs}$
  - 胸廓所承受的壓力(與肥胖或全身水腫相關)

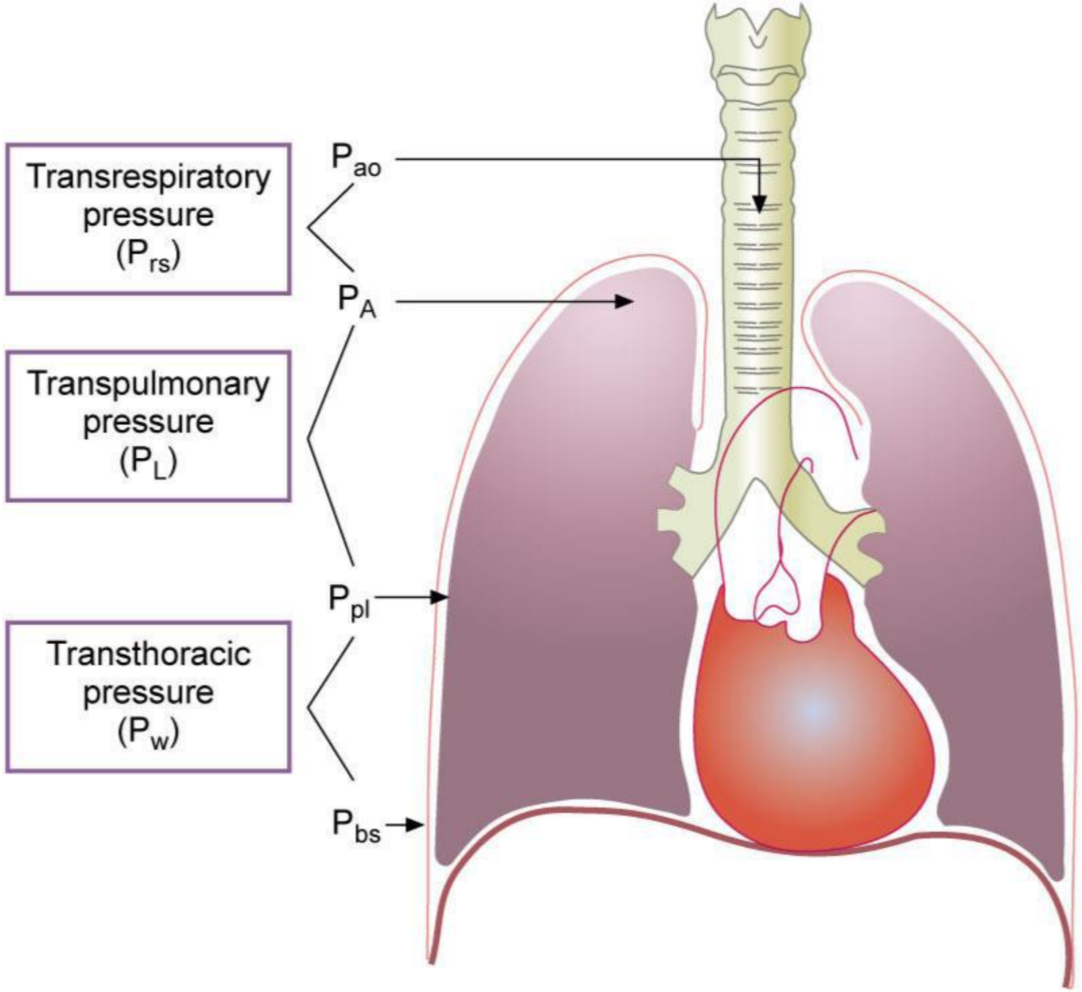
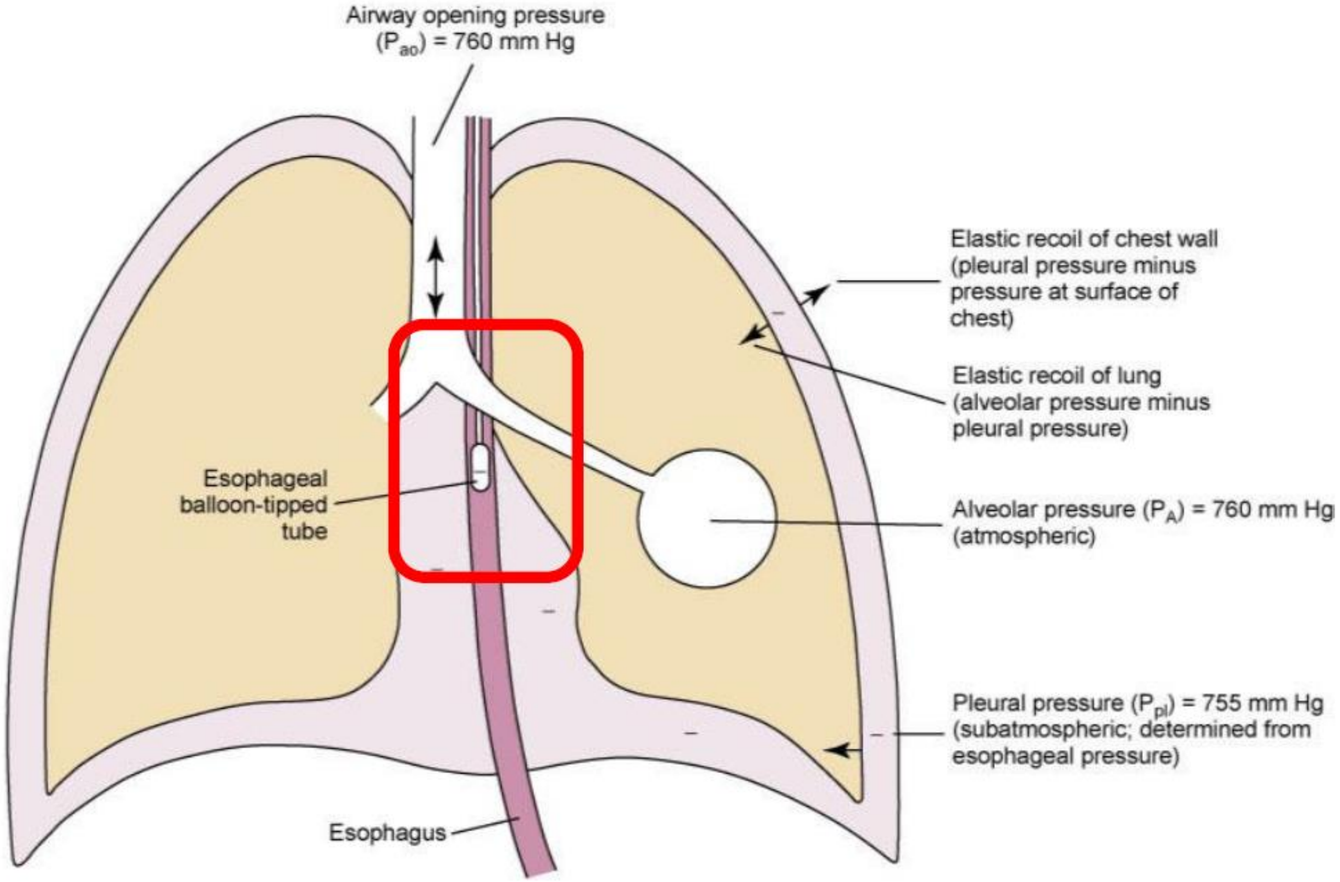


Fig. 3-2. Pressure gradients involved in ventilation. P_{ao}, Pressure at the airway opening; P_A, alveolar pressure; P_{pl}, intrapleural pressure; P_{bs}, pressure at the body surface; P_{rs}, transrespiratory pressure; P_L, transpulmonary pressure; P_w, transthoracic pressure. P_{rs} is equal to either ($P_{ao} - P_A$) or ($P_{bs} - P_A$) in a spontaneously breathing individual and can be thought of as the pressure gradient between the mouth and alveoli or the transairway pressure.

