Physiology and **Setting** of **Mechanical Ventilation**

115年機械通氣繼續教育課程(北區)
2026/08/16 1020-1110
新店耕莘醫院重症醫學部
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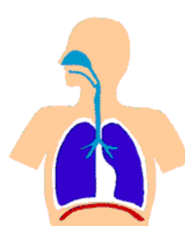
1

Respiratory Physiology (Mechanics) of Mechanical Ventilation



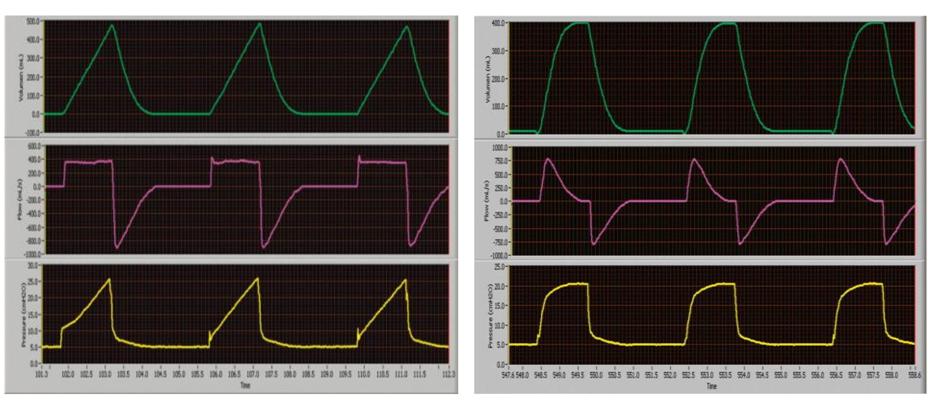
2

Respiratory Mechanics

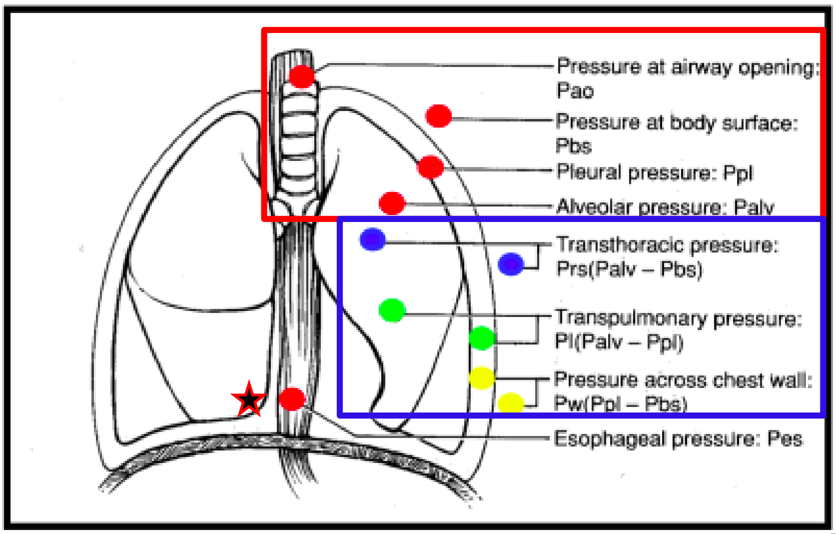
- The expression of **lung function** through measures of **Volume**, **Flow**, and **Pressure**
- Derived indices
  - Compliance (Volume/Pressure)
  - Resistance (Pressure/Flow)
  - Work Of Breathing (WOB) (Flow x Pressure)
- Wave form: one of the parameters
  - plotted as function of **Time** (*trend,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

Volume-Controlled *vs.* ***Pressure-Controlled*** *Continuous Mandatory Ventilation*

(縱軸自上而下： Volume – Flow – Pressure ； 橫軸均為 Time)



Pressure .....



5

Airway Pressure

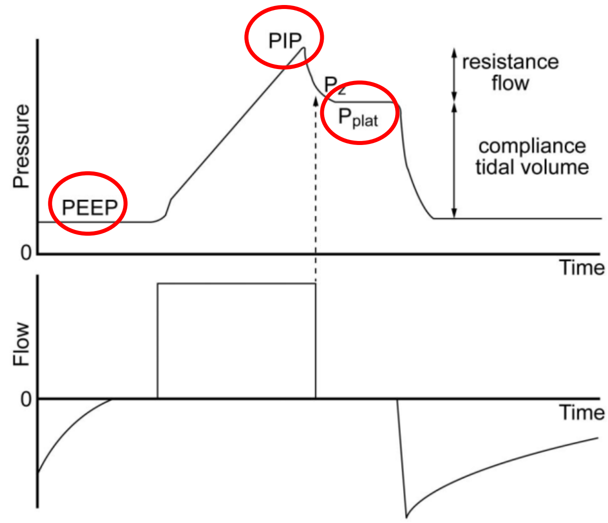
- The shape of the airway pressure waveform
  - flow and tidal volume (V_T) *from the ventilator*
  - lung mechanics *of the patient*
  - active breathing efforts *of the patient*
- **Equation of Motion**

