Basic Physiology of Mechanical Ventilation

2020.07.26 機械通氣訓練課程

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Basic Physiology

- Respiratory Mechanics
- Gas Exchange
- Cardiovascular-Pulmonary Interactions

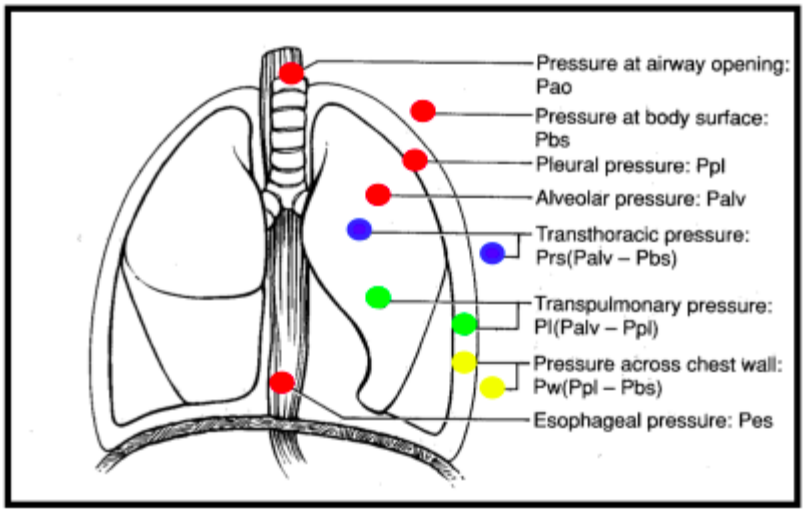
Respiratory Mechanics

Respiratory Mechanics

- The expression of **lung function** through measures of **pressure** and **flow (volume)**
- Derived indices
  - Compliance (volume/pressure)
  - Resistance (pressure/flow)
  - Work Of Breathing (WOB) (flow x pressure)
- Wave form: one of the parameters
  - plotted as function of time (trend, tracing…)
  - As a function of one of the other parameters (loop)

Pressure

- **Airway Pressure**
- **Equation of Motion**
- Alveolar Pressure
- Plateau Pressure
- Mean Airway Pressure
- **Auto-PEEP**
- **Esophageal Pressure**
- Transpulmonary Pressure (PL), Transthoracic Pressure (Pw), Transrespiratory Pressure (Prs)
- Intra-abdominal Pressure, Transdiaphragmatic Pressure
- **Applications: Asynchrony, Stress Index**



Airway Pressure

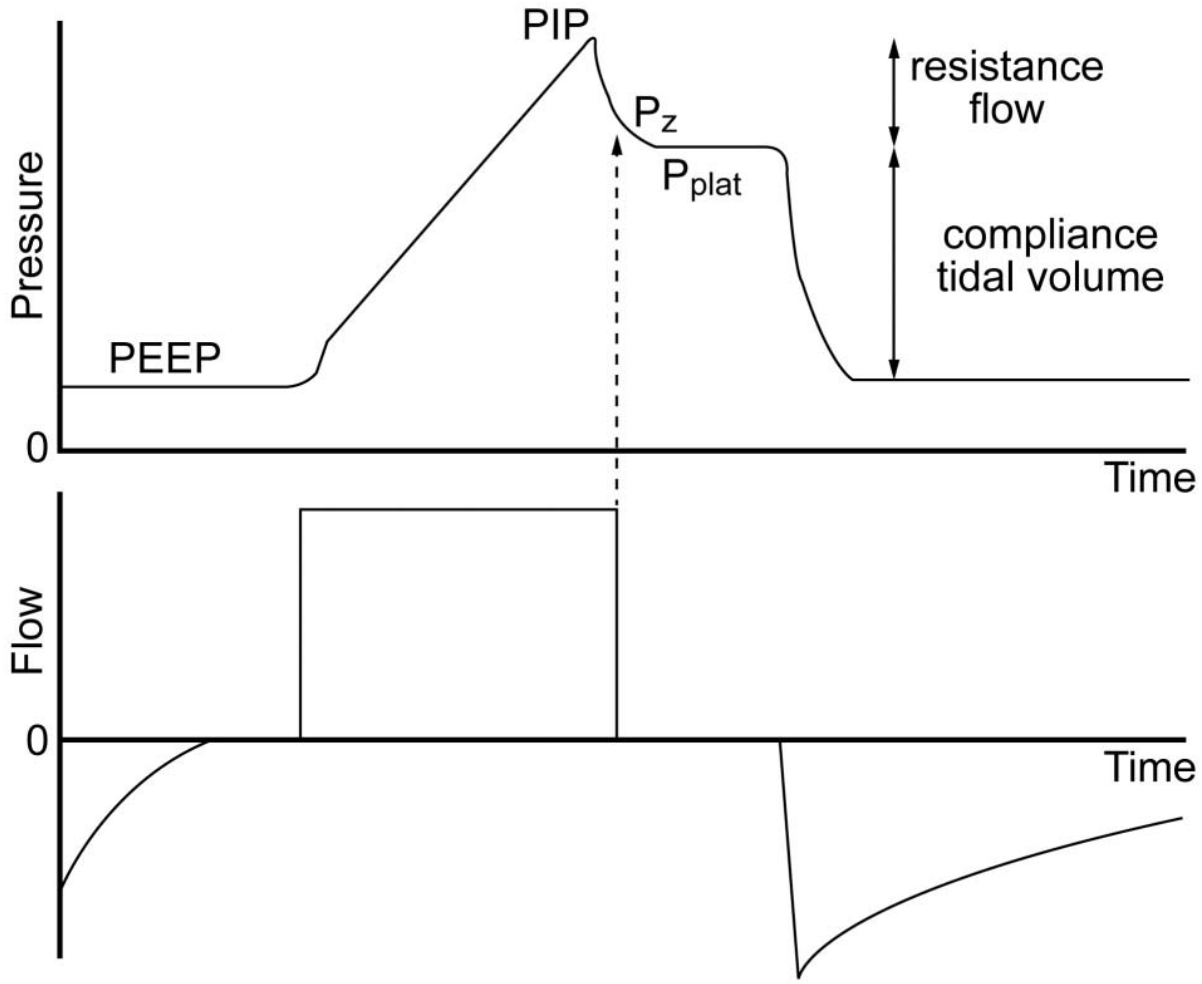
- The shape of the airway pressure waveform
  - flow and tidal volume (V_T) *from the ventilator*
  - lung mechanics *of the patient*
  - active breathing efforts *of the patient*
- **Equation of Motion**

$$P_{vent} + P_{mus} = V_T/C_{RS} + R_{aw} \times \dot{V}_I$$

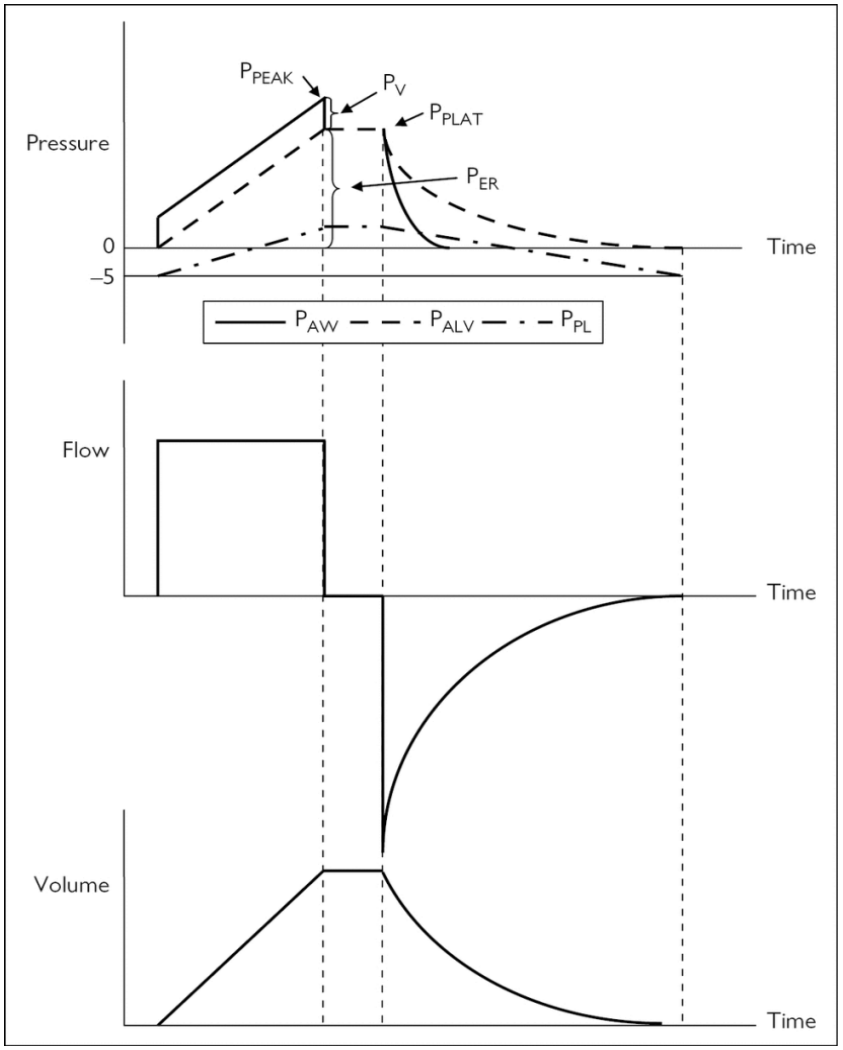
$$+ PEEP + PEEPi + inertance$$

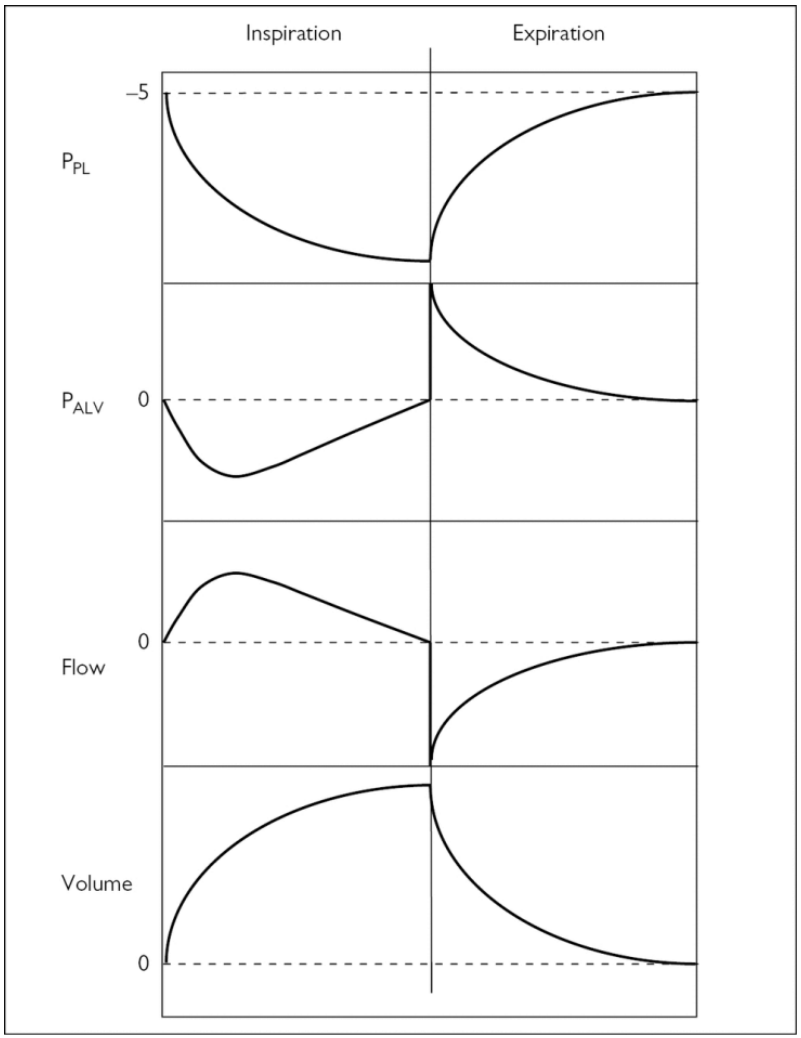
Airway pressure and **flow** waveforms during constant flow volume control ventilation