Measure pleural pressure (Ppl): ***Esophageal balloon***

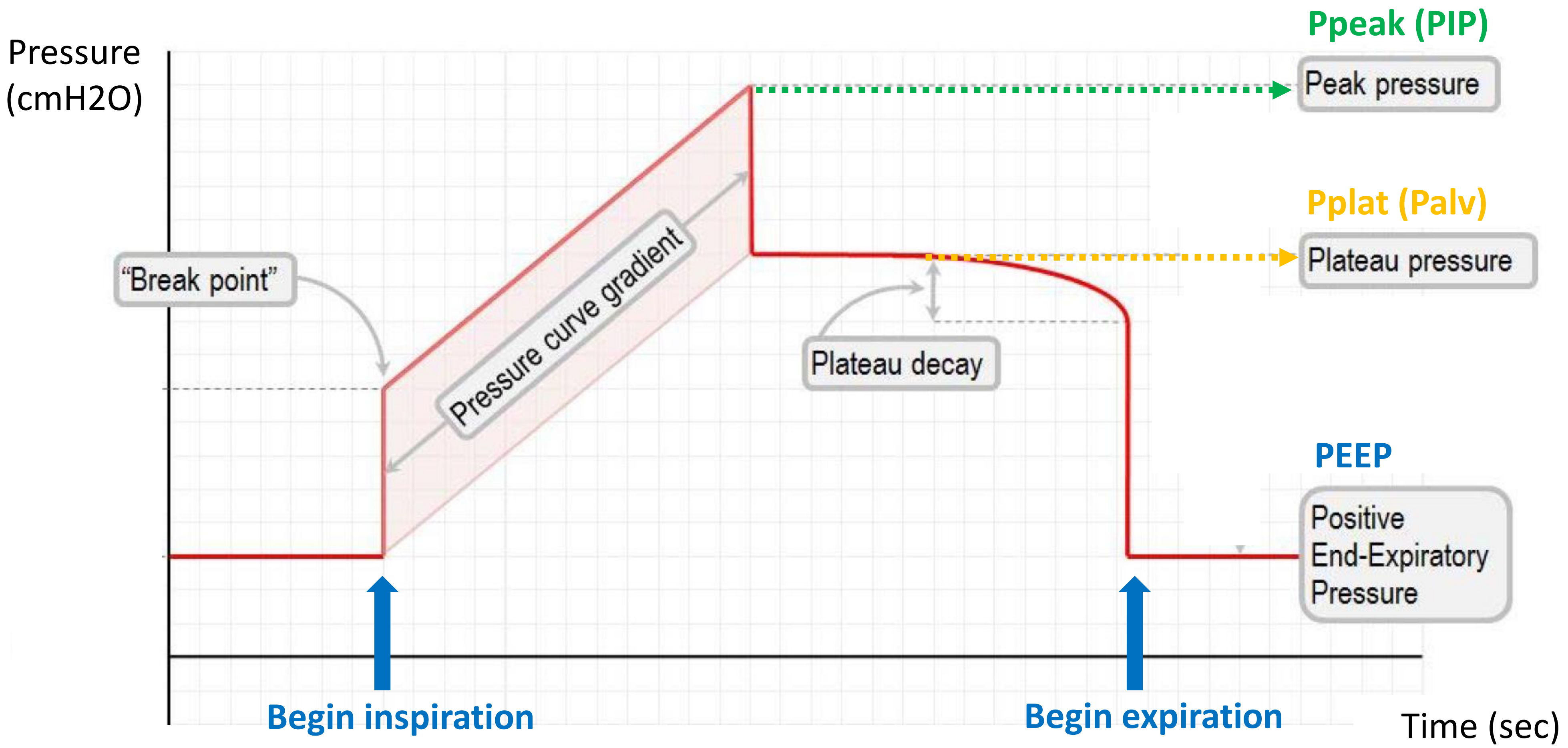


From Martin L: *Pulmonary physiology in clinical practice*, St Louis, 1987, Mosby.

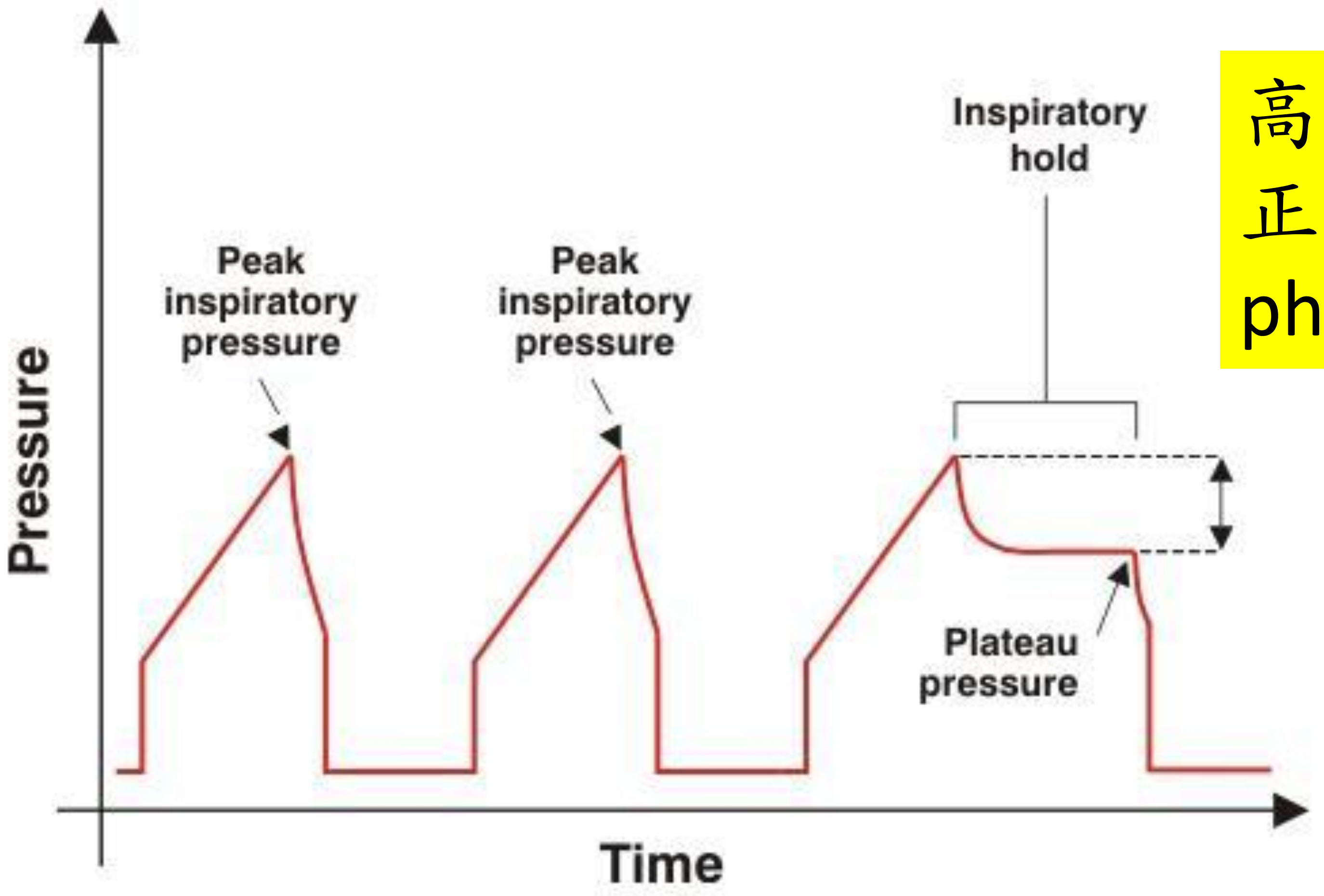
Fig. 3-1. Measuring intrapleural pressure with an esophageal balloon. Subatmospheric intrapleural pressure is transmitted through the esophagus to the balloon-tipped catheter. Equal and oppositely directed recoil forces of the lungs and chest wall create this subatmospheric pressure.

Component of inflation pressure

- Pressure-time curve



To measure P_{plat} (P_{alv}): Inspiratory-hold

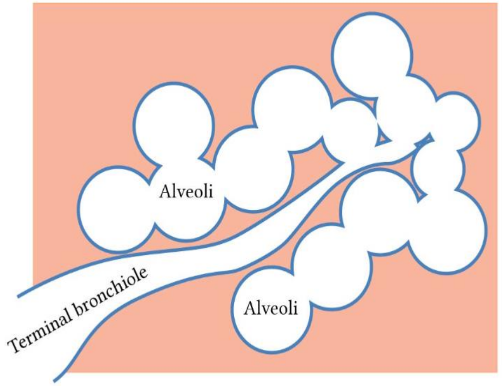


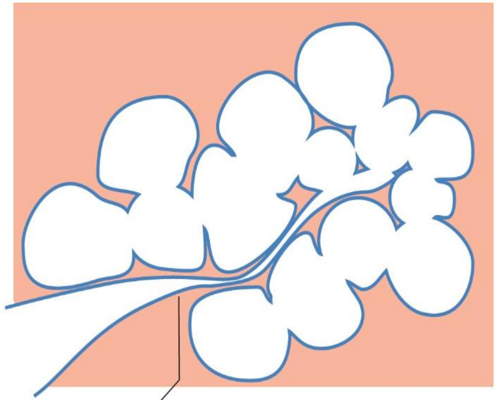
高原壓 (P_{alv}) : 正壓呼吸時static phase之肺泡壓力

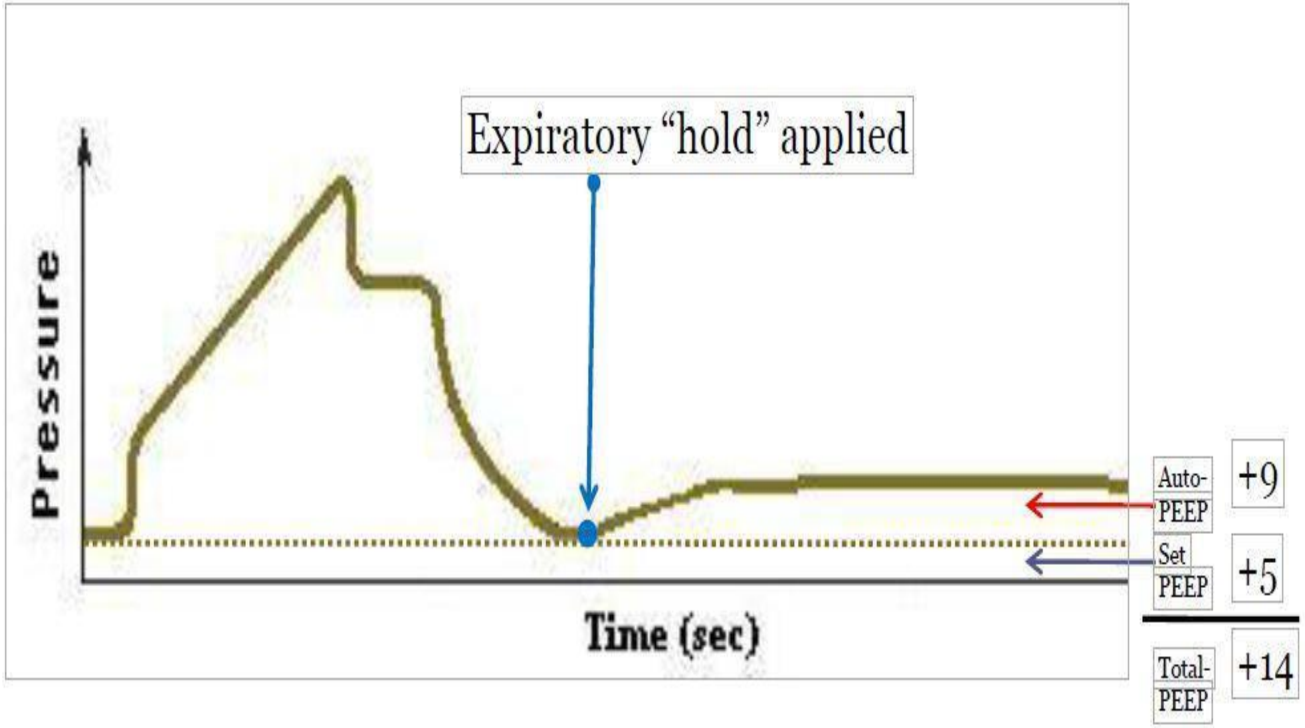
V/C mode, constant flow, Pressure-time curve