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

Respir Care 2014;59(11):1773–1794

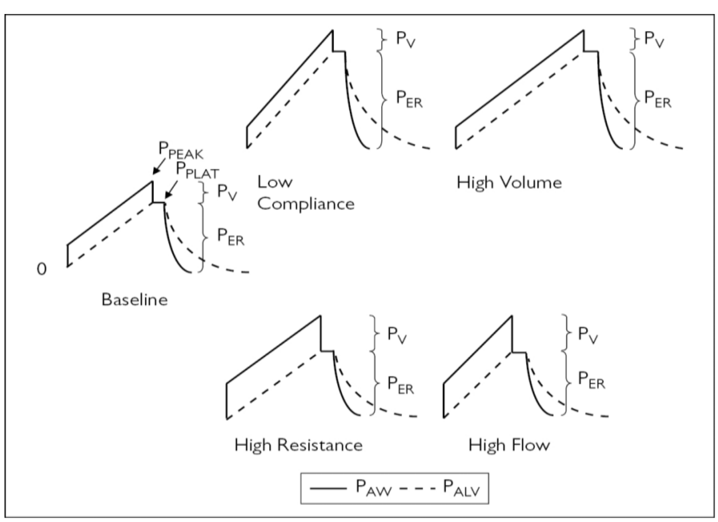
6

Airway pressure and **flow** waveforms
during constant flow volume control ventilation
(effect of an end inspiratory breath-hold: 0.5-2s)



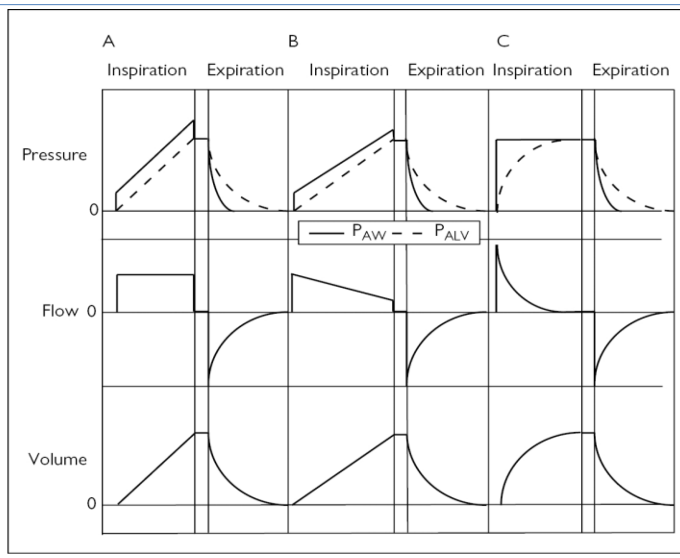
7

The effect of changes in **Compliance**, **Volume**, **Resistance**, and **Flow** on the pressures



Oxford medicine online. Mechanical Ventilation: physiology and practice (2 ed.) 2017

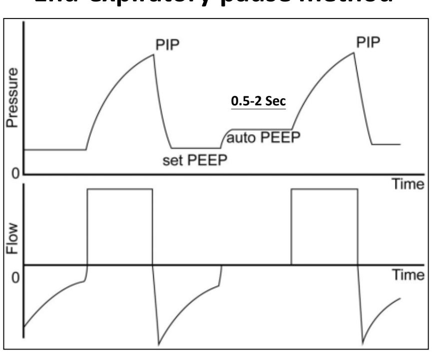
The effect of changes in ***flow profiles*** on the pressures and volume