(effect of an end inspiratory breath-hold: 0.5-2s)

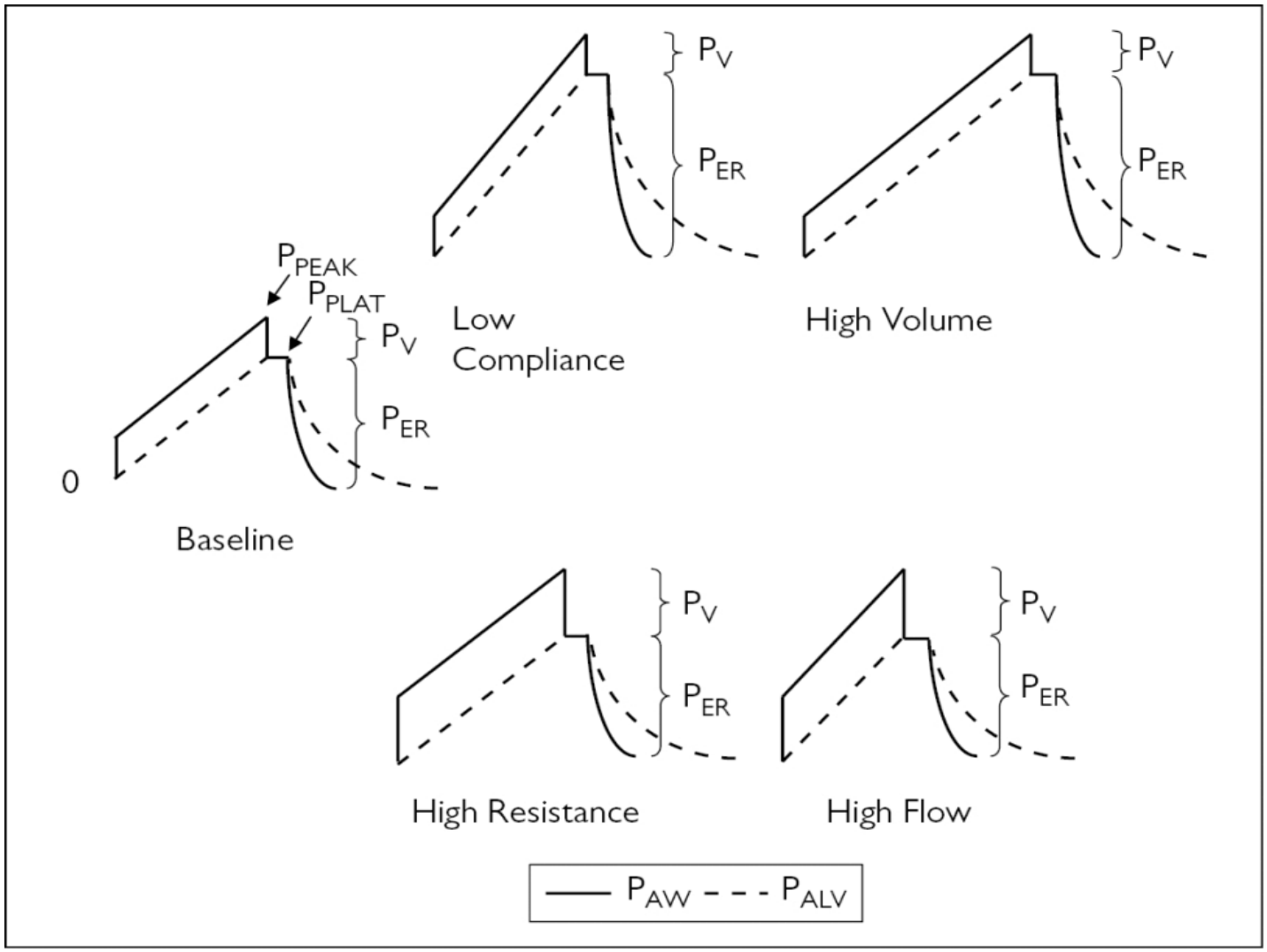


Mechanical *vs.* Spontaneous Ventilation

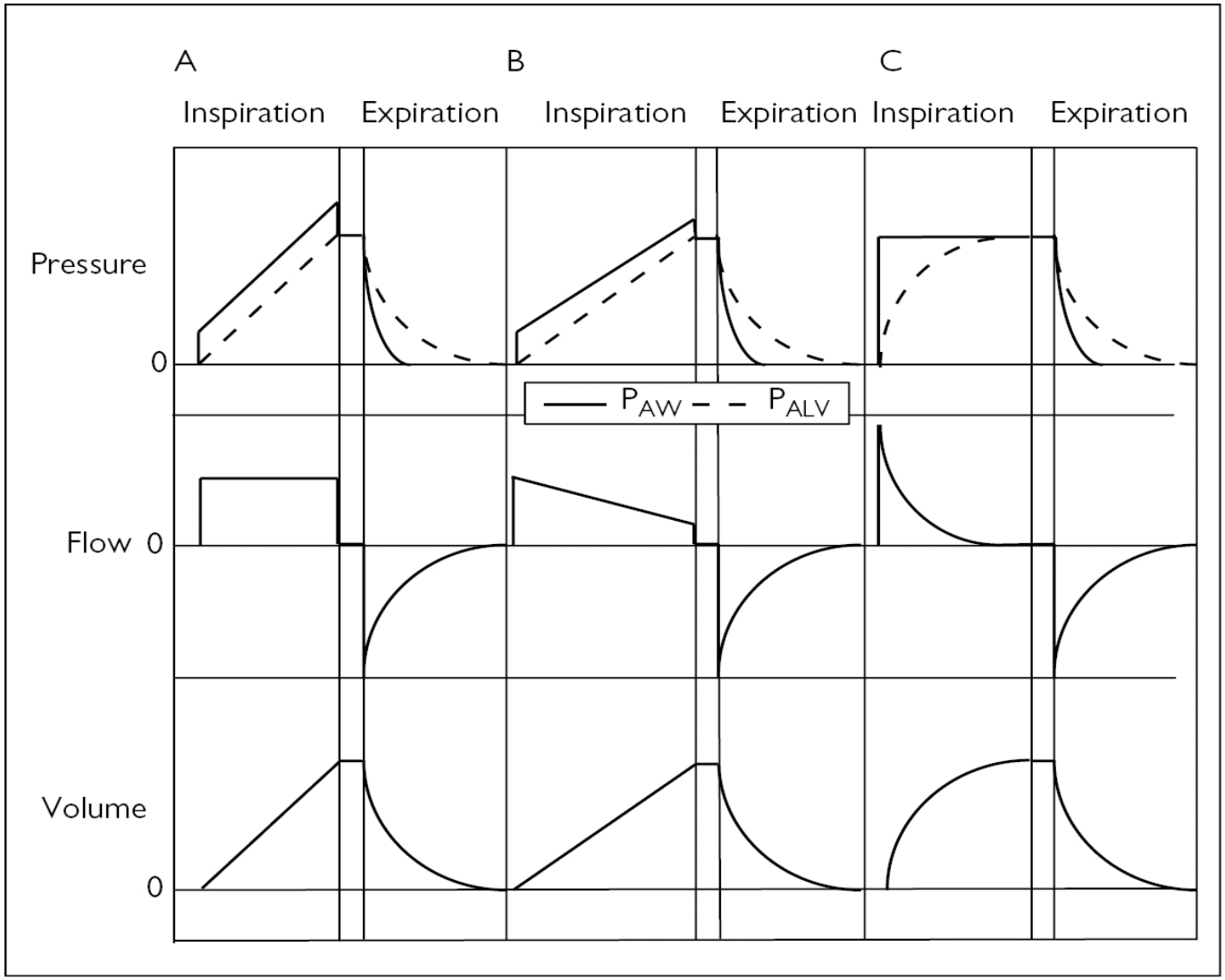




The effect of changes in compliance, resistance, volume, and flow on the pressures