Auto-PEEP (intrinsic-PEEP)
- *measure true PEEP: Expiratory-hold*

- Incomplete emptying of the lung gas at the end of expiration
- The pressure produced by this trapped gas is called "auto-PEEP" (or intrinsic-PEEP (iPEEP) or occult PEEP







Alex Yartsev - Jun 17, 2015

Auto-PEEP (intrinsic PEEP)受下列因素影響

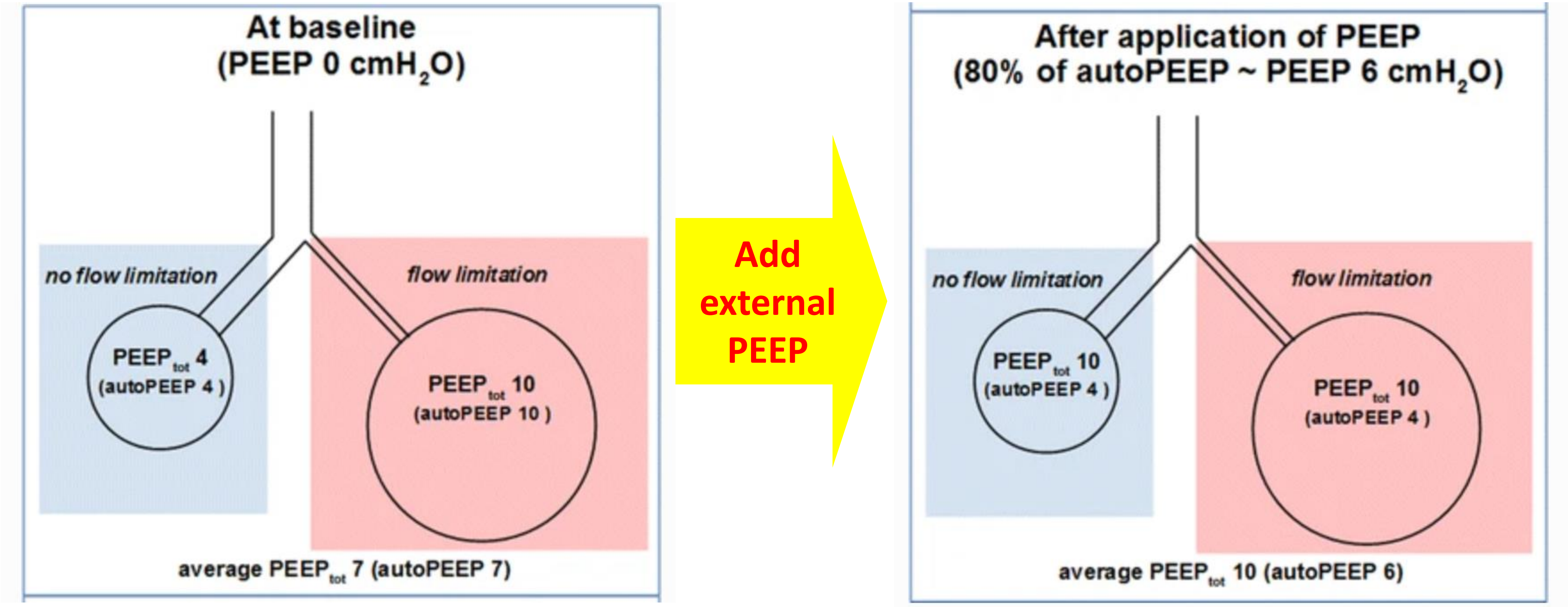
Auto-PEEP increased when:

- Increased resistance (e.g. AECOPD or asthma)
- Increased breathing rate or increased inspiratory time (Ti) (both decrease Te)
- Increased tidal volume

Auto-PEEP decreased when:

- Decreasing resistance (e.g. add bronchodilator)
- Increased expiratory time (Te) or decreasing rate or decreasing Ti
- Decreased minute ventilation (decrease rate or tidal volume)

External PEEP (extrinsic PEEP)



The average result of PEEP application on the whole lung will be a rise in total PEEP from 7 to 10 cmH2O: The two parts react to PEEP as either flow-limited or non-flow-limited areas, and the overall observed response to PEEP is intermediate between them.

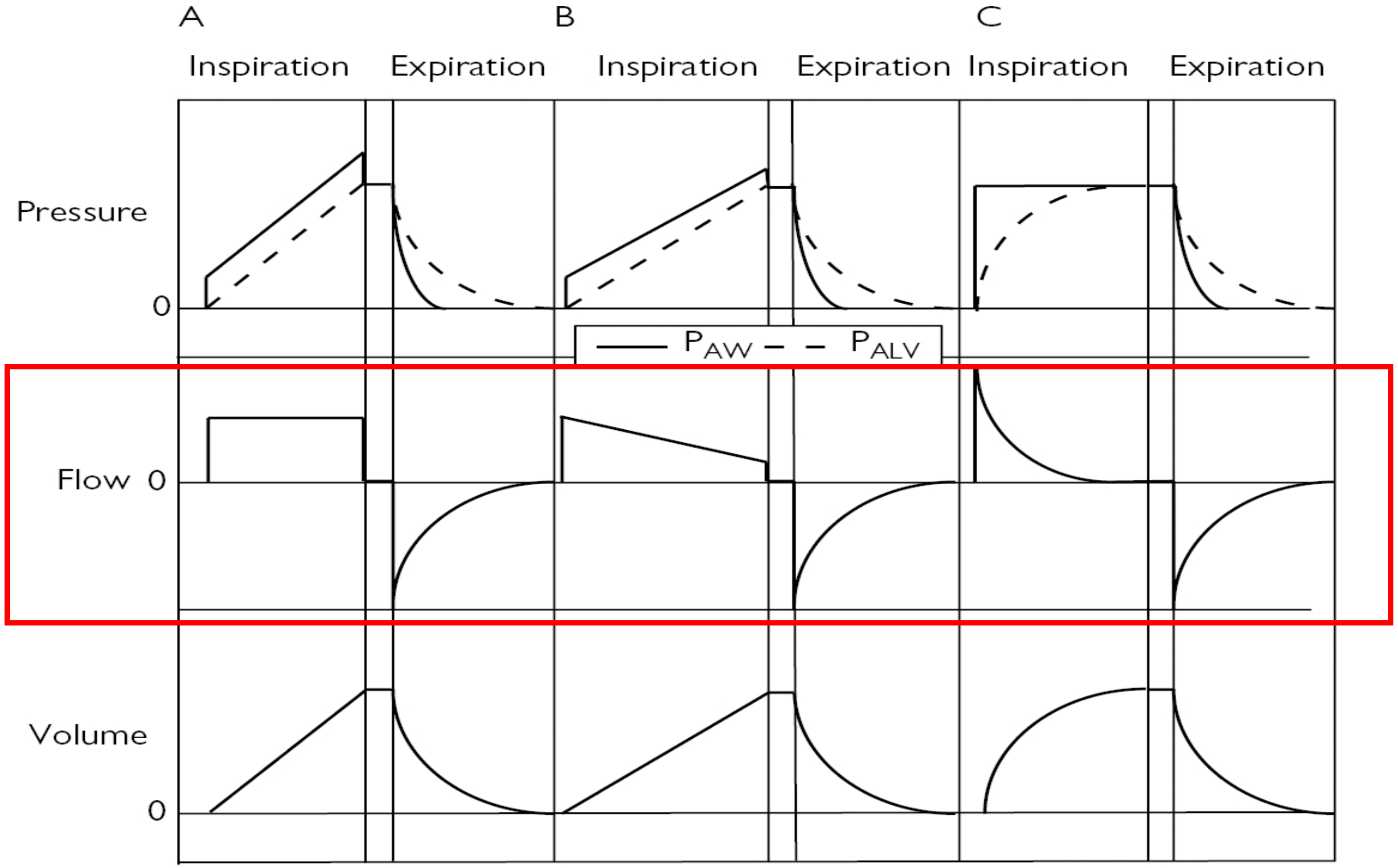
Giuseppe Natalini, Annals of Intensive Care volume 6, Article number: 53 (2016)

Management to relieve auto-PEEP

- 短暫disconnect (10-15 sec) (讓呼吸道或管路累積過高壓力先釋放出)
- 延長吐氣期時間(讓肺內氣體慢慢呼出)
  - **降低respiratory rate** (必要時上sedation)
  - **增加吸氣的flow** (目的:縮短吸氣期)
  - **降低tidal volume** (須注意ventilation volume 是否足夠-> f/u $PaCO_2$)
- 降低呼吸道阻力(治療bronchospasm)
  - **Bronchodilators** / steroid / antibiotics to control airway infection
- 降低ventilation demand
  - Reduce dead space / anxiety / pain / fever / asynchronization: **Anxiolytic + sedation**
  - Reduce carbohydrate intake: **high-fat diet**
- 使用external-PEEP 克服intrinsic PEEP
  - Mostly applied in COPD
  - Applied **PEEP ~ 80% of auto-PEEP**