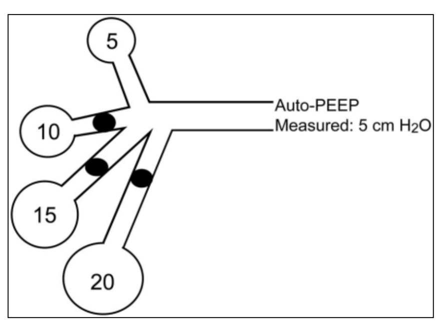
9

Auto-PEEP measurement - 1

*** End-expiratory pause method**



*** The underestimated auto-PEEP**

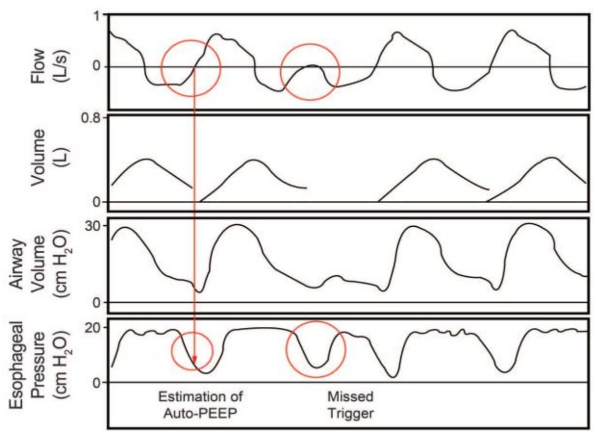


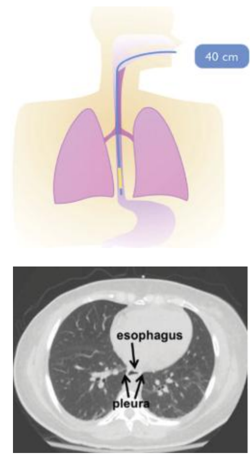
- Incomplete emptying of the lungs (air trapping) at the end of expiration
- Also called "*intrinsic PEEP*", "*PEEPi*", or "*occult PEEP*"

10

Auto-PEEP measurement -2

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





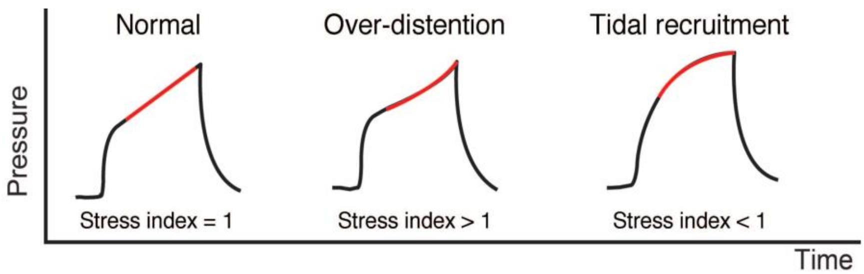
Auto-PEEP is a function of ***ventilator settings*** and ***lung function***

↑ **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)

