CRITCARE BITES

INTRODUCTION TO MECHANICAL VENTILATION

Clare Fong
Alexandra Hospital, National University Hospital

SICM
Society of Intensive Care Medicine
SINGAPORE

MAD FOR MEDICINE

INDICATIONS FOR MECHANICAL VENTILATION

- Hypoxemic respiratory failure
- Hypercarbic respiratory failure
- Airway protection
- Anticipated clinical deterioration – severe metabolic acidosis, multi organ dysfunction

RESPIRATORY FAILURE

- Failure to oxygenate
  - Decrease in arterial O_2 tension
  - 5 causes: low PiO_2, hypoventilation, V/Q mismatch, shunt, diffusion defect
- Failure to ventilate
  - Increase in arterial CO_2 tension
  - Insufficient minute ventilation
  - Minute ventilation = Tidal volume x Breaths per minute
  - Two components: dead space ventilation + alveolar ventilation

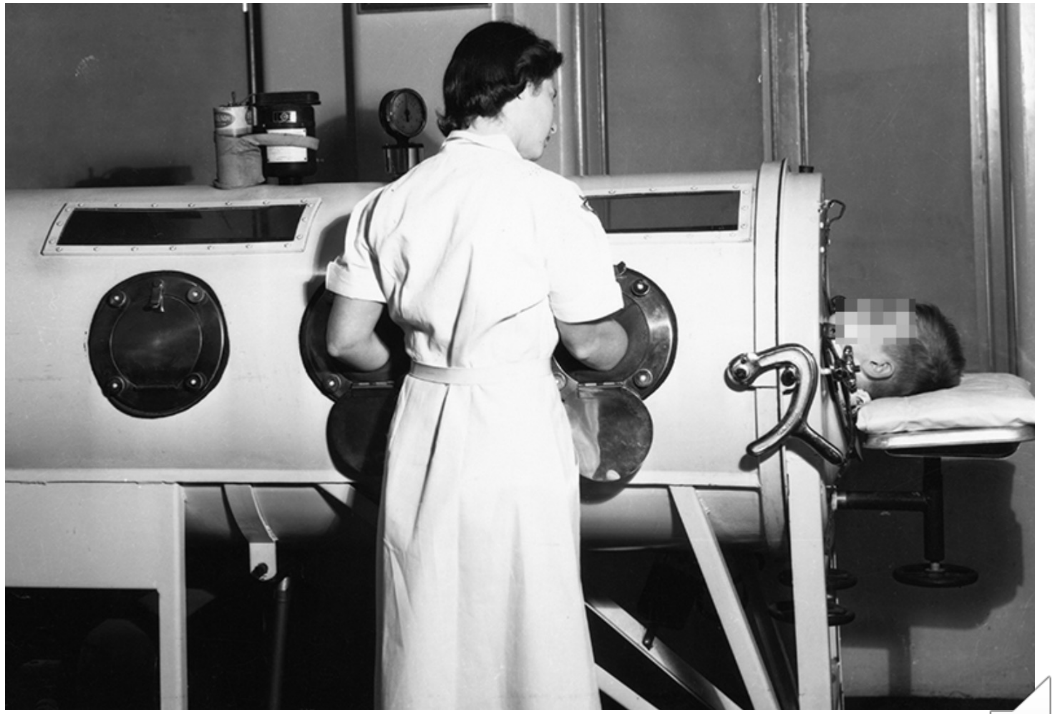
MECHANICAL VENTILATION

- Air is forced into the central airways and alveoli
- Can fully or partially replace spontaneous breathing
- Goals of mechanical ventilation
  - Improve oxygenation
  - Improve ventilation
  - Reduce work of breathing

CLASSIFICATION

- Negative Pressure
- Positive Pressure

- Invasive
- Non-invasive
  - NIV: BiPAP, CPAP
  - HFNC



Photos: Boston Children's Hospital Archives

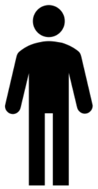
POSITIVE PRESSURE VENTILATION