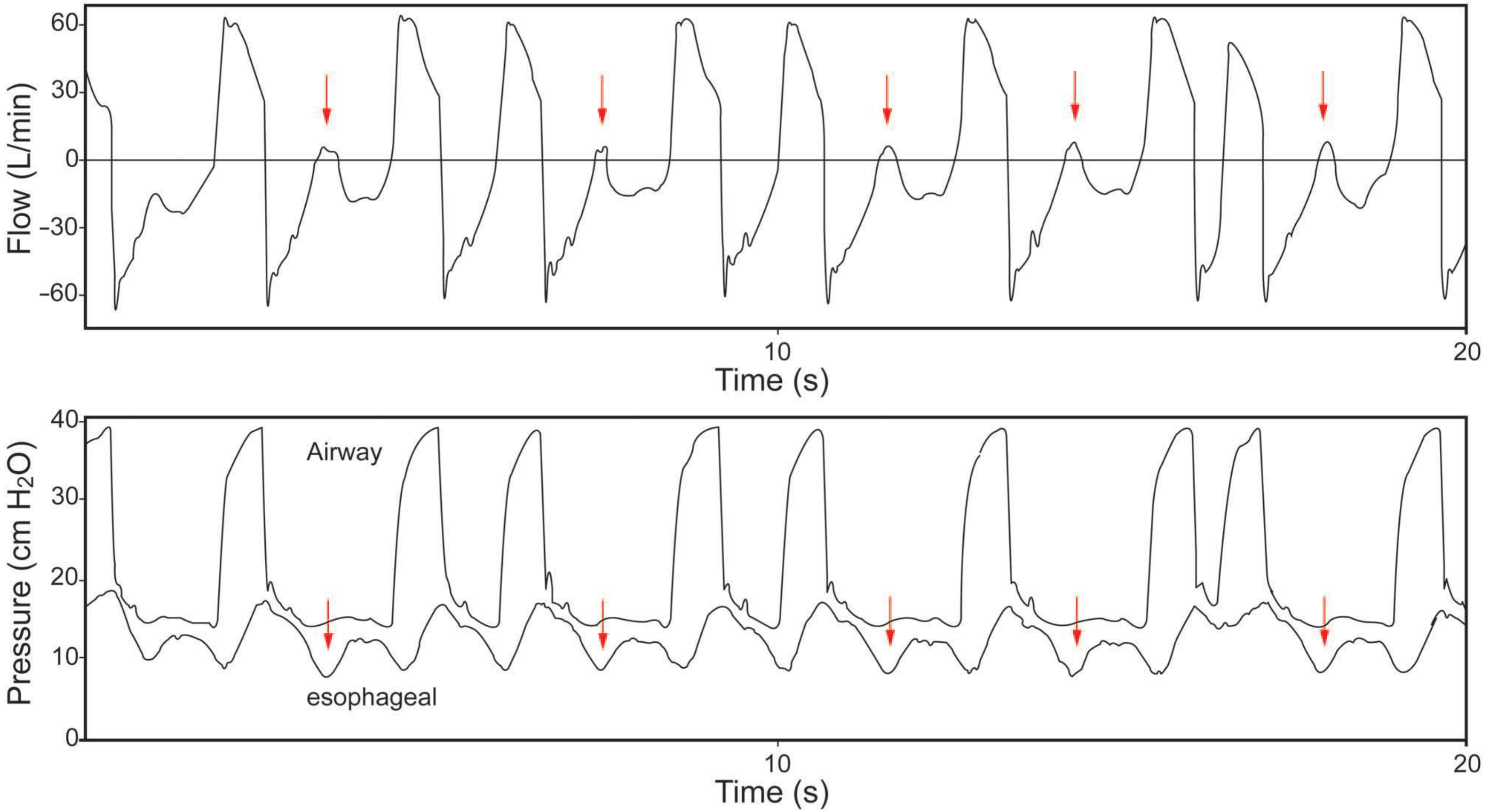
Changes in *flow profiles* on the pressures and volume during volume control ventilation

- Flow (L/min) $\dot{V}$
  - Inspiratory flow
  - Expiratory flow
- Flow pattern:
  - Constant
  - Decelerated



Detect auto-PEEP by Expiratory flow

(e.g. severe COPD)



Physical parameters in lung mechanics

- **Basic parameters**
  - Pressure
  - Flow / Volume
- **Derived indices**
  - Compliance
  - Resistance
  - Work of breath
  - Time constant (τ)

Respiratory system compliance (Crs 順應性)

- $C_{rs} = \Delta V / \Delta P = V_t / (P_{plat} - PEEP)$
  - Normal range (MV): 50~100 mL/cm H_2O
  - Determined by the compliance of **Chest wall (C_{CW})** **and** **lungs (C_L)**

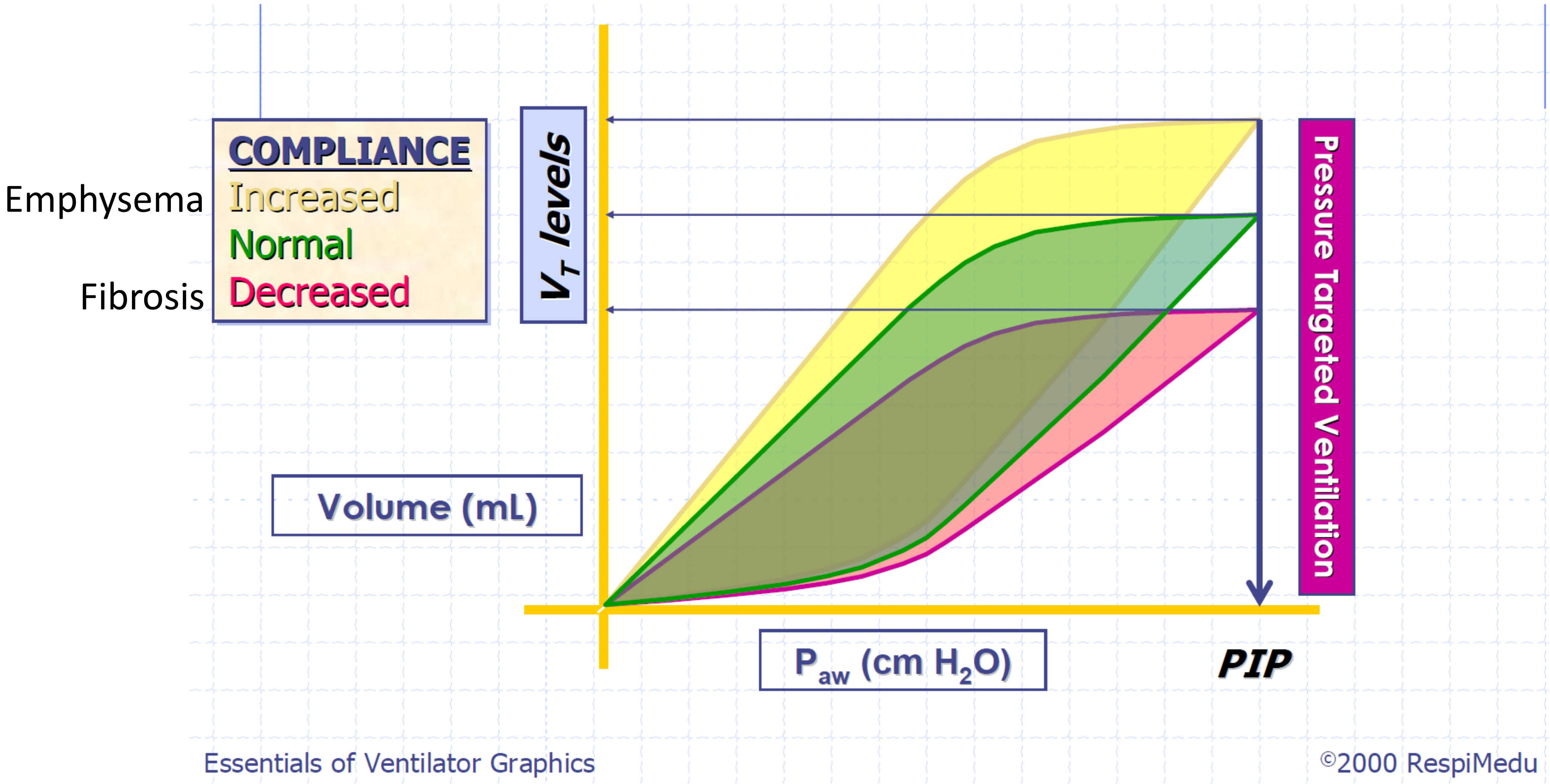
- $C_{cw} = \Delta V / \Delta P = V_t / \Delta P_{es}$ (P_{pl})
  - Normal: 200 mL/cm H_2O
  - Decreased with **obesity**

$$1/C_{RS} = 1/C_{CW} + 1/C_L$$

- $C_L = \Delta V / \Delta P = V_t / \Delta P_L$
  - Normal: 200 mL/cm H_2O
  - Decreased with **pulmonary edema, consolidation**
  - Increased with **emphysema**

- Clinical applicate to determine the optimal level of PEEP
  - **Highest level of Crs** corresponds to best PEEP
  - The optimal PEEP results in **the lowest driving pressure (Pplat-PEEP)** with constant Vt

Lung compliance changes in P-V loop



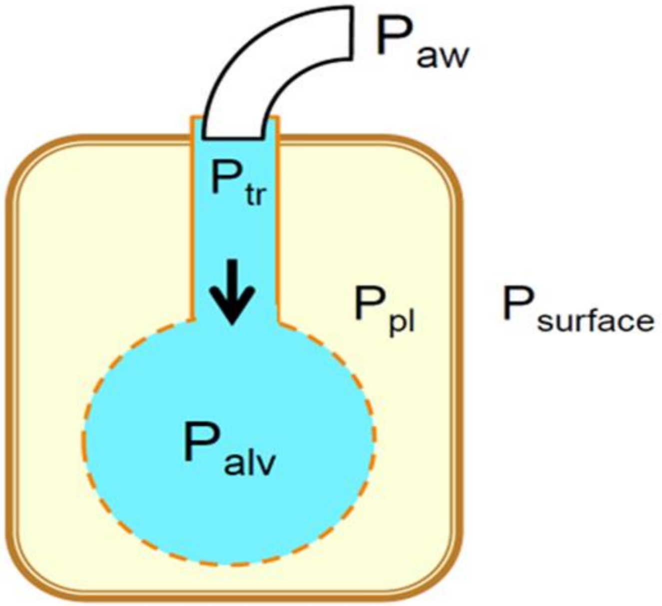
Airway resistance

- Airway diameter: the major determinant of resistance
  - Resistance varies with lung volume
  - Resistance have significant regional variation
  - Resistance differs during inspiration and expiration