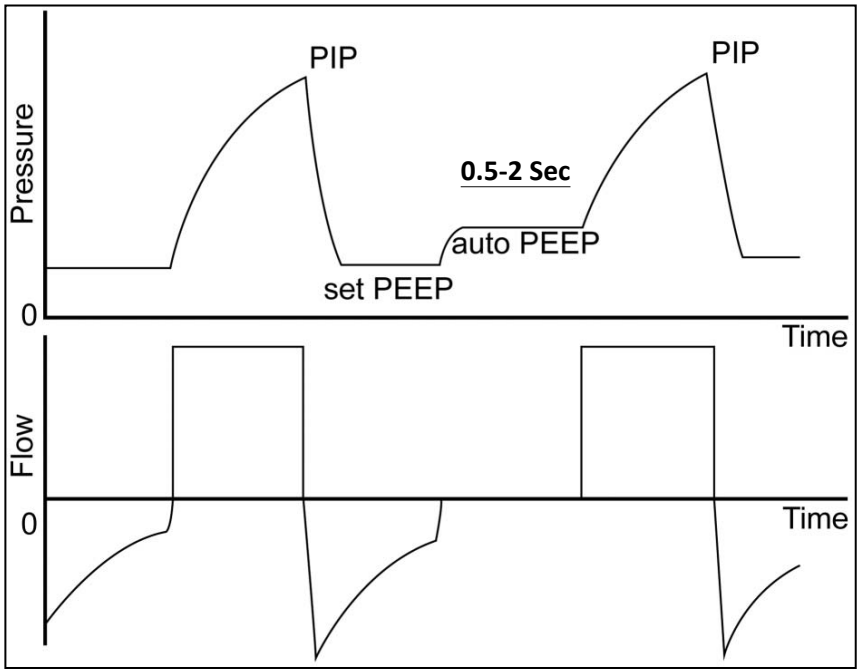


The effect of changes in flow profiles on the pressures and volume

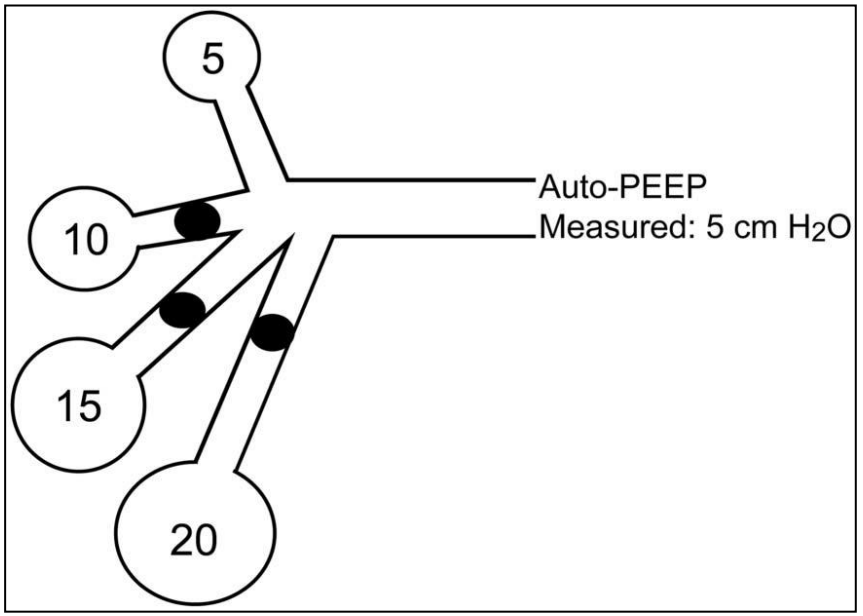


Auto-PEEP measurement - 1

*** End-expiratory pause method**



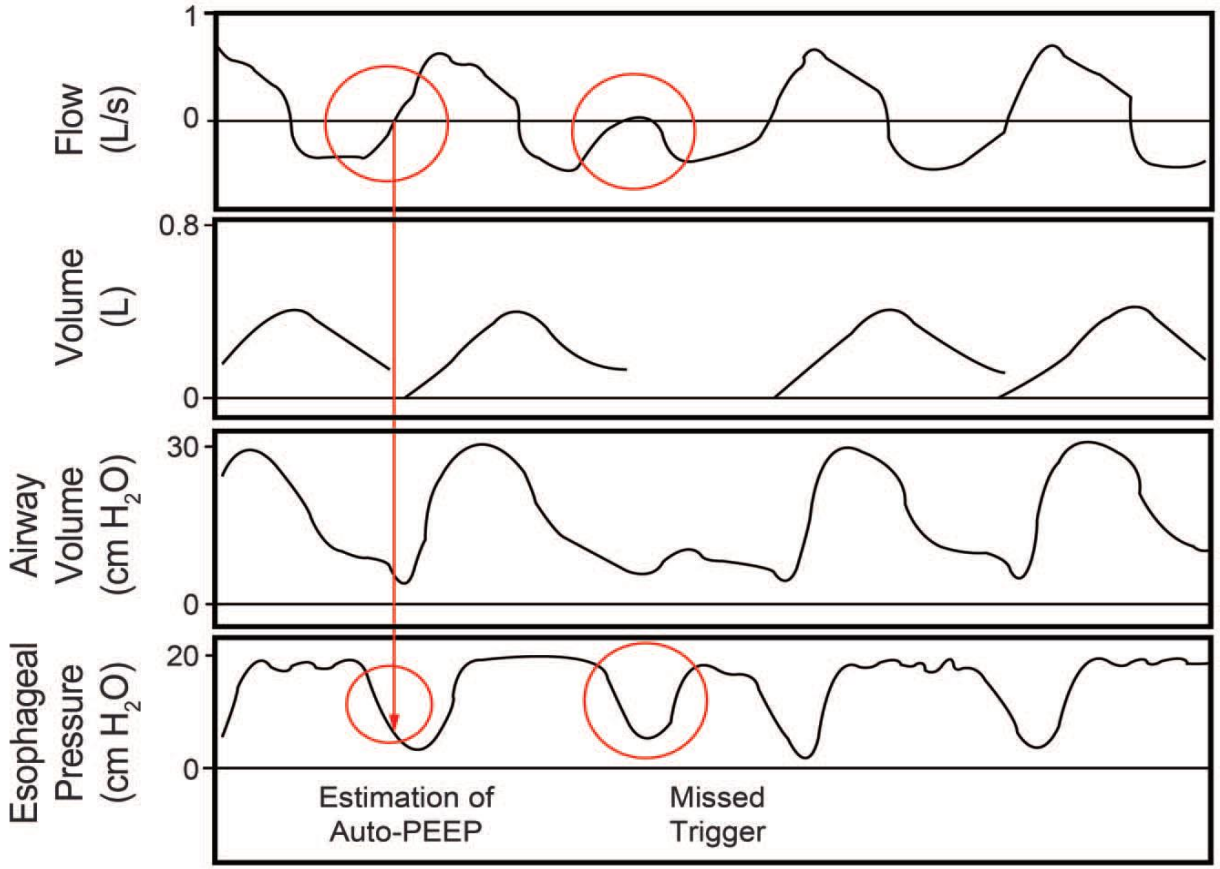
*** The underestimated auto-PEEP**

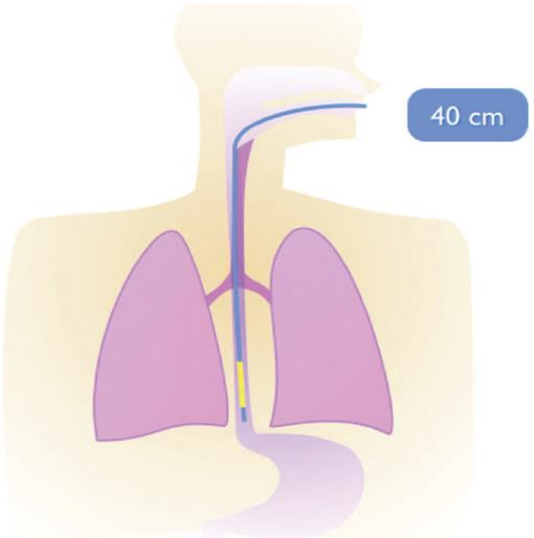


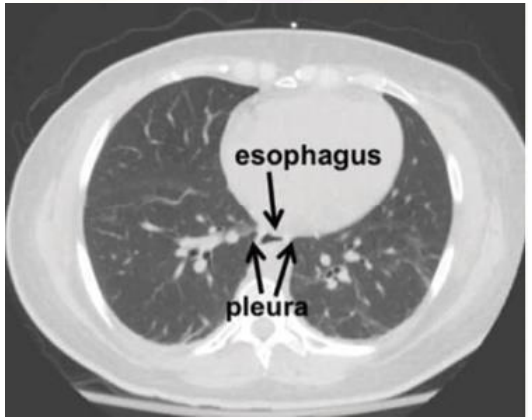
- Incomplete emptying of the lungs at the end of expiration.
- The pressure produced by this trapped gas is called auto-PEEP, intrinsic PEEP, PEEPi, or occult PEEP

Auto-PEEP measurement -2

In spontaneously breathing patients, measurement of esophageal pressure (Pes) can be used to determine auto-PEEP







Auto-PEEP is a function of *ventilator settings* and *lung function*

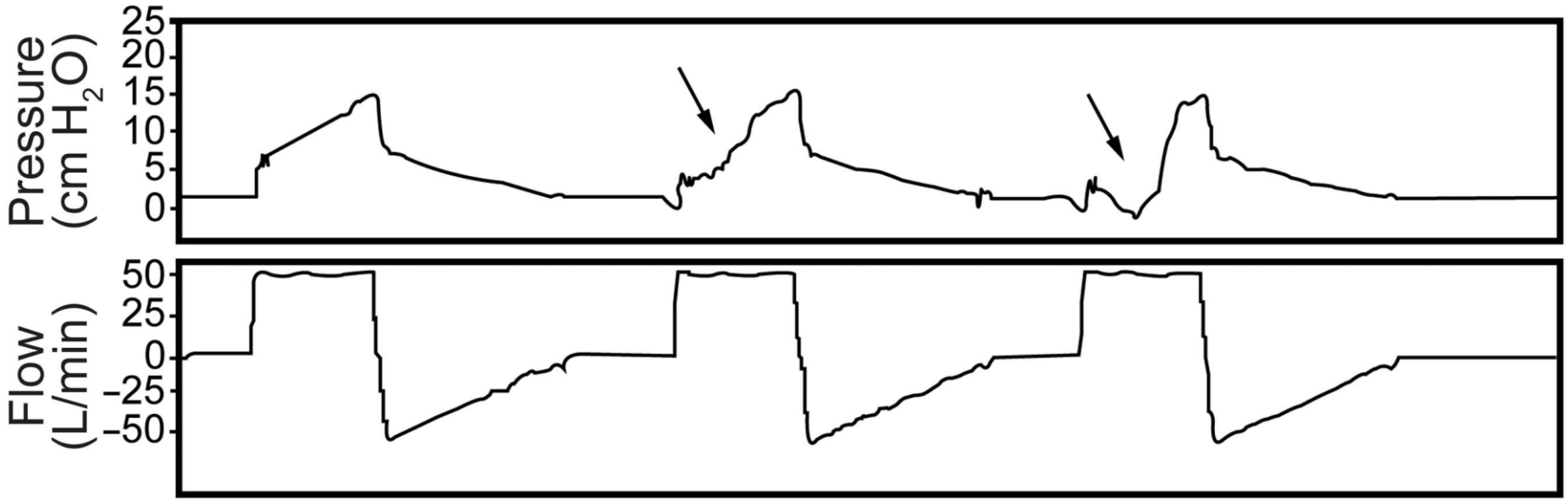
↑ **Increased with**	↓ **Decreased by**
• increased resistance and compliance • increased breathing frequency or increased inspiratory time (Ti) (both decrease Te) • increased Vt	• Decreasing minute ventilation (rate or Vt) • increasing Te (decreasing rate or Ti) • decreasing Raw (eg, bronchodilator administration)

$$\text{auto-PEEP} = V_T/(C_{RS} \times (e^{Kx \times T_E} - 1)$$

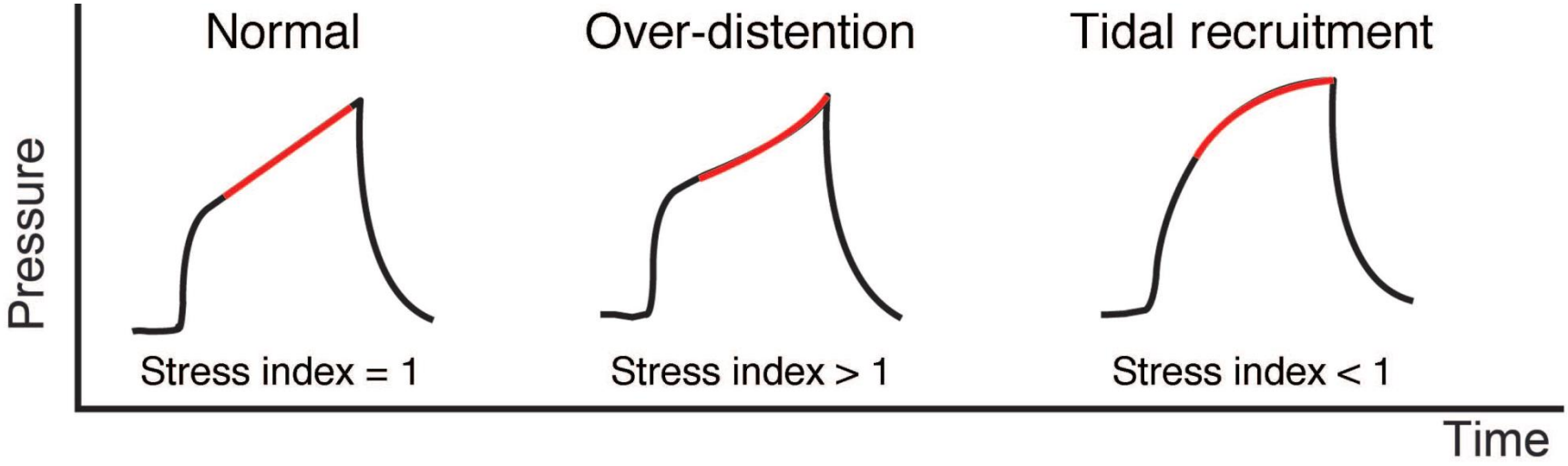
Asynchrony

- Patient-ventilator asynchrony
  - Volume control mode: airway pressure waveform
  - Pressure control mode: flow/volume waveform

- Effect of asynchrony on the airway pressure waveform during



Stress Index:

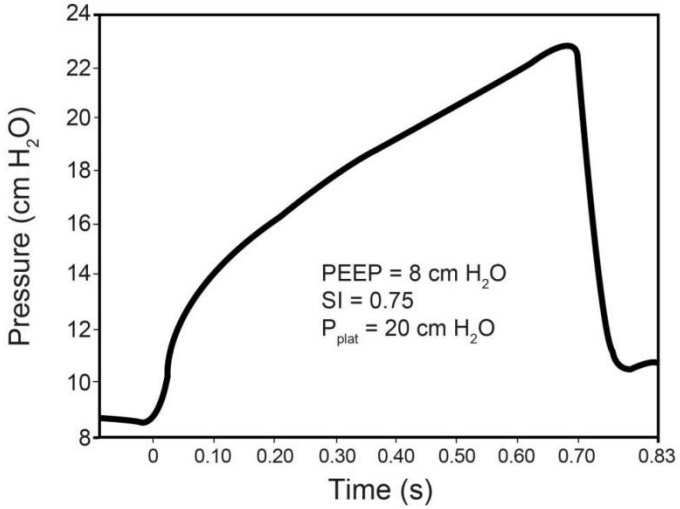


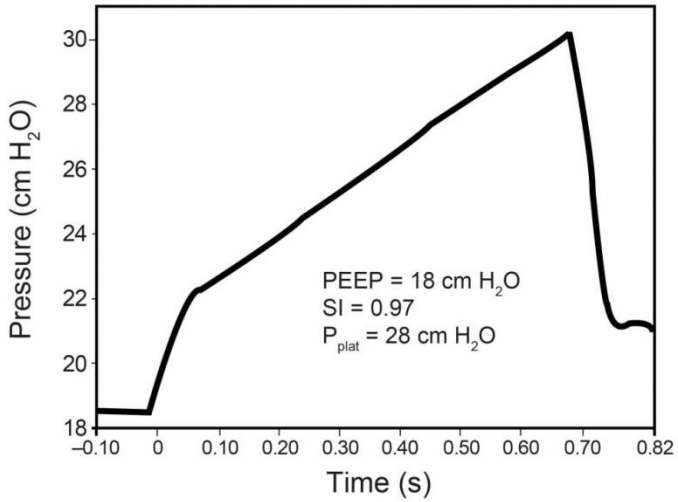
* The stress index is used to assess the shape of the pressure-time curve during constant flow-volume control ventilation

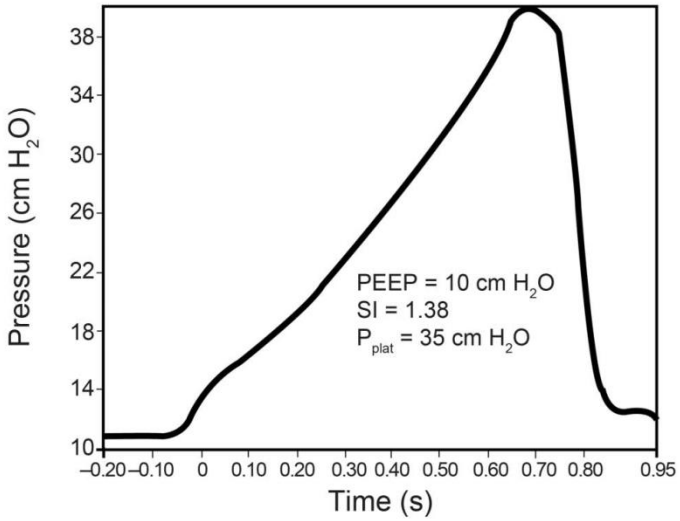
- Stress index = 1: linear increase in pressure (constant compliance)
- Stress index > 1: compliance worsens as the lungs inflated, suggests over-distension >> recommendation: decrease PEEP
- Stress index < 1: compliance improved as the lungs inflated, suggests tidal recruitment/potential for additional recruitment > recommendation: increase PEEP

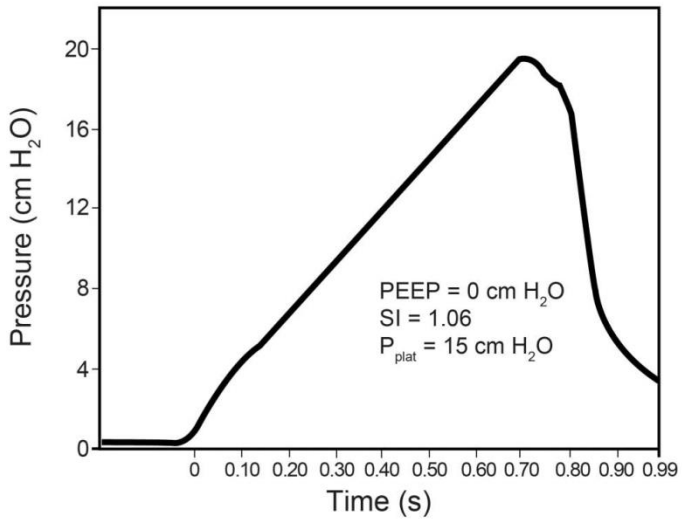
Am J Respir Crit Care Med 2007;176(8):761-767

Application of Stress Index









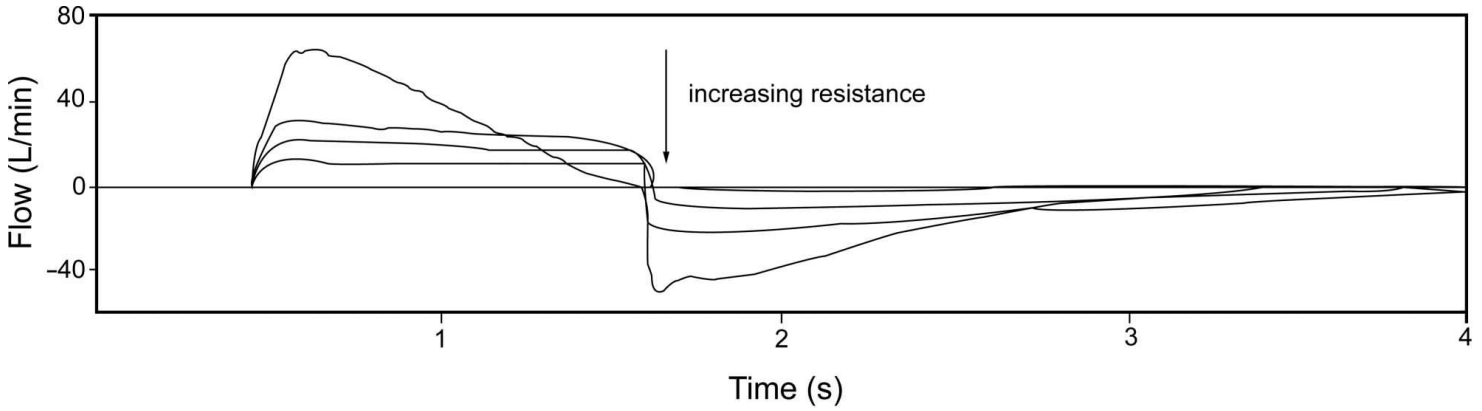
Respir Care 2011; 56(10):1555-1572

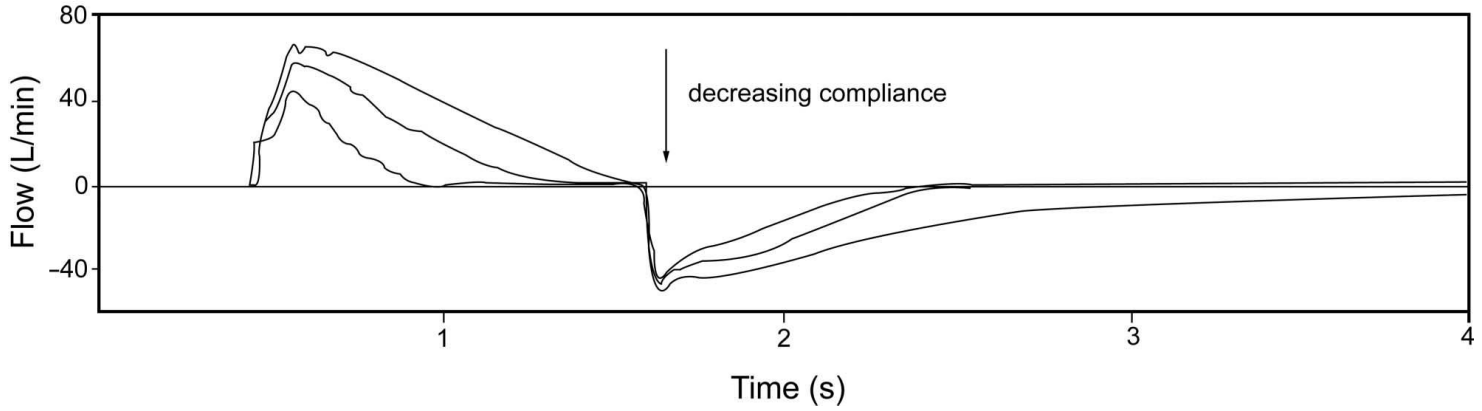
Flow and Volume

- **Inspiratory Flow**
- **Expiratory Flow**
- **Tidal Volume**
- **End-Expiratory Lung Volume**
- **Time Constant**

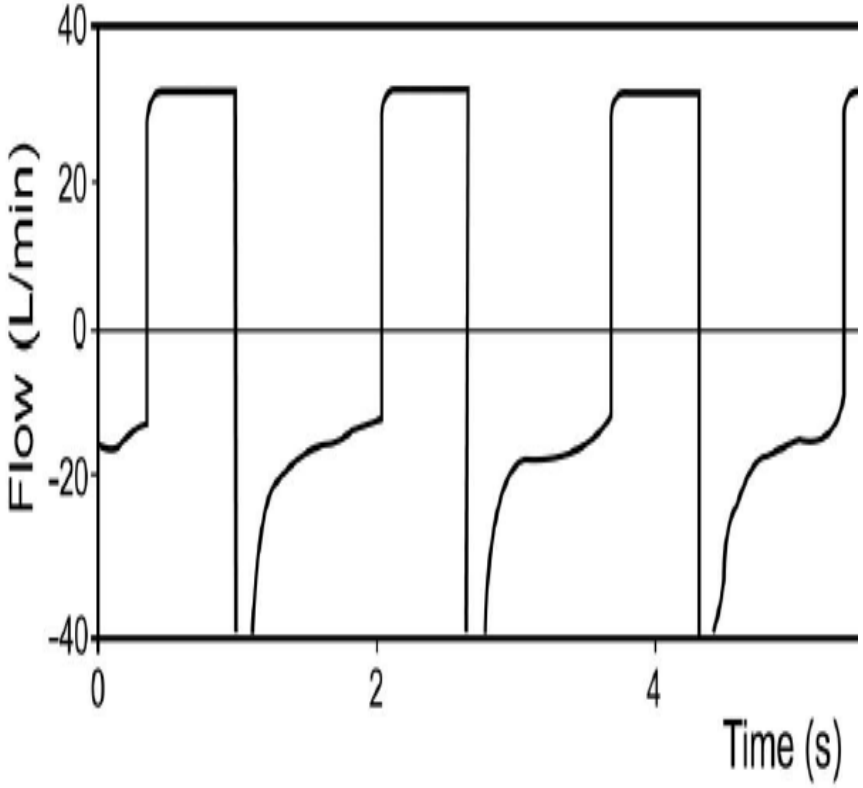
Inspiratory Flow / Expiratory Flow

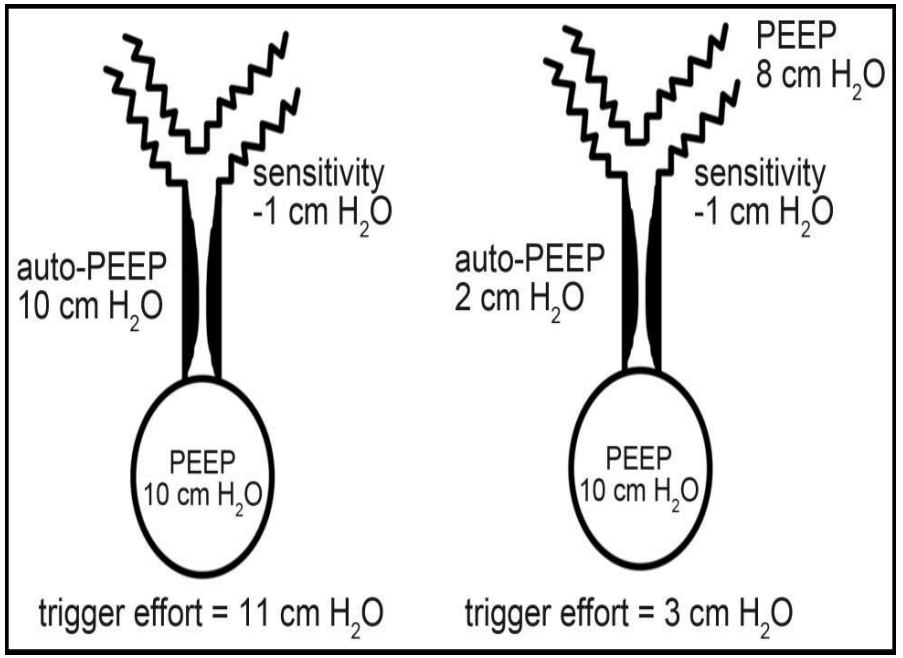
- During pressure control ventilation
  - Insp. flow: $\dot{V}_I = (\Delta P/R_{aw}) \times e^{-t/\tau}$
  - Exp. flow: $\dot{V} = -(P_{alv}/R_{aw}) \times e^{-t/\tau}$