Stress Index: $P = a \times T_I^{b} + c$



* 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

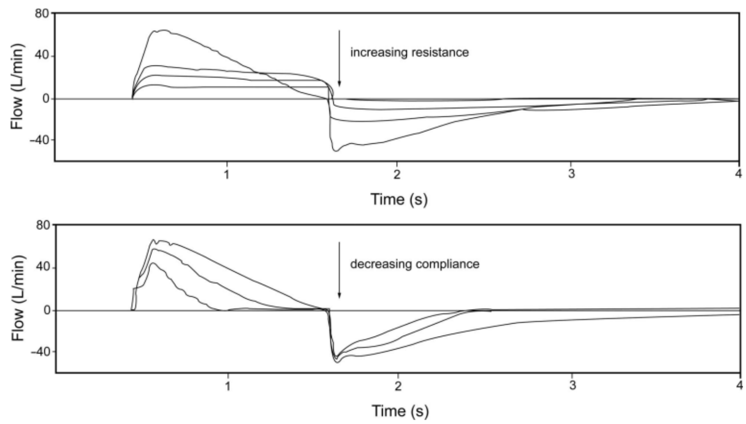
AJRCCM 2007;176(8):761-767

Flow and Volume

- **Inspiratory Flow**
- **Expiratory Flow**

Inspiratory Flow / Expiratory Flow

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



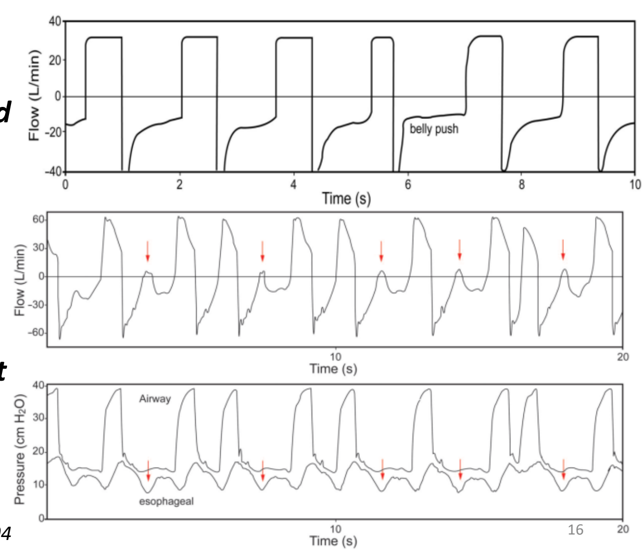
15

Expiratory flow

End-expiratory flow while autoPEEP existed

Notching

= Missed trigger effort

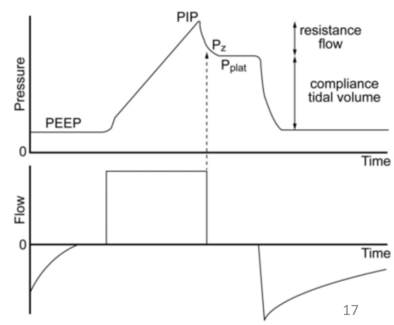


Respir Care 2014;59(11):1773–1794

16

Derived Measurements

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



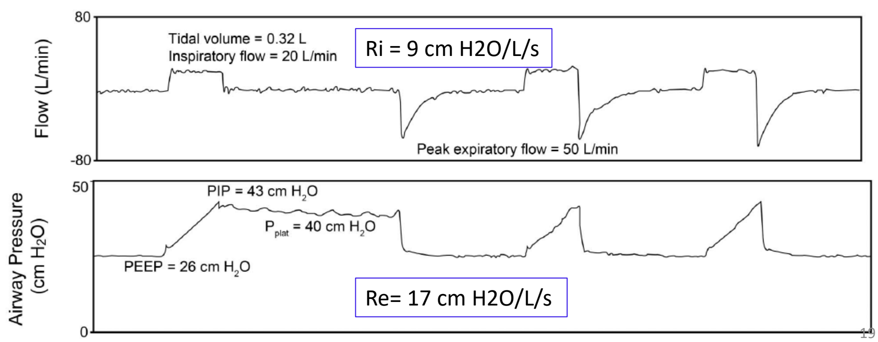
Respiratory System Compliance

- Crs = ΔV/ΔP = Vt/(Pplat – PEEP)
  - Normal range (in MV): 50-100 mL/cm H2O
- Determined by the compliance of
  - Lungs: ΔV/ΔP = Vt/ ΔP_L (N: 200 mL/cm H2O)
  - Chest wall: ΔV/ΔP = Vt/ ΔPes (Ppl) (N: 200 mL/cm H2O)
  - $1/C_{RS} = 1/C_{CW} + 1/C_L$
- 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 (ΔP = Vt/Crs) with constant Vt

N Engl J Med 2015; 372:747-755
N Engl J Med 2008;359:2095-104

Airway Resistance

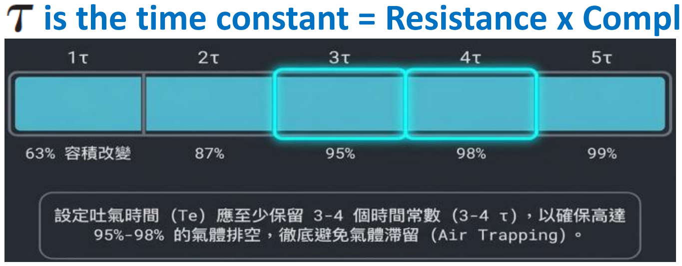
- Ri = (PIP-Pplat)/ $\dot{V}_I$
  - For intubation and MV patient: < 10 cm H2O/L/s
- Re = (Pplat-PEEP)/ $\dot{V}_{EXH}$
  - Greater then Ri



Time Constant (τ)

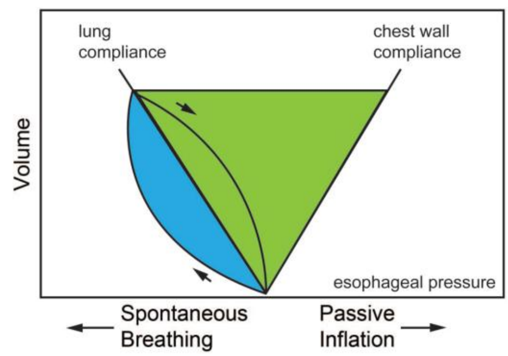
- The **rate of change** in the **volume** of a lung unit that is **passively** inflated or deflated

* $$V_t = V_i \times e^{-t/\tau}$$
  - 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**