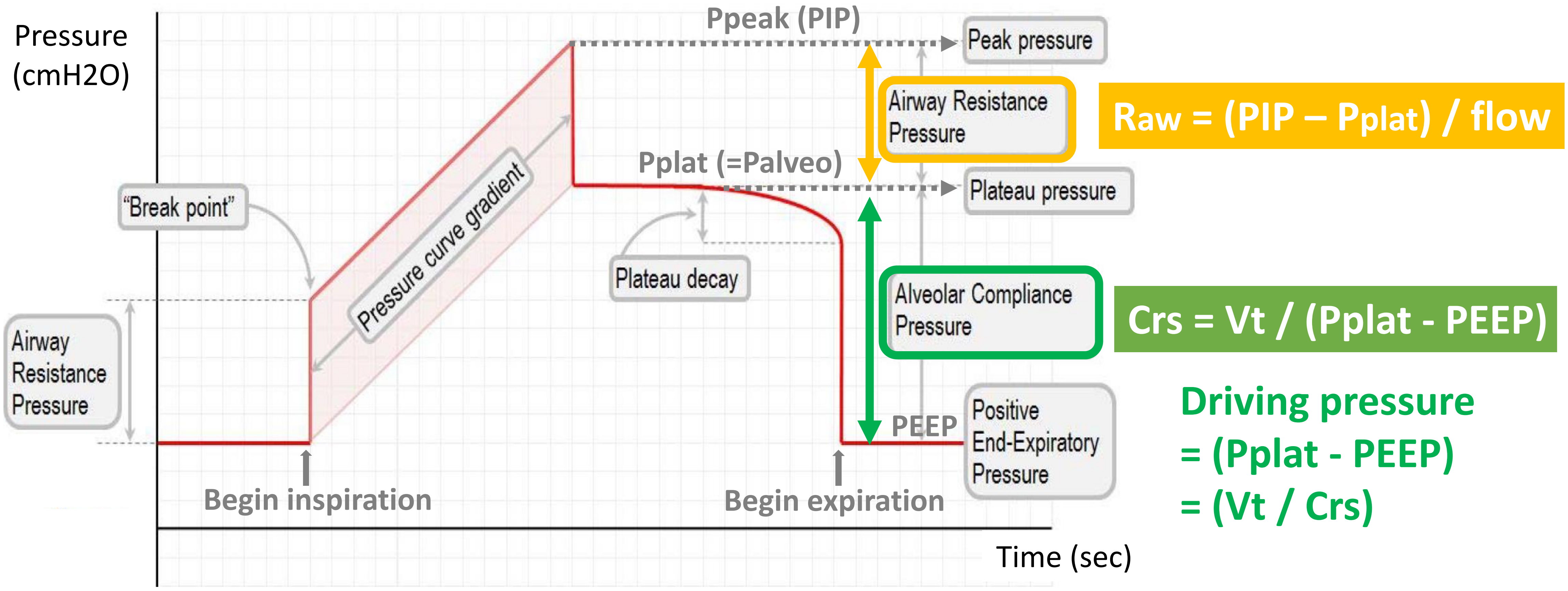
- Two airway resistances in series during mechanical ventilation
  - Artificial airway
  - Natural airway

Airway Resistance

- **Resistance** = $\frac{\Delta Pressure}{Flow}$
- Airway resistance (R_{aw}) = $\frac{P_{aw} - Pal_v}{Flow}$
- Pulmonary resistance (R_L) = $\frac{P_{aw} - Ppl}{Flow}$
- Chest wall tissue resistance (R_w) = $\frac{P_{pl} - Psu_{rface}}{Flow}$



Respiratory system compliance (Crs)
Airway resistance (RAW)

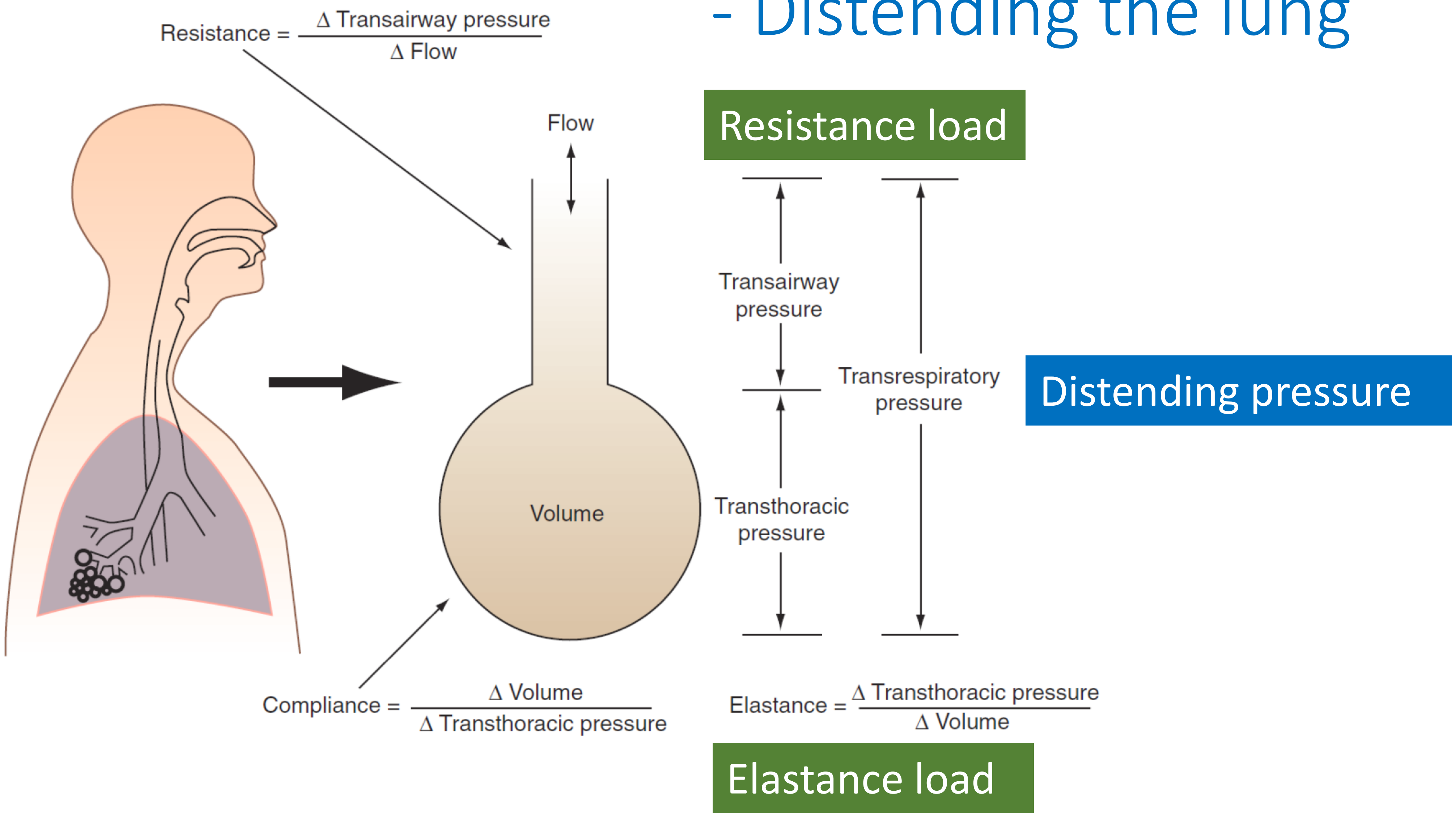


Driving pressure
= (Pplat - PEEP)
= (Vt / Crs)

Work of breath

- Work = force x distance (功=力作用在物體上使其移動某段距離)
- Overcome the elastic and frictional opposition to lung inflation
- Work of breath = pressure x volume (cmH_2O*L)
- Normal WOB: 0.05 Kg*m/L or 0.5 J/L

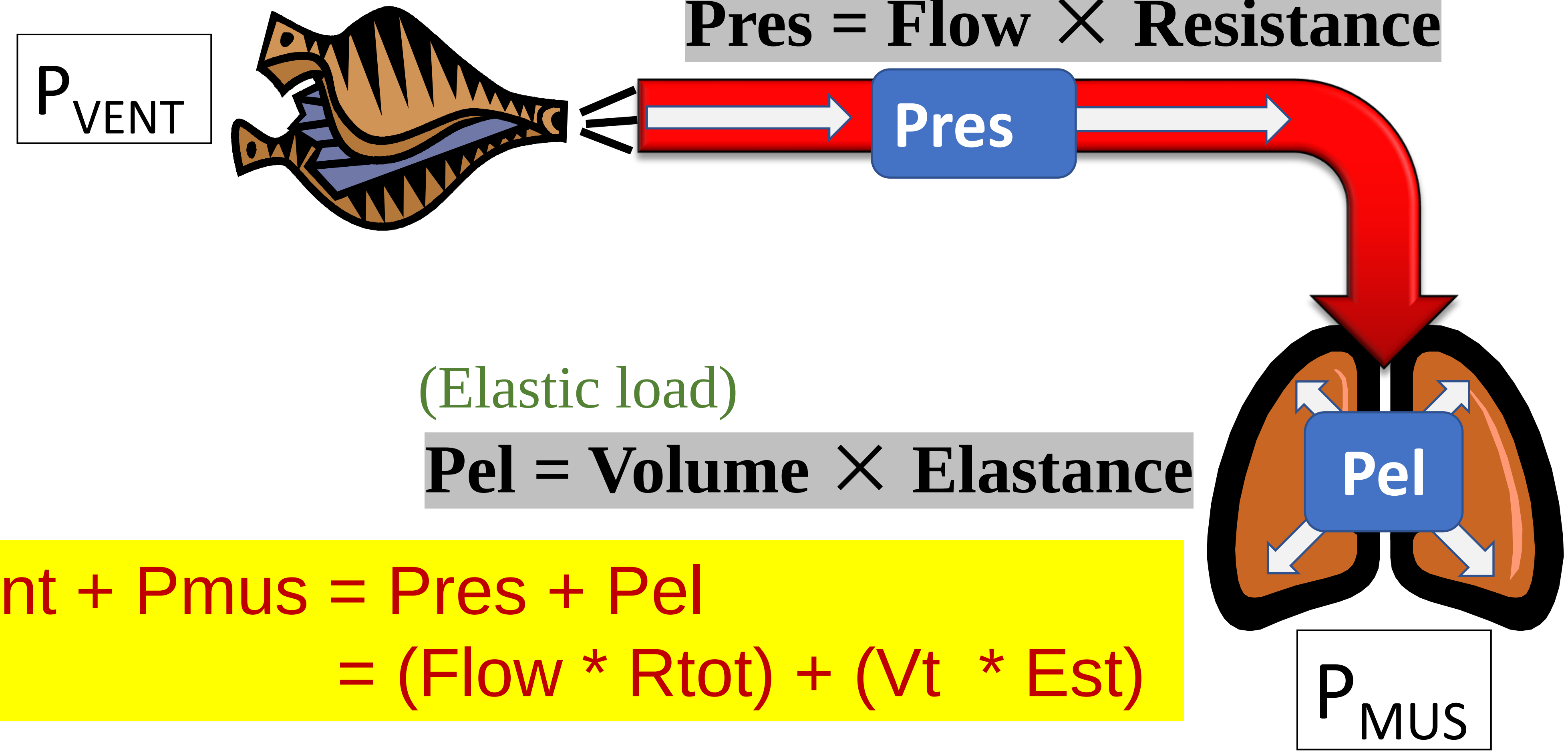
Work of Breath
- Distending the lung



Calculate patient effort (Work of breath)