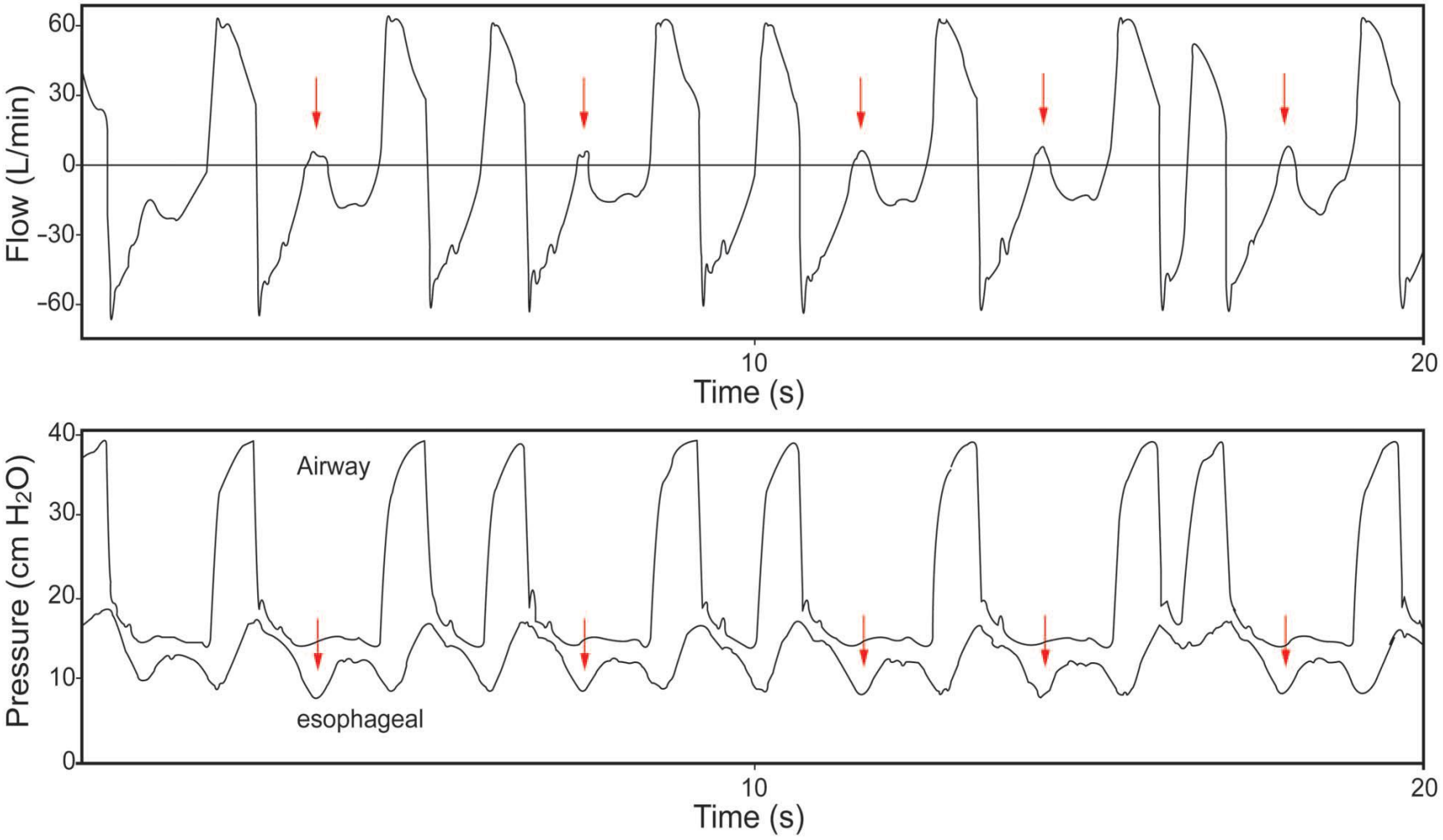


Detect auto-PEEP by Expiratory flow



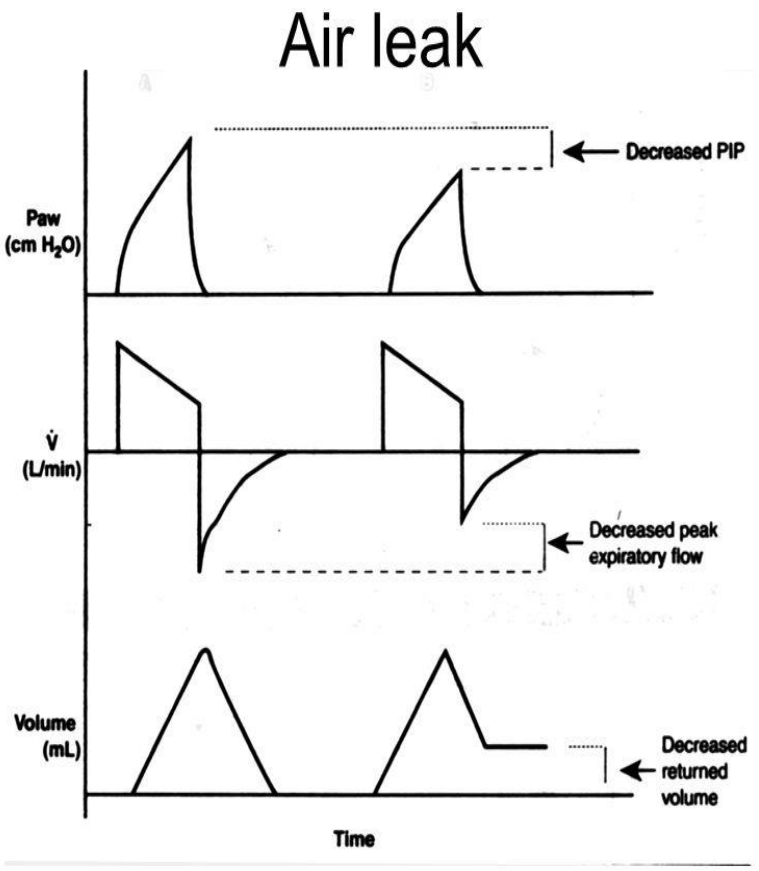


Patient with severe COPD



Tidal Volume

- Modern critical care ventilator
  - Not measure volume directly, but derived this from integration of flow
  - Correct volume for circuit compression
  - The volume waveform
    - Detect the presence of a ***leak*** or ***trapping***



Time Constant (τ)

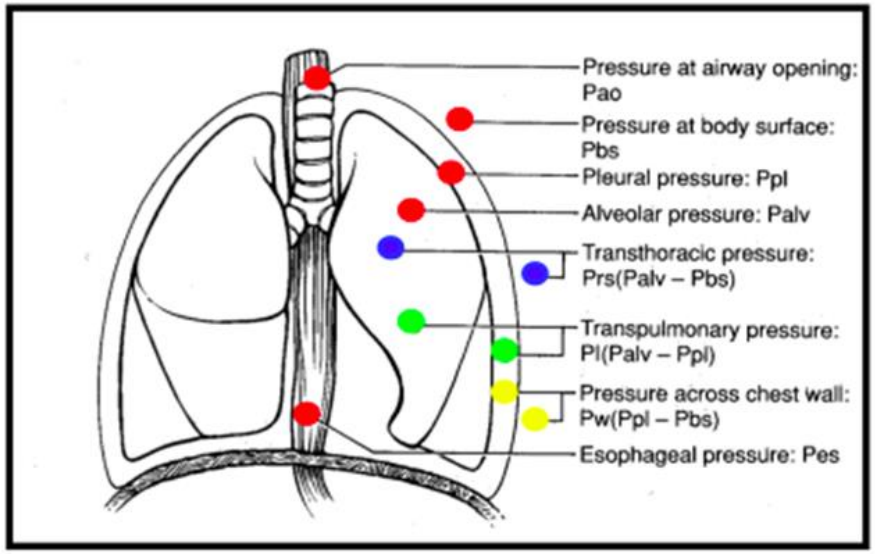
- The **rate of change** in the **volume** of a **lung unit** that is **passively** inflated or deflated

* $$V_t = V_i \times e^{-t/\tau}$$
  - Vt is the volume of a lung unit at time t,
  - Vi is the initial volume of the lung unit,
  - e is the base of the natural logarithm,
  - **τ is the time constant = Resistance x Compliance**
    - 63% volume change in 1 *T*, – 87% volume change in 2 *T*
    - 95% volume change in 3 *T*, – 98% volume change in 4 *T*
    - 99% volume change in 5 *T*

* $\tau_E = \text{exhaled } V_T/\dot{V}_{EXH}$

Derived Measurements

- Respiratory System Compliance
- Chest-Wall Compliance
- Lung Compliance
- Airway Resistance
- Work of Breathing



Respiratory System Compliance

- Crs = $\Delta V/\Delta P$ = Vt/(Pplat – PEEP)
  - Normal range (MV): 50-100 mL/cm H2O
- Determined by the compliance of
  - Lungs
  - Chest wall
- Used to determined the optimal level of PEEP
  - The highest level of Crs corresponds to best PEEP
  - The optimal PEEP results in the lowest driving pressure (Pplat-PEEP) with constant Vt