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

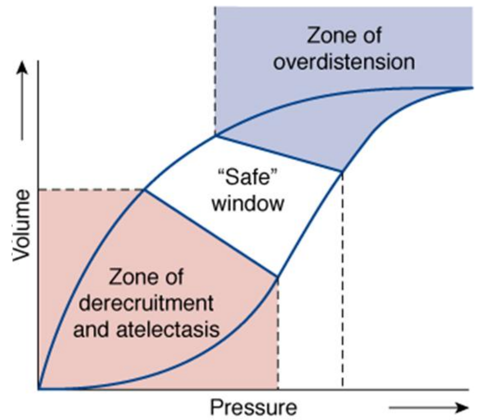


Others

- **Pressure-Volume Curves**
- **Flow-Volume Loops**
- **Stress and Strain**

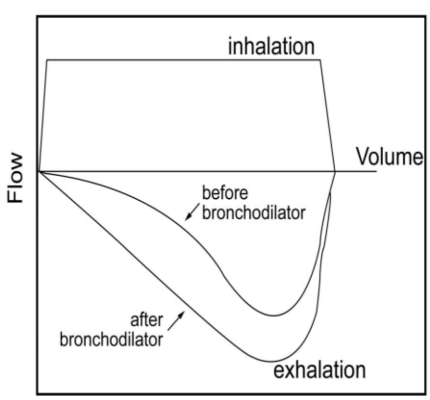
Pressure-Volume Curves

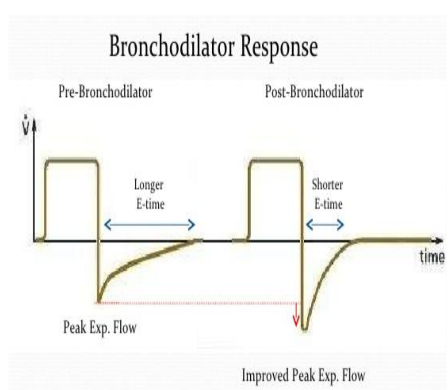
- P-V curve:
  - **Volume** as function of **Pressure**
- Measurements
  - Super syringe method:
    - Inflation with a constant flow (< 10 L/min)
  - Ventilator with PV tools
- The slope of P-V curve: Crs
- PEEP Setting
- Concept of Stress Index



Source: Tobin MJ: *Principles and Practice of Mechanical Ventilation, 3rd Edition:* www.accessanesthesiology.com

Flow-Volume Loops
: **Flow** as a function of **Volume**



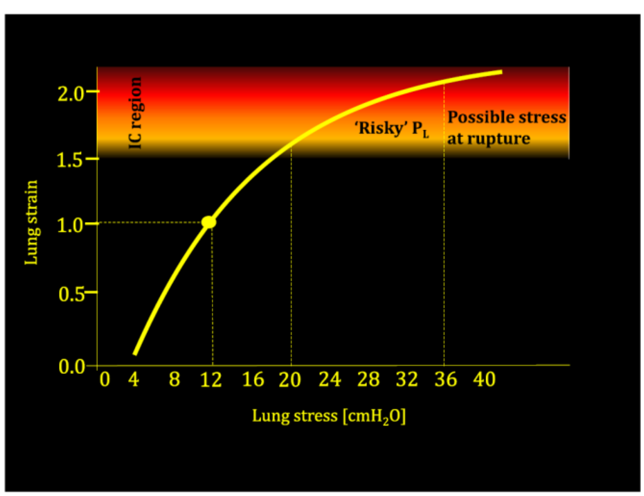


Stress and Strain

- **Stress**: a force applied to an area
  - 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 (alveolus, usually caused by stress)
- Transpulmonary pressure (stress) = specific lung elastance X ΔV/FRC (strain)
  - ΔV: the change in lung volume above FRC with the addition of PEEP & VT
- $Stress = E_{Lspec} \cdot Strain$
- $Barotrauma = k \cdot Volutrauma$

Critical Care (2017) 21:183

Lung strain (tidal volume/FRC) as a function of lung stress (transpulmonary pressure)



Critical Care (2017) 21:183

Setting of Mechanical Ventilation

Oxygenation | Ventilation

- *Pilbeam's Mechanical Ventialtion 6th edit; Chap 6*
- *Uptodate*
- *Intensive Care Med (2026) 52:104–117*

The primary goal of IMV

Goal 1: Support
Support adequate gas exchange.