(Resistive load)

Pres = Flow × Resistance



(Elastic load)

Pel = Volume × Elastance

Pvent + Pmus = Pres + Pel

= (Flow * Rtot) + (Vt * Est)

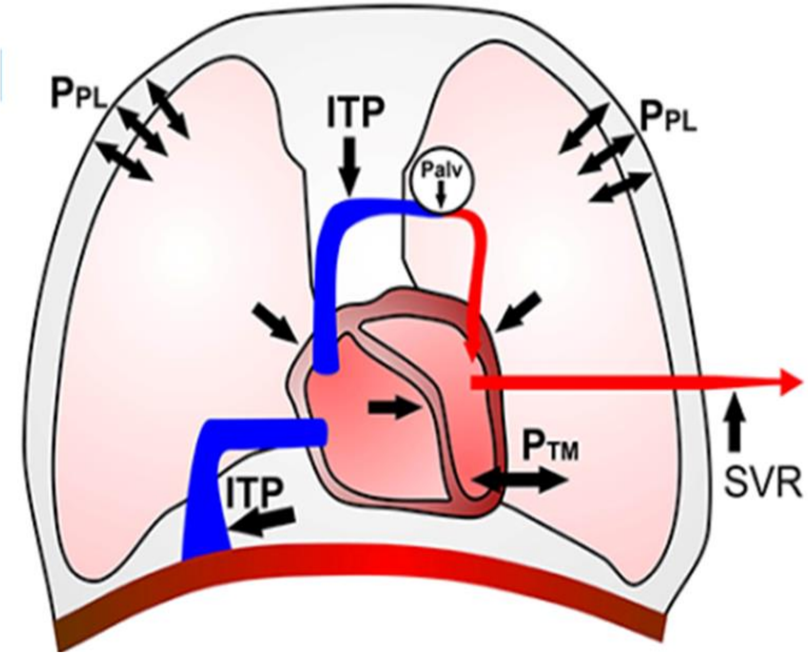
Time constant (τ)

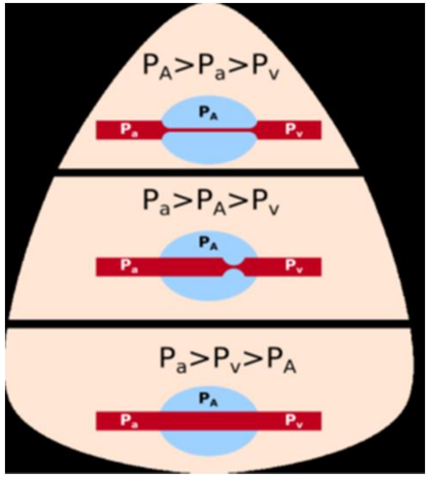
- The rate of change in the volume of a lung unit that is passively inflated or deflated
- Time constant (τ) = R X Crs
- Time constant determines how the lungs empty during expiration
  - **Short time constants** favor rapid emptying when R and Crs are low
    - Fibrosis, ARDS
  - **Long time constants** favor slow emptying and occur when Crs and R are high
    - Emphysema

Heart-lung interaction

Heart-lung interaction

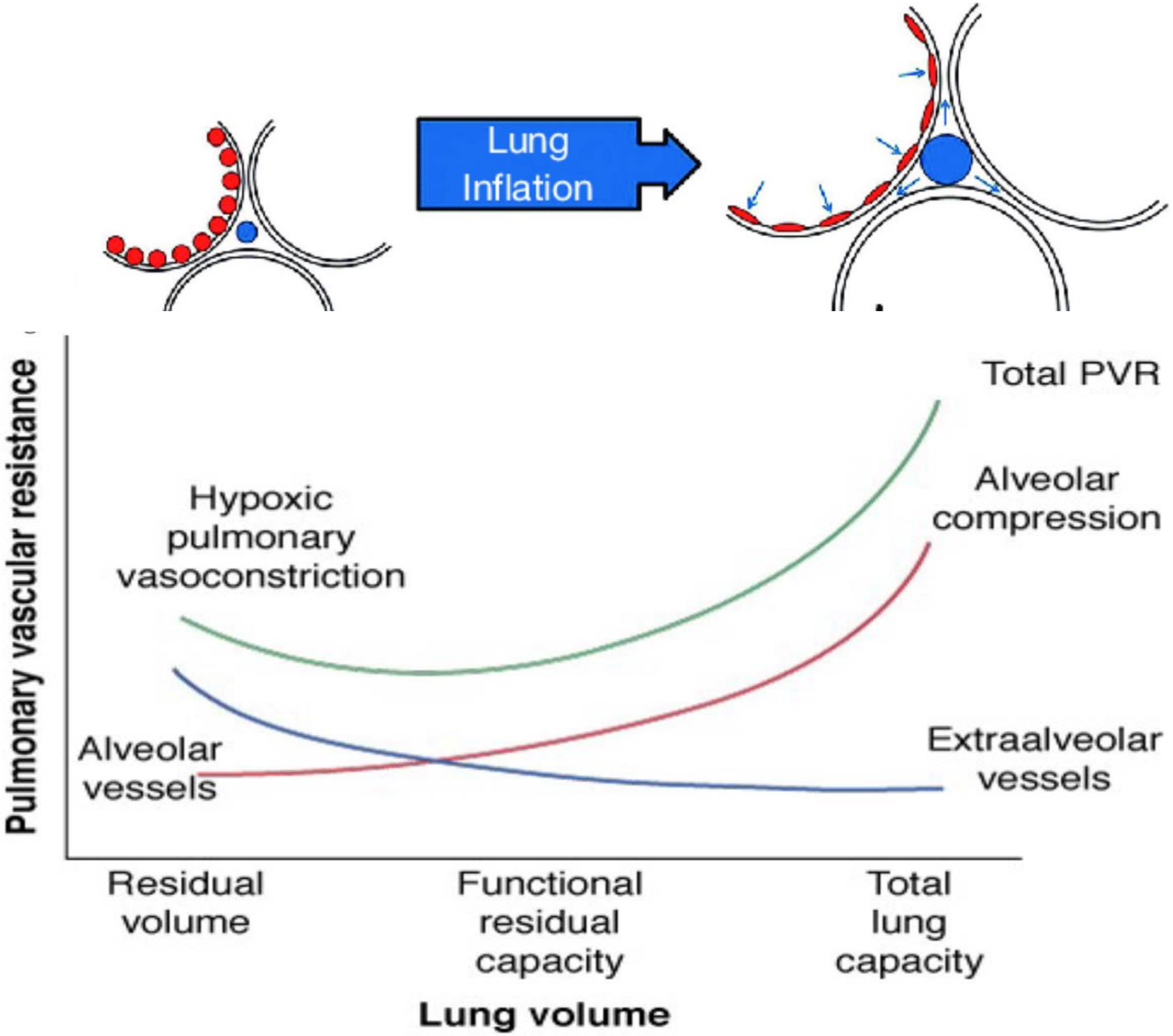
- Effect of lung on **pulmonary vascular resistance**
  - ➢ Hypoxic Pulmonary Vasoconstriction
  - ➢ Volume-dependent changes in pulmonary vascular resistance (PVR)
    - PVR is the main determinant of RV (right ventricular) afterload
  - ➢ Transpulmonary pressure
- **Ventricular interdependence**
- **Systemic venous return**