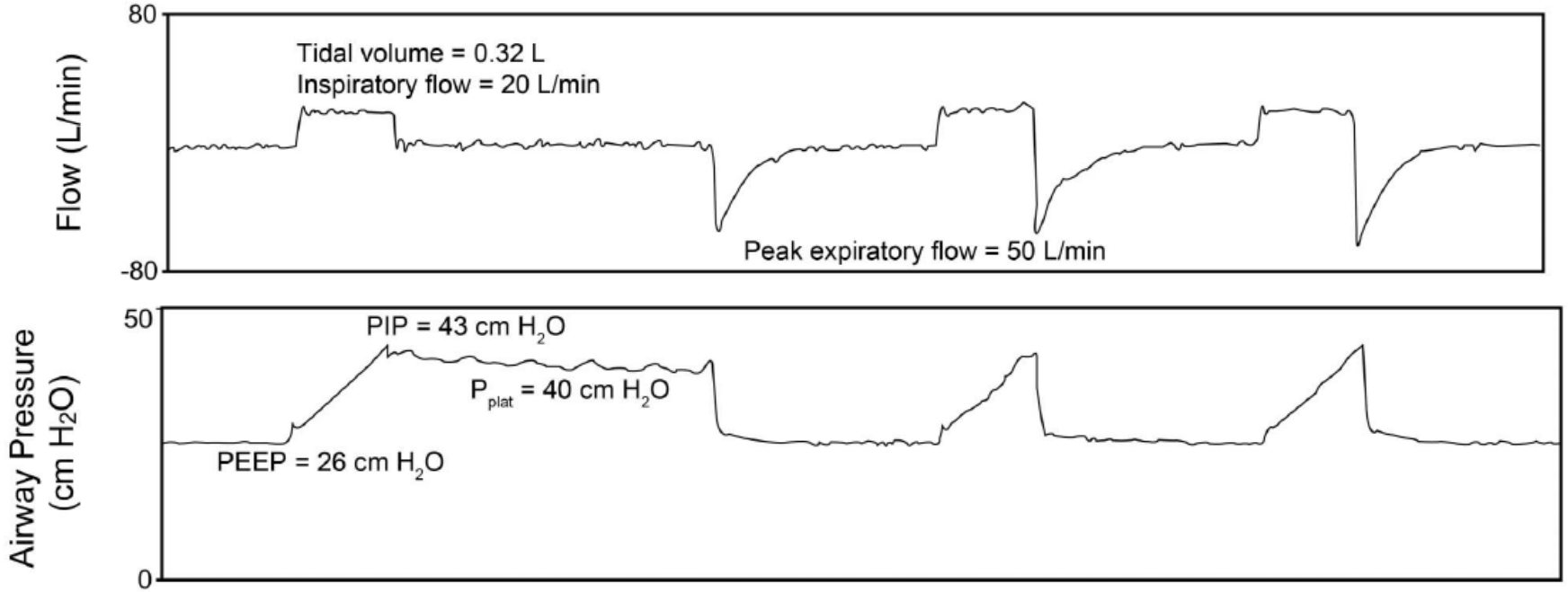
Chest Wall/Lung Compliance

- Ccw = $\Delta V/\Delta P$ = Vt/ ΔPes (Ppl)
  - Normal: 200 mL/cm H2O
  - Decreased with obesity
- $C_L = \Delta V/\Delta P$ = Vt/ ΔP_L
  - Normal: 200 mL/cm H2O
  - Decreased with pul. edema, consolidation….
  - Increased with emphysema

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

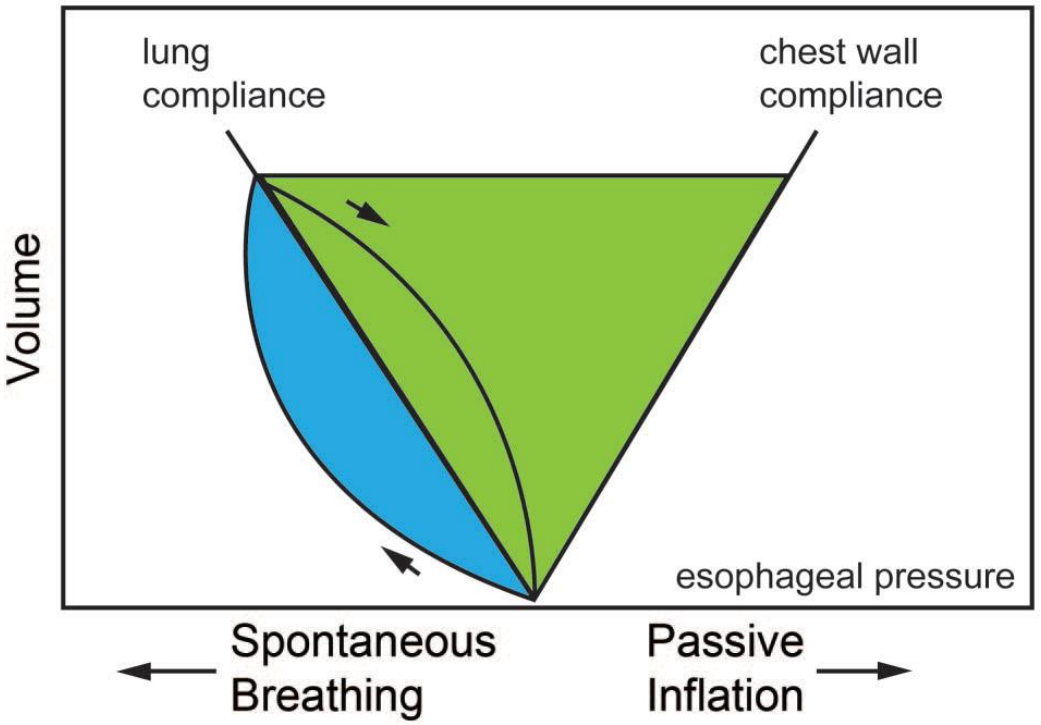
Airway Resistance

- Ri = (PIP-Pplat)/ $\dot{V}_I$
  - For intubation and MV patient: < 10 cm H2O/L/s
- Re = (Pplat-PEEP)/ $\dot{V}_{EXH}$
  - Greater then Ri



Work of Breathing (WOB)

- WOB = $\int P \times V$
  - affected by Ccw, C_L, Raw
- Normal: 0.3-0.7 J/L
  - 4-8 J/min
  - <10 J/min (weaned)
- Campbell diagram:
  - The green area : elastic WOB
  - The blue area : resistive WOB
  - The total shaded area: total WOB

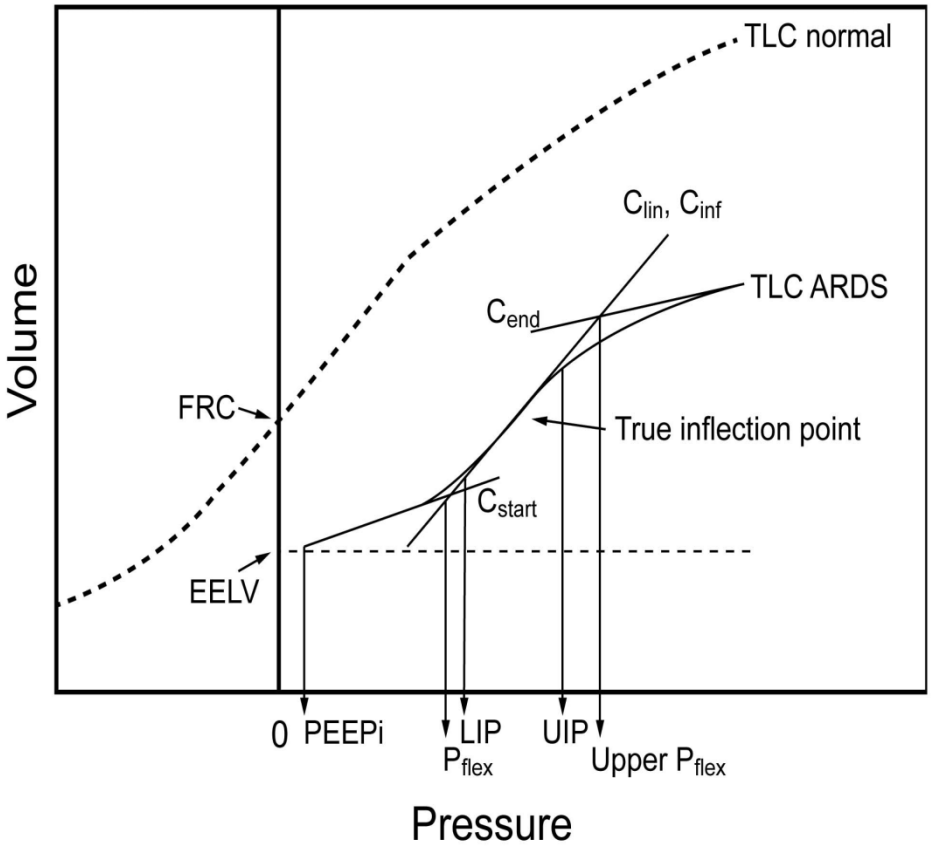


Others

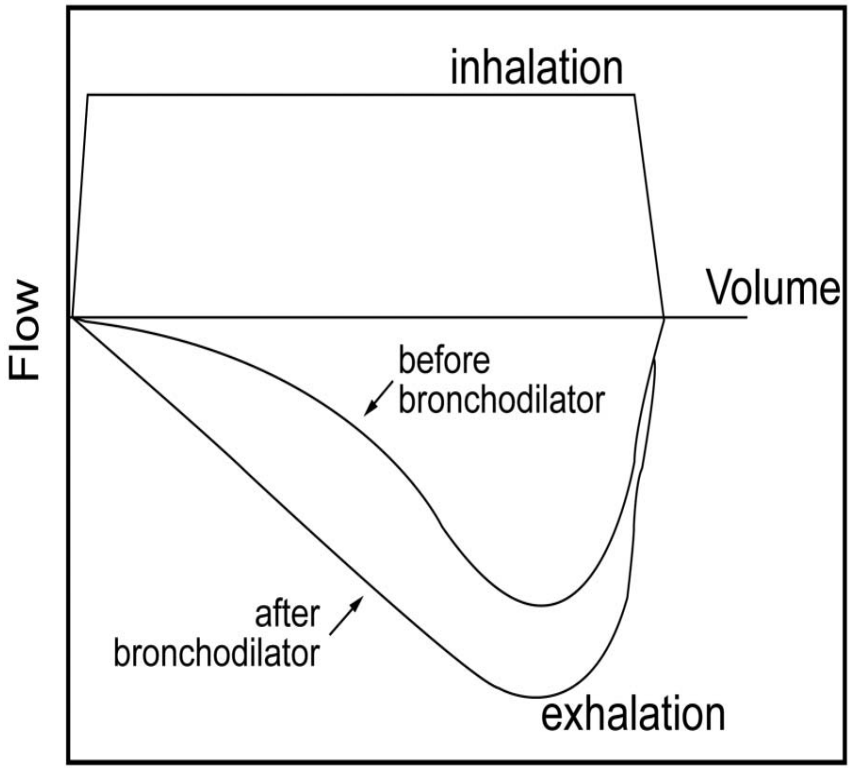
- Pressure-Volume Curves
- Flow-Volume Loops
- Tension-Time Index
- Pressure-Time Product
- Stress and Strain

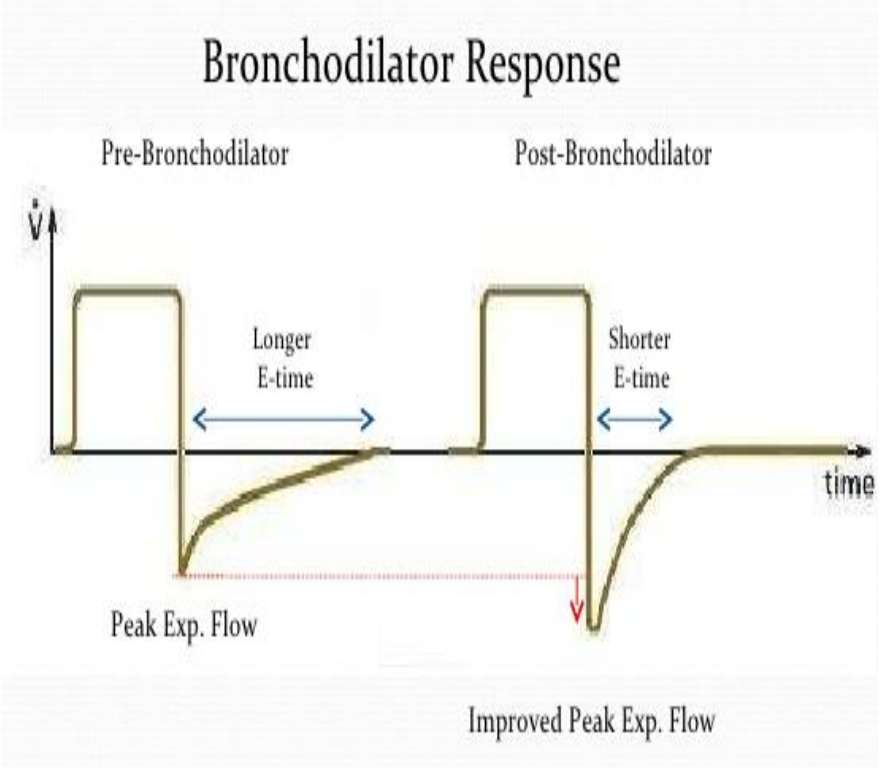
Pressure-Volume Curves

- P-V curve: volume as function of pressure
- The slope of P-V curve: Crs
- Super syringe method:
  - Inflation with a constant flow (< 10 L/min)
  - Pplat at various inflation volumes
- Ventilator with PV tools
- Setting PEEP based on inflection points