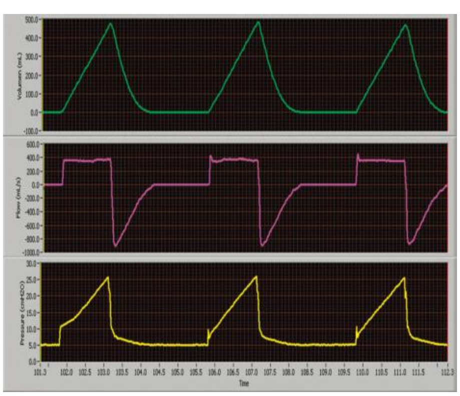
Goal 2: Offset
Offset the extra-workload of respiratory muscles to meet ventilatory demands.

Goal 3: Protect
Protect the lung from VILI and Patient Self-Inflicted Lung Injury (PSILI).
- Limiting excess stress and strain
- Maintaining lung homogeneity

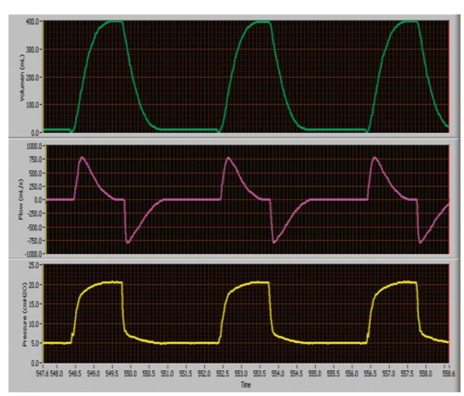
Start from mode

Volume-Controlled *vs.* ***Pressure-Controlled*** *Continuous Mandatory Ventilation*

(縱軸自上而下： Volume – Flow – Pressure ； 橫軸均為 Time)



Guaranteed volume; **Pressure varies** based on compliance, resistance, setting



Guaranteed pressure; **Volume varies** based on compliance, resistance, setting

Initial settings

Volume Control	Pressure Control
Minute Ventilation (Ve) = Tidal Volume (V_T) X Respiratory Rate (RR)	
FiO2	
PEEP	
Trigger sensitivity	

Initial settings

Volume Control	Pressure Control
Tidal Volume (V_T) and Inspiratory Flow ($\dot{V}$)	Pressure control (PC) and Inspiratory time (Ti or I_{Time})
Respiratory Rate (RR)	
FiO2 - 1.0	
PEEP	
Trigger sensitivity	

Establishing Baseline Minute Ventilation (VE)

Baseline Calculation

Men: VE = 4 × BSA

Women: VE = 3.5 × BSA

Rule of Thumb: Around 100 mL/kg of Ideal Body Weight (IBW)

Physiological Modifiers

Increase VE by:

- 10%/°C above 37°C
- 20% for metabolic acidosis
- 50% to 100% if resting energy expenditure is increased

Stress Factors:
Pneumonia with ARDS: 1.2 to 1.3
Minor surgery: 1.1 to 1.3
Major surgery: 1.2 to 1.4
Multiple trauma: 1.4 to 1.6
Trauma with closed head injury: 1.5 to 1.7

Decrease VE by:

- 10%/°C between 35°C and 37°C

VCV

Tidal Volume (VT)

Principle: Do No Harm.

Setting: 6–8 mL/kg IBW
(± sigh/recruitment maneuver and high PEEP).

Respiratory Frequency (f)

Setting: f = VE / VT

Typically 12 to 18 breaths/min (Maximum ≤ 35) to match baseline VE.

Inspiratory Flow

Setting: Initial peak flow 60 L/min (range 40 to 80 L/min).

Deliver inspiration in ~1 sec (0.8 - 1.2 sec). Flow must meet patient demand.

I:E Ratio

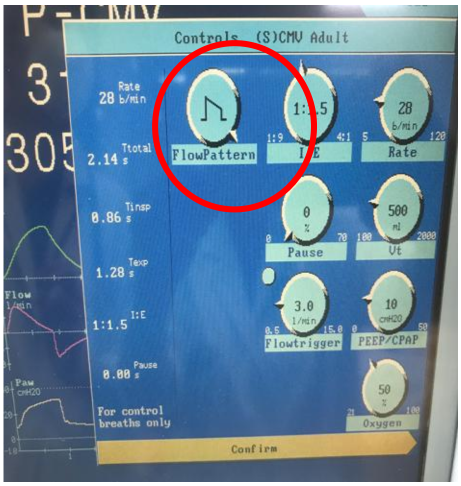
Setting: 1:2 or less (usually about 1:4).

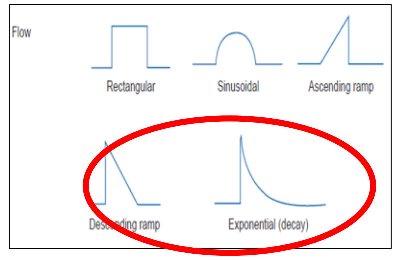
Expiratory time (Te) must allow 3-4 time constants to avoid air trapping.

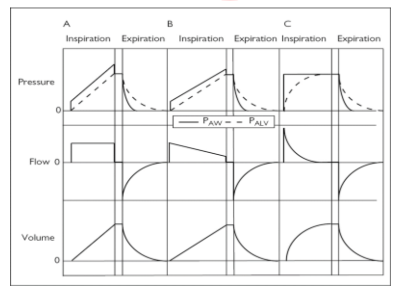
Inspiratory Pause

Setting: Usually zero (inflation hold).

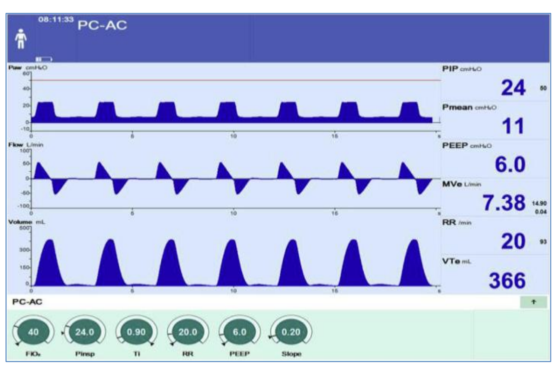
Inspiratory flow and flow pattern







PCV



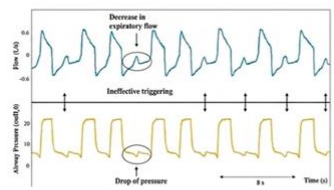
- Set **pressure** to achieve VT as described for VCV
  - ∆P = Pplateau – PEEP, May **start 5-10 cm H2O**
  - Consider Lung volume available, compliance/resistance
- Set frequency to achieve the same VE (f = VE /VT)
- Set **Ti** or **I : E ratio** (dependent on ventilator)
  - **Ti:** 0.8-1.2 sec **> start 1 sec**
  - **I:E ratio** about **1 : 2 to 1:4**

36

Initial PEEP & Triggering

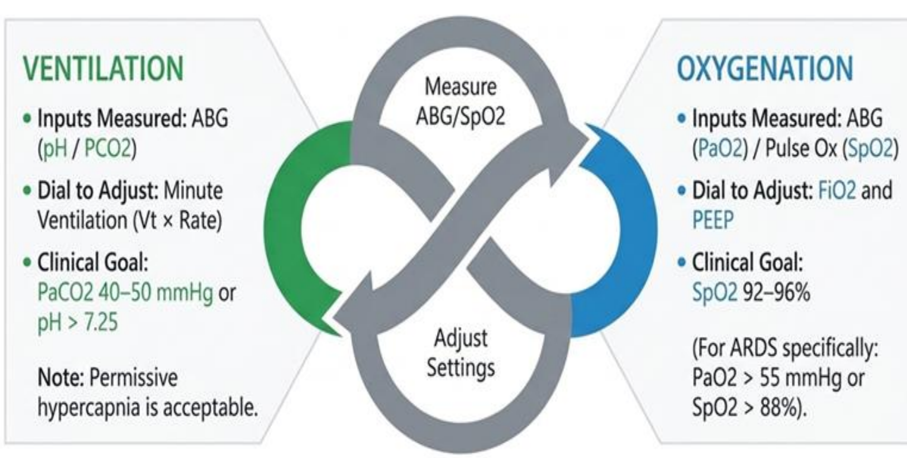
- Initial PEEP setup
  - Start at **5 cm H2O**
  - Adjustment 1: adjust by FiO2 formula: **(FiO2 x 20)±2**
  - Adjustment 2: use PV tool – lower inflection point±2

- Trigger sensitivity setting
  - Flow-triggering: **2 L/min**
  - Pressure-triggering: **-1 to -2 cm H2O**
    - **Warning:** Don't use pressure-triggering if auto-PEEP suspected



37

The Adjustment Feedback Loop



38

Special considerations: ARDS & IICP

Acute Respiratory Distress Syndrome (ARDS)

- **Strategy:** Protective lung strategy (Low Vt and Personalized PEEP). Avoid high PEEP in mild/focal ARDS.
- **Permissive Hypercapnia**: Maintain pH > 7.25. Tolerance of high $PaCO_2$ (≥ 50 mmHg) requires serial assessment of hemodynamics and RV function, as it is independently associated with mortality in moderate-severe ARDS.

Increased Intracranial Pressure (ICP)

- **Strategy:** Prioritize oxygenation and cerebral perfusion.
- **Ventilation target:** $PaCO_2$ targeted tightly to 25–30 mmHg temporarily during acute herniation.
- **PEEP Warning**: Be extremely careful with PEEP use (keep restricted to 5–8 cmH_2O to avoid impairing venous return from the brain).

Special Considerations: COPD & Chronic disease

Obstructive Lung Disease

- **Primary Goal**: Avoid dyssynchrony and dynamic hyperinflation.
- **Key Settings**: Use lower tidal volumes, moderate respiratory rates, and **HIGH INSPIRATORY FLOW RATES** (**70 to 100 L/min**) to allow maximum time for expiration.
- **PEEP**: Apply adequate extrinsic **PEEP** to offset intrinsic PEEP (**iPEEP / Auto-PEEP**). Measure auto-PEEPs using respiratory mechanics.

Chronic Hypercapnic Respiratory Failure

- **Primary Goal:** The clinical goal is strictly to normalize the **pH**, but not the **$PaCO_2$**.
- **Warning**: Do not over-ventilate these patients back to a 'normal' **PCO_2** of **40**.

Advanced Lung Protection: Low Vt

Tidal Volume (Vt)

- Target: 6 (4–8) ml/kg Predicted Body Weight (PBW).
- Strict Target: 4–6 ml/kg PBW if RR & acid-base status allow.

Plateau Pressure (P_{plat})

- Passive ventilation limit: < 30 cmH_2O.
- Exceptions: Obese/abdominal distension (30–35 cmH_2O; consider esophageal manometry). High risk for RV dysfunction (< 26–28 cmH_2O).

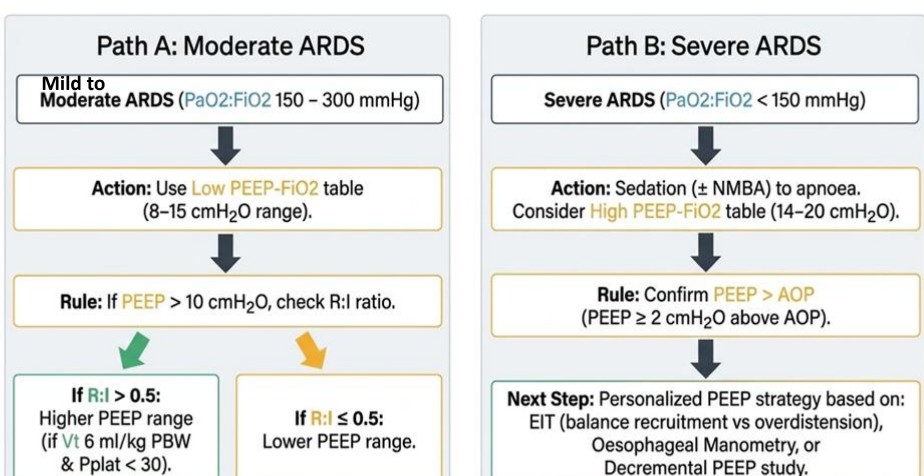
Driving Pressure (ΔP)

- Formula: $\Delta P = P_{plat} - PEEP$. (Predictor of mortality; relates to 'baby lung' concept).
- Limit: Keep < 16 cmH_2O (after PEEP optimization) to avoid high risk of RV dysfunction.

Mechanical Power (MP)

- Target: Lowest value of '4 × ΔP + RR' for a given V_E.
- Concept: Integrates V_t, ΔP, flow, and RR into energy (Joules/min). The energy transferred is responsible for VILI.

The PEEP Optimization Algorithm



* The R/I ratio is the ratio between the compliance of the recruited lung to that of the respiratory system. Values >= 0.5 suggest more potential for lung recruitment

Summary: The Ventilator Setup Checklist

1. **Choose mode:** VCV vs. PCV, based on patient need or your favorite
2. **Set Minute Ventilation:** Establish VE, then define VT, Rate, Flow, IE, and pressure Parameters
3. **Do No Harm:** Enforce advanced lung protection (Pplat < 30, Delta P < 16) to avoid VILI and auto-PEEP
4. **Set FiO2 and PEEP:** Start baseline, assess recruitability (R/I ratio), and follow PEEP algorithms
5. **Follow up with ABGs:** Tune Oxygenation and Ventilation independently based on results
6. **Adjust for Special considerations:** radically adapt strategies for ARDS, IICP, COPD….
7. **Integrated Physiology and waveforms analysis:** fine tune and detecting dyssynchrony