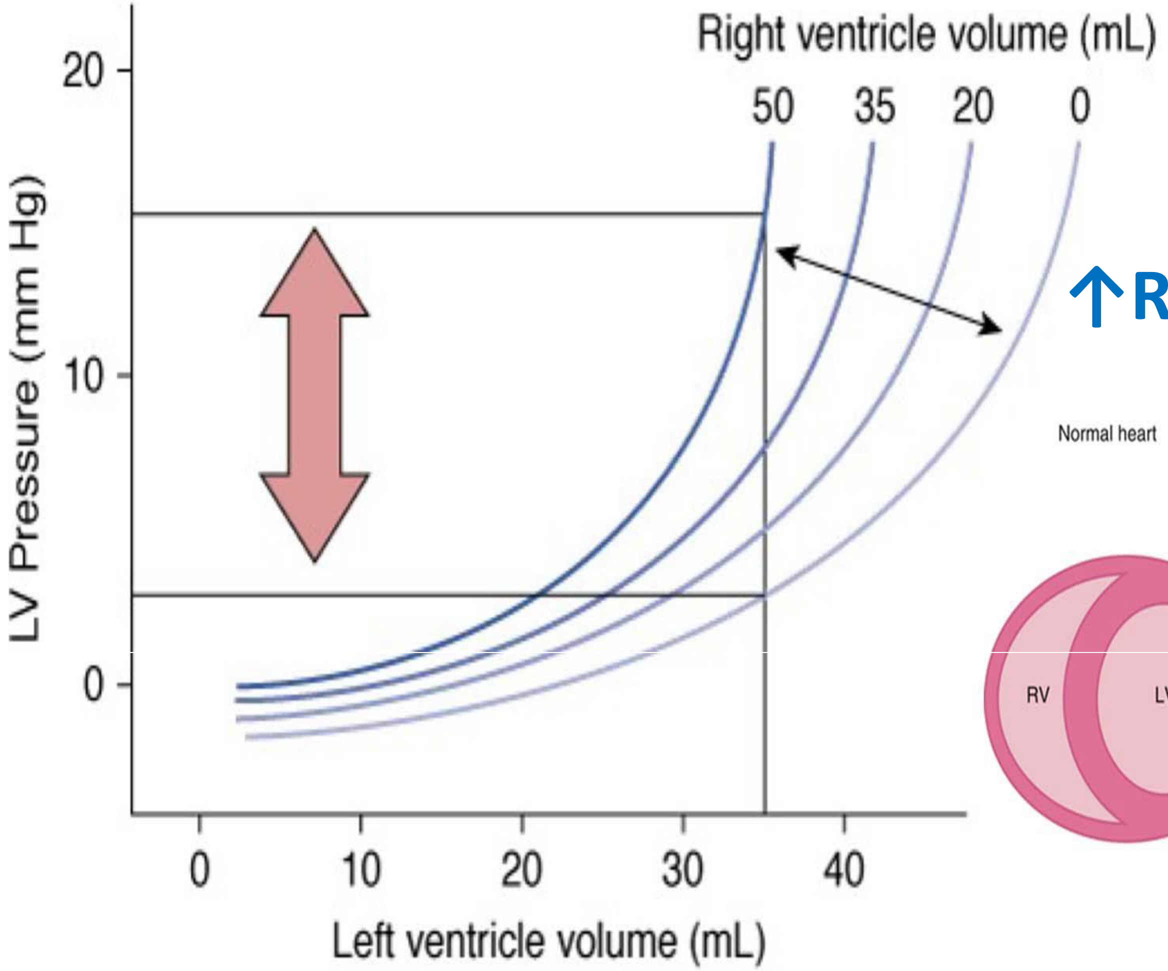
Zone I
No blood flow
Zone II
Moderate blood flow
Zone III
Greatest blood flow

Relation between lung volume and pulmonary vascular resistance (PVR)

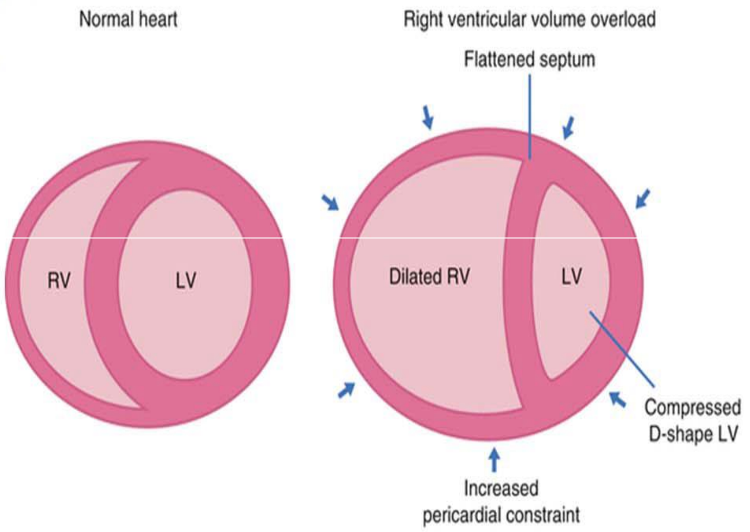


Ventricular interdependence

A phenomenon whereby the function of one ventricle is altered by changes in the filling of the other ventricle. This leads to increase in volume of one ventricle associated with a decreased volume in the opposite ventricle.