Flow-Volume Loops
: flow as a function of volume



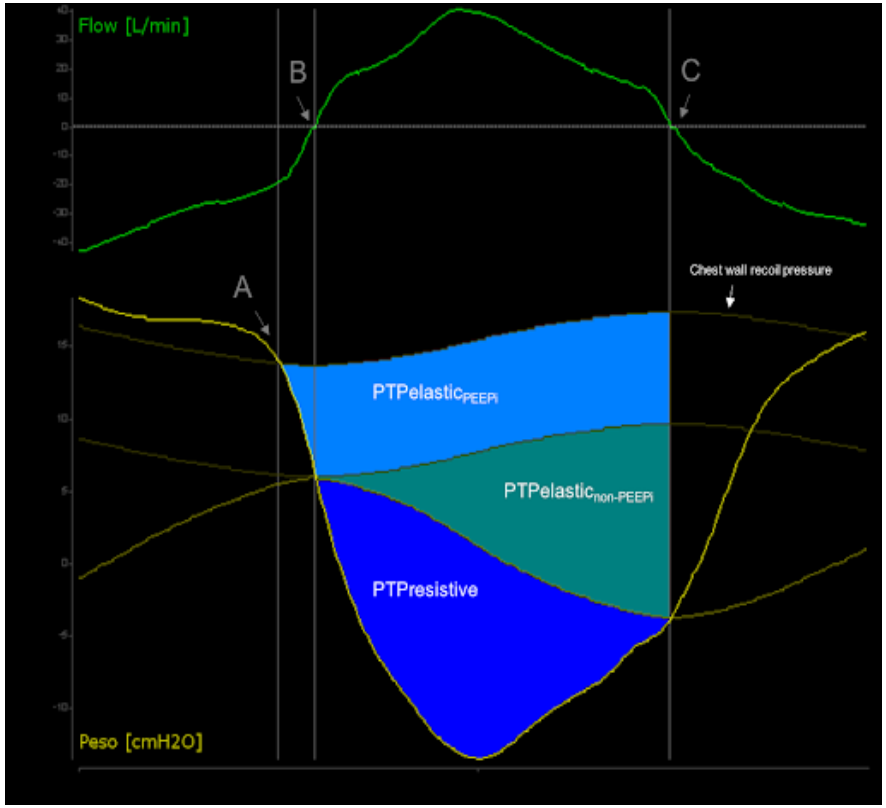


Tension-Time Index (TTI)

- TTI
  = (Pdi/Pdimax) X (Ti/Ttot)
  - (Contractile force of the diaphragm) X (the contraction duration)
- > 0.15: Predict diaphragmatic fatigue
- Requires esophageal and gastric pressure measurement > clinically, replaced by
  - Pressure time Index (PTI)
    = (Pbreath/PImax) X (TI/Ttot)

Pressure-Time Product (PTP)

- PTP:
  Quantify patient's effort
- account for energy expenditures during the **dynamic** and **isometric** phase of respiration
- As the time integral of the difference between the **Pes tracing** and the **chest wall recoil pressure**
- Normal: 120 cmH2O.sec/min
  - < 125 for weaning



Stress and Strain

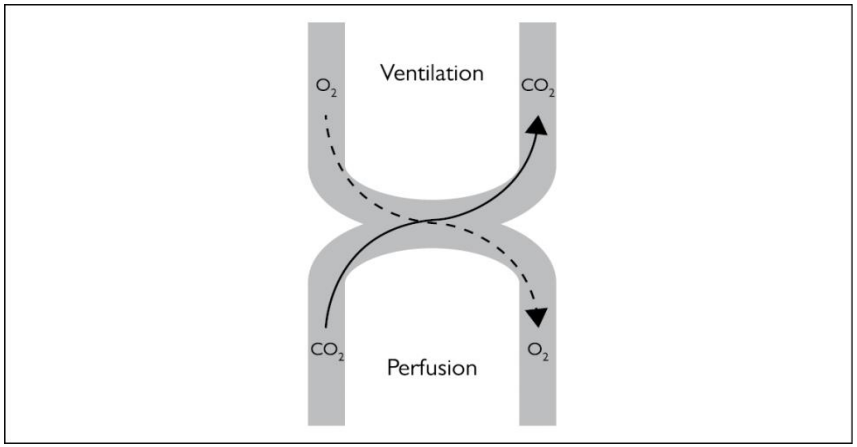
- Stress: a force applied to an area
  - such as pressure applied to the lung parenchyma
  - force applied at an angle generates shear stress
- Strain: the physical deformation or change in shape of a structure
  - such as an alveolus, usually caused by stress
- PL (stress)
  = specific lung elastance (13.5) X ΔV/FRC (strain)
  - ΔV: the change in lung volume above FRC with the addition of PEEP & VT
- A harmful threshold of strain is > 2
- The harmful threshold of stress (PL) is 27 cm H2O

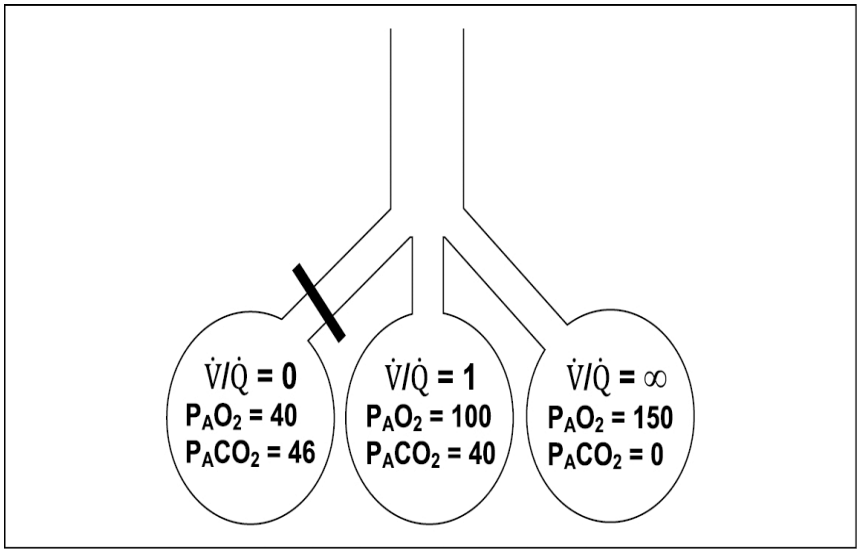
Gas Exchange

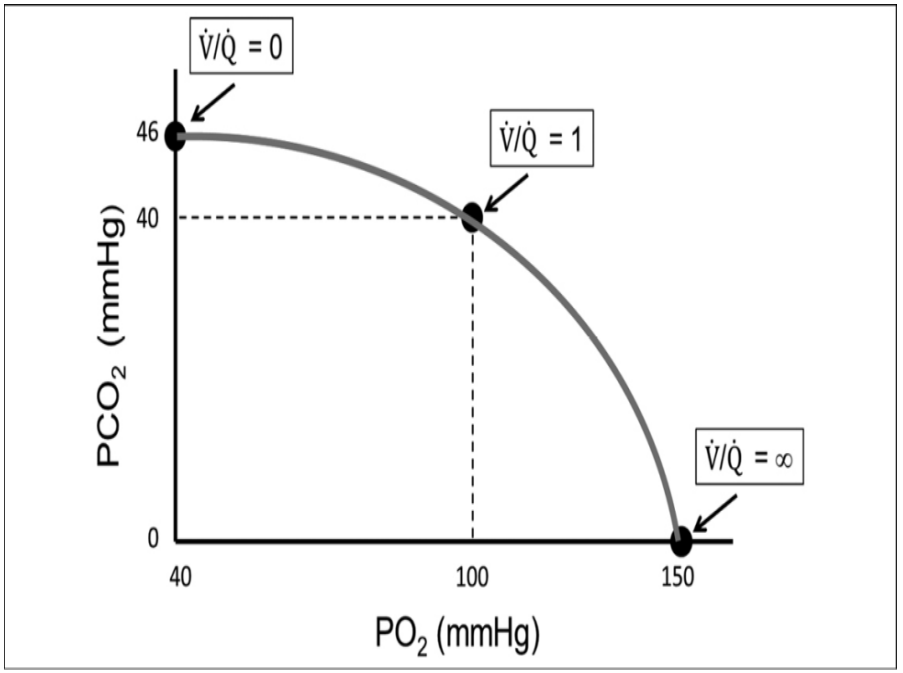
The components of normal gas exchange

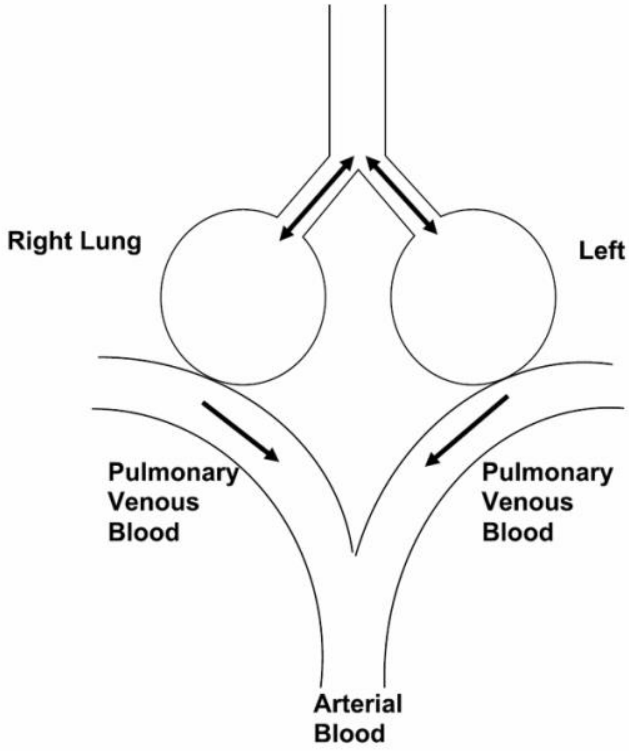
- Delivery of oxygen
- Excretion of carbon dioxide
- Matching of ventilation and perfusion
- Gas diffusion

Matching of Ventilation and Perfusion

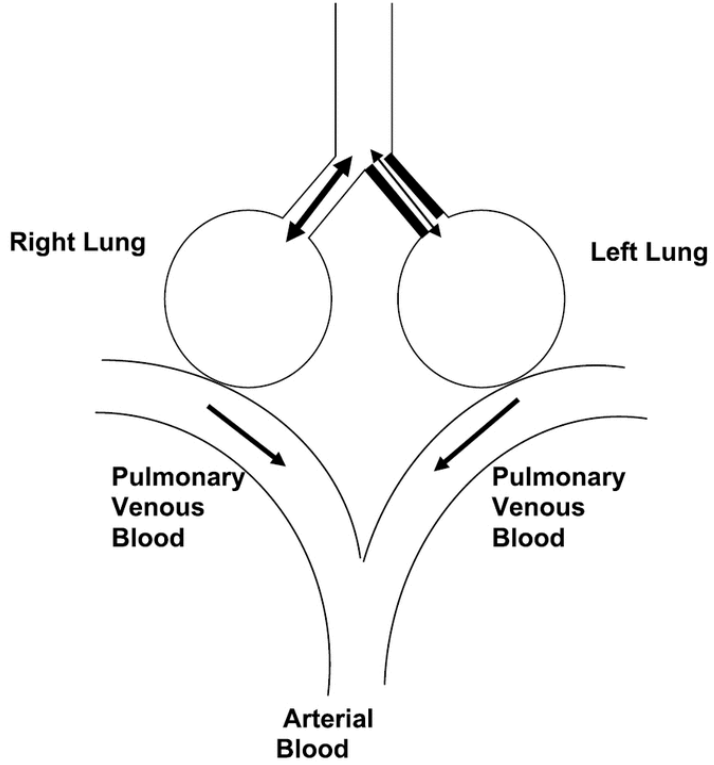






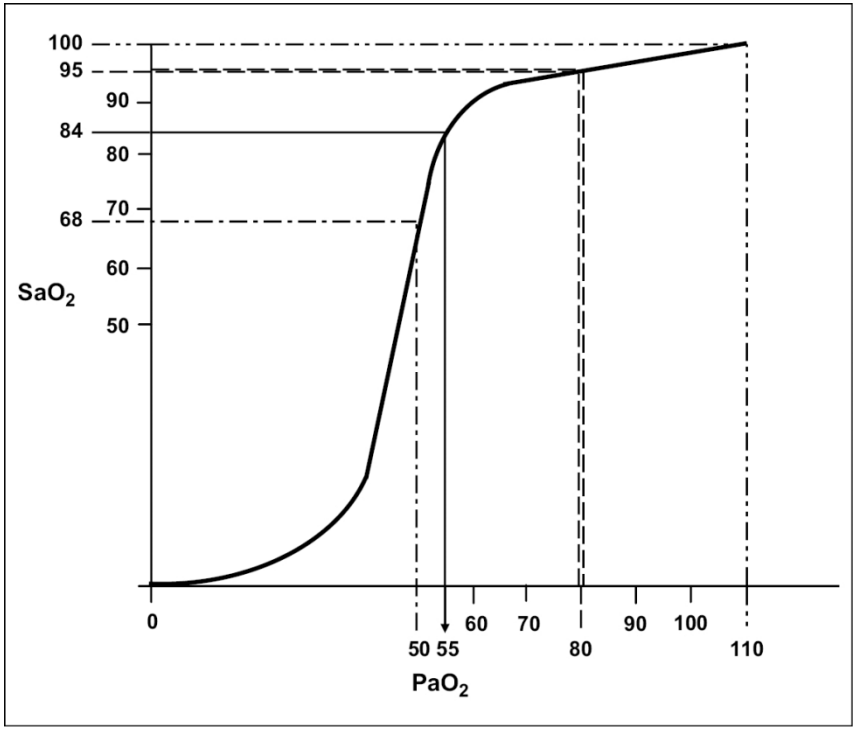


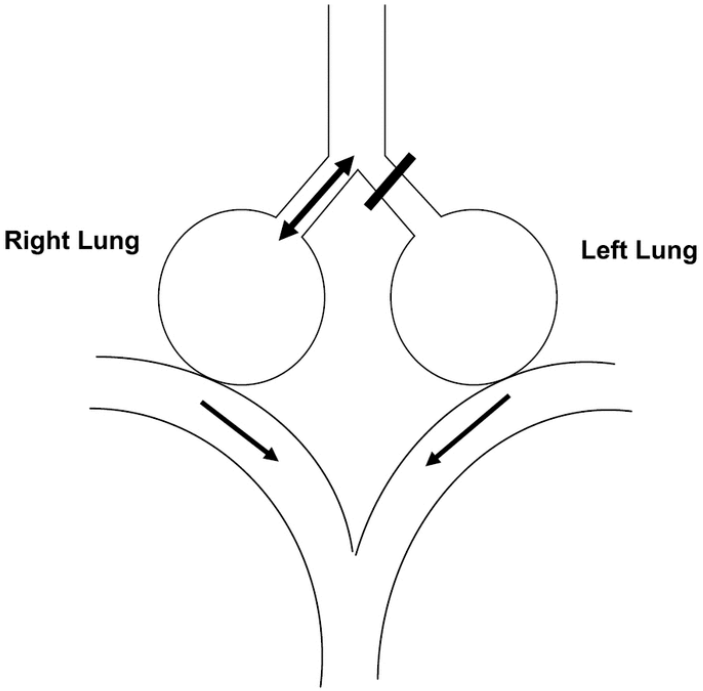
	Right Lung	Left Lung	R + L
Ventilation (L/min)	4.0	4.0	8.0
Perfusion (L/min)	4.0	4.0	8.0
$\dot{V}/\dot{Q}$	1.0	1.0	
P_AO_2 (mmHg)	100	100	100
P_ACO_2 (mmHg)	40	40	40
P_VO_2 (mmHg)	100	100	
P_VCO_2 (mmHg)	40	40	
S_VO_2 (%)	98	98	
C_VO_2 (ml/dl)	18.4	18.4	
CaO_2 (ml/dl)			18.4
SaO_2 (%)			98
PaO_2 (mmHg)			100
$PaCO_2$ (mmHg)			40
A-a gradient			0



	Right Lung	Left Lung	R + L
Ventilation (L/min)	6.0	2.0	8.0
Perfusion (L/min)	4.0	4.0	8.0
$\dot{V}/\dot{Q}$	1.5	0.5	
P_AO_2 (mmHg)	120	50	102.5
P_ACO_2 (mmHg)	36	44	38
P_VO_2 (mmHg)	120	50	
P_VCO_2 (mmHg)	36	44	
S_VO_2 (%)	100	80	
C_VO_2 (ml/dl)	18.8	15.0	
CaO_2 (ml/dl)			16.9
SaO_2 (%)			90
PaO_2 (mmHg)			60
$PaCO_2$ (mmHg)			41
A-a gradient			42.5

Why shunt responds poorly to oxygen therapy ?



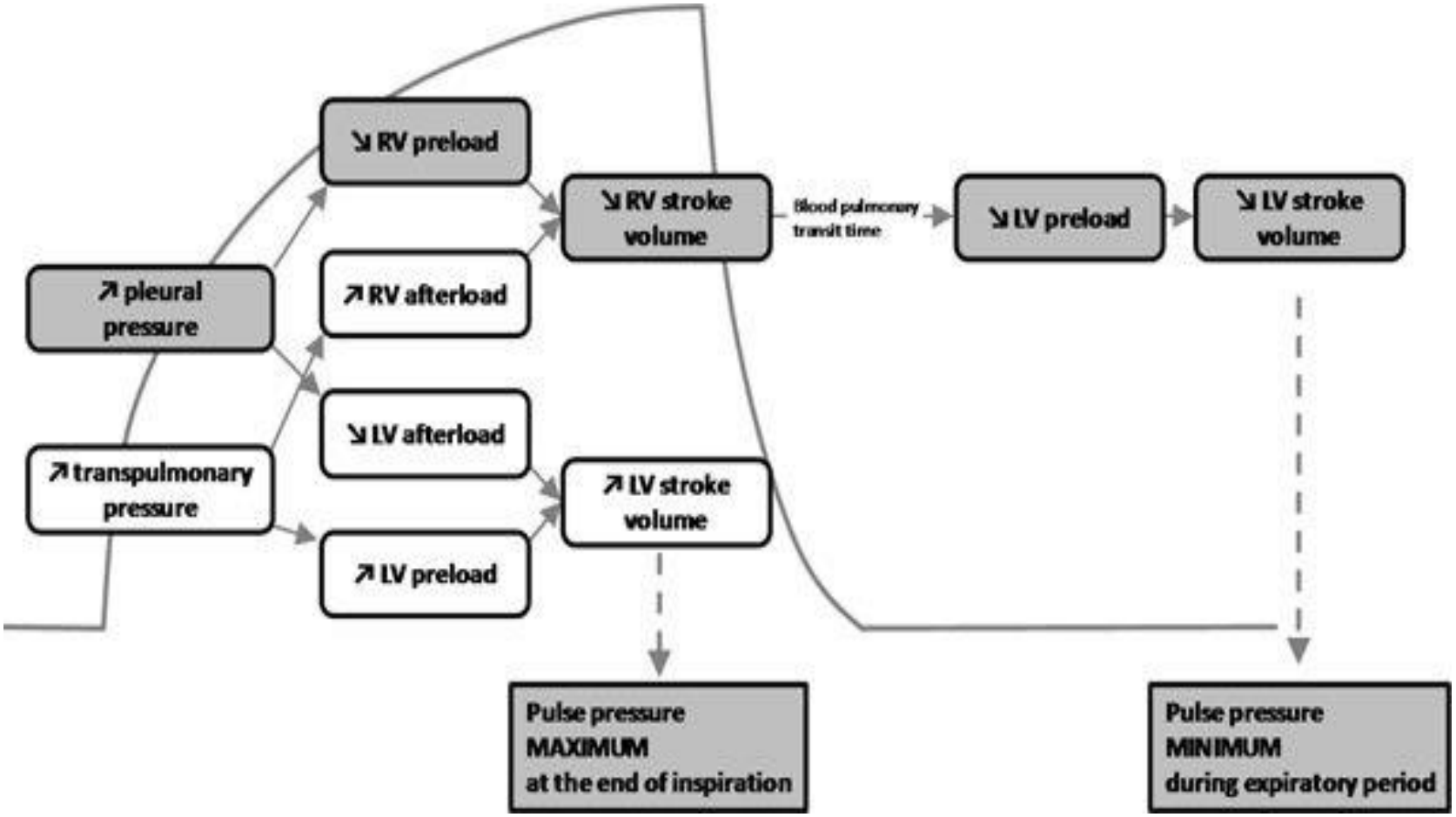


	Right Lung	Left Lung	R + L
Ventilation (L/min)	8.0	0	8.0
Perfusion (L/min)	4.0	4.0	8.0
$\dot{V}/\dot{Q}$	2.0	0	
P_AO_2 (mmHg)	125	40	
P_ACO_2 (mmHg)	34	46	
P_VO_2 (mmHg)	125	40	
P_VCO_2 (mmHg)	34	46	
S_VO_2 (%)	100	60	
C_VO_2 (ml/dl)	18.8	11.2	
CaO_2 (ml/dl)			15.0
SaO_2 (%)			80
PaO_2 (mmHg)			48
$PaCO_2$ (mmHg)			42

Cardiovascular-Pulmonary Interactions

The interaction between positive pressure ventilation and
its effects on right and left ventricular pre- and afterload and ventricular interdependence

Haemodynamic effects of PPV



Annals of intensive Care 2011;1(1):1

Summary

- Be familiar with the factors (MV setting, resp. mechanics, and effort) affecting pressure/ flow/ volumes and related waveforms
- Measurement & management of auto-PEEP
- Using basic (P/F/V) and derived (compliance, resistance, SI, WOB, TTI, PTP..) parameters to evaluate mechanical ventilated patients
- Determined the cause of hypoxemia (V? Q?)
- Keep in mind the heart-lung interaction,
  esp. in severe heart failure with acute pulmonary edema
- Look at the ventilator monitor and patient simultaneously !
  - Numbers and Waveforms