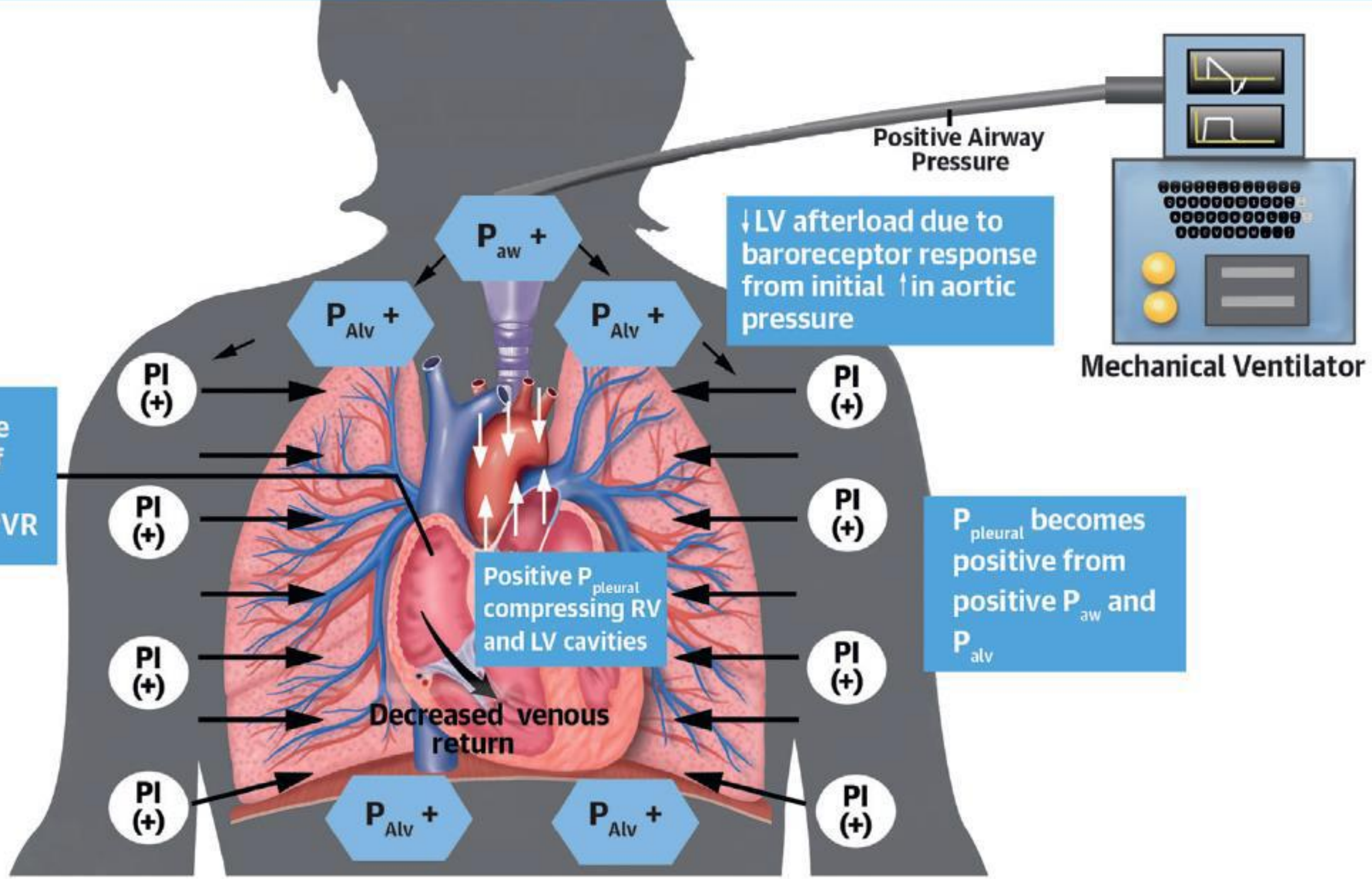


↑RV volume ➔ ↓LV volume



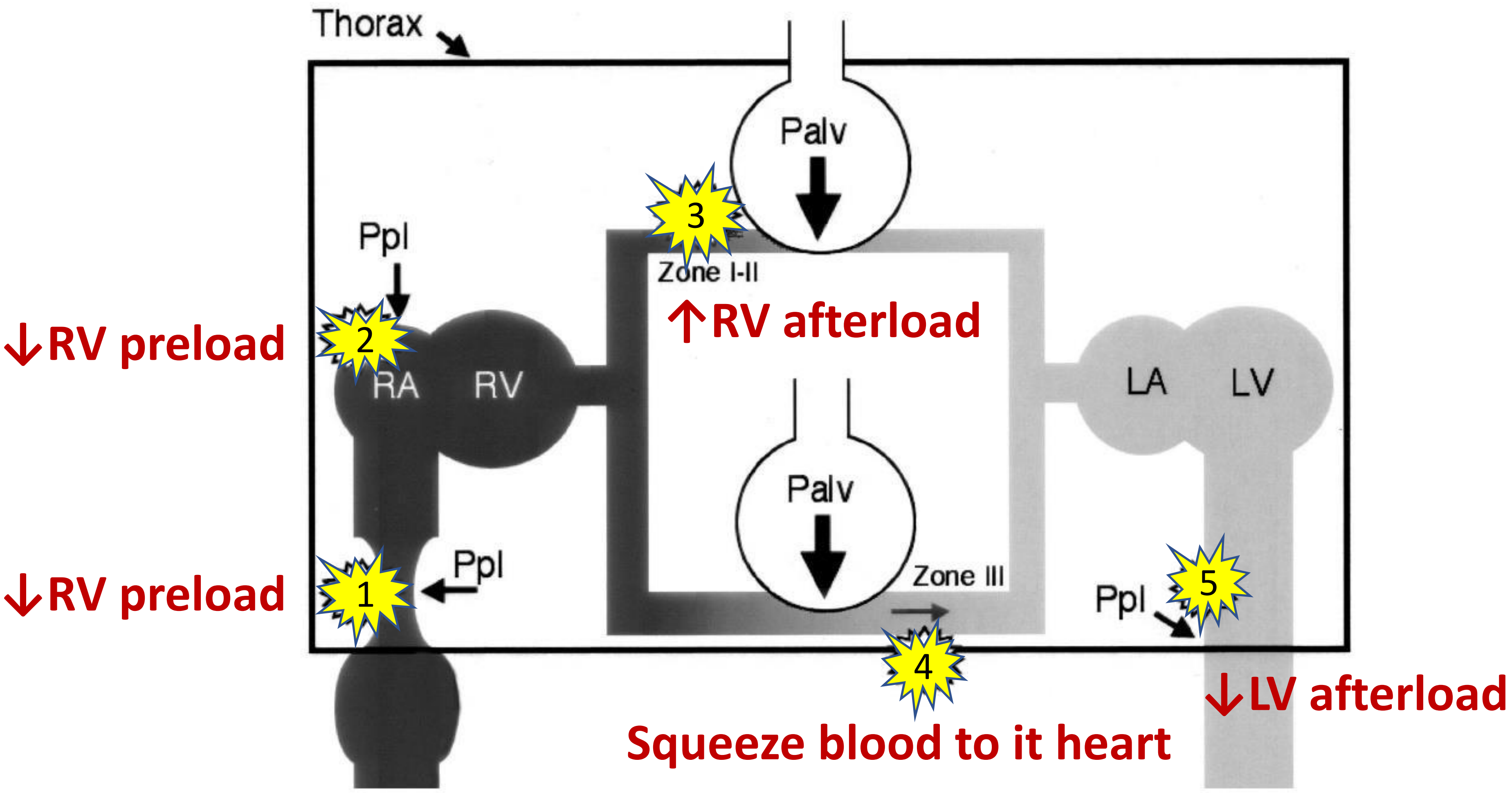
A. Postive Pressure Ventilation

P_{aw}, P_{alv} and $P_{pleural}$ Become Positive



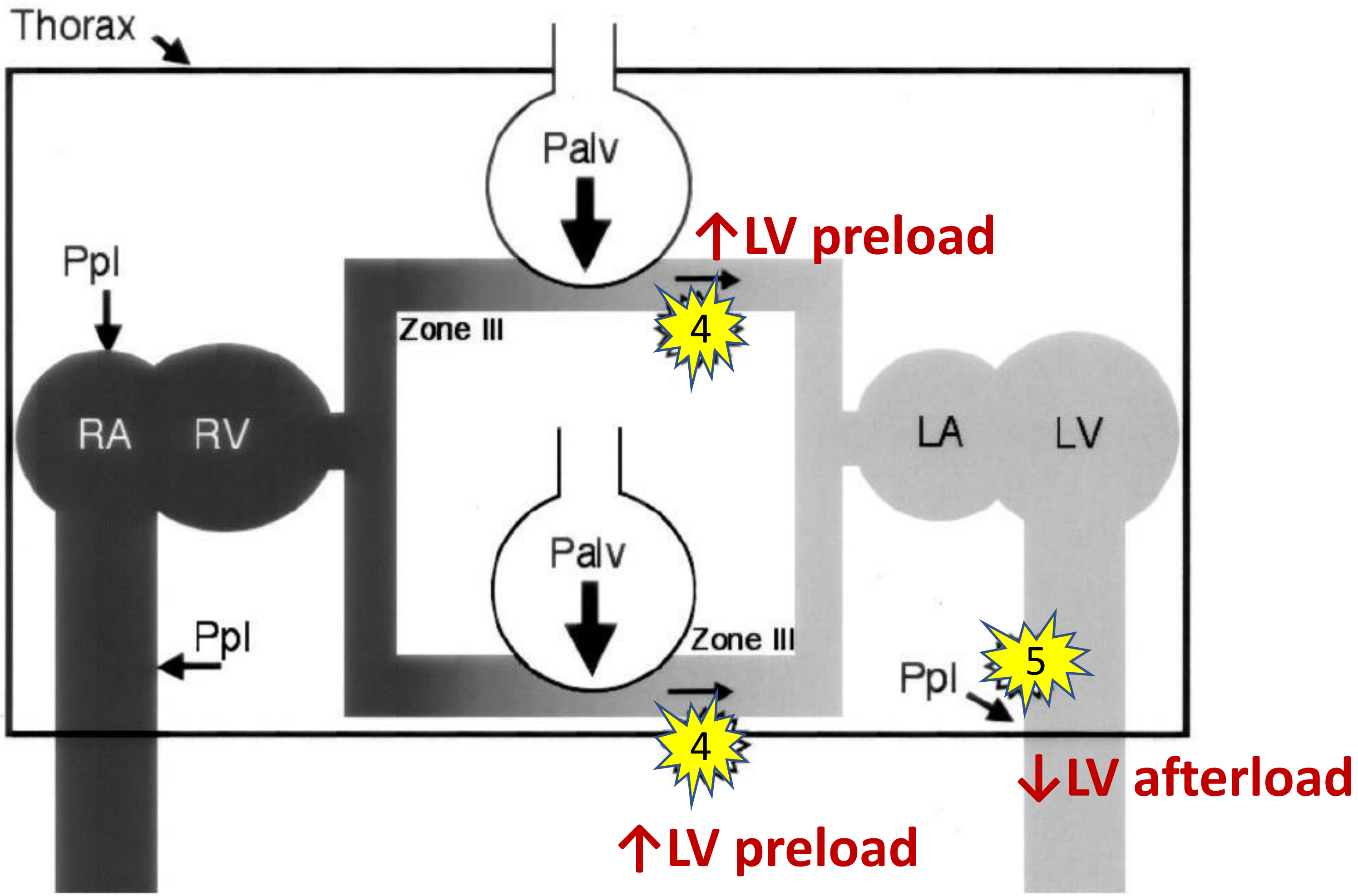
Summary of Effects: $+P_{aw}$ → $+P_{alv}$ → $P_{pleural}$ → Compression of RV and pulmonary vessels → ↓Venous return, ↑RV afterload and ↓LV afterload by baroreceptor reflex

*In **Hypo**-volemic condition*



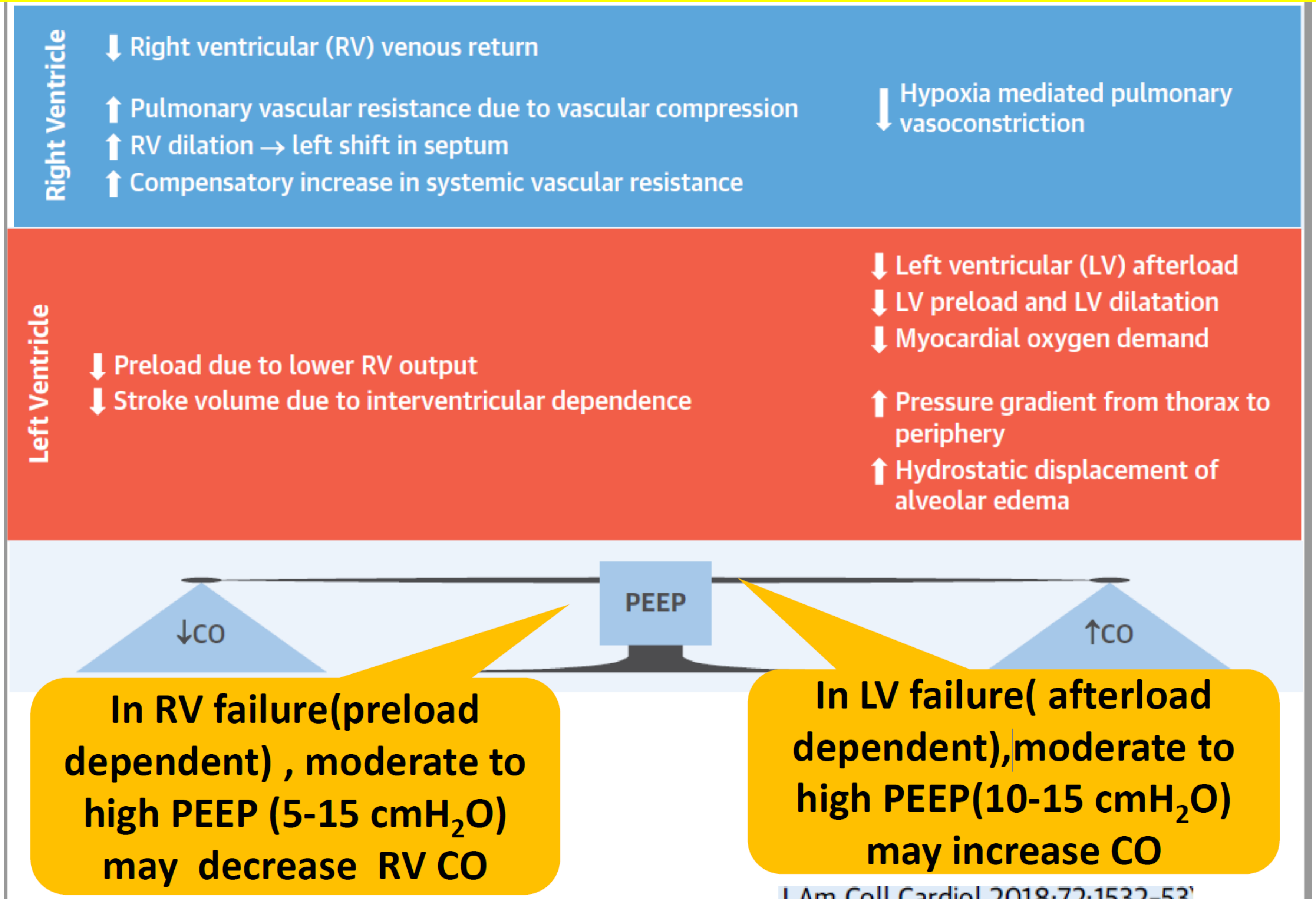
Anesthesiology 2005;103:419-28

*In **Hyper**-volemic condition*



Anesthesiology 2005;103:419-28

Potential physiologic effect of PEEP on ventricular function and cardiac output



J Am Coll Cardiol 2018;72:1532-53

How to minimize detrimental heart-lung interaction

- Minimize work of breath
- Prevent hyperinflation
- Minimize negative swings in intrathoracic pressure
- Fluid resuscitation during initiation of PEEP
- Prevent volume overload during weaning
- Augment cardiac contractility

Take home message

- Be familiar with the factors affecting pressure, flow and volume
- Measurement and management of auto PEEP
- Application of parameters to evaluate mechanical ventilated patients
  - Basic (Pressure, flow, volume)
  - Derived (compliance, resistance, WOB,..)
- Beware of the heart lung interaction (especially in severe heart failure with acute pulmonary edema)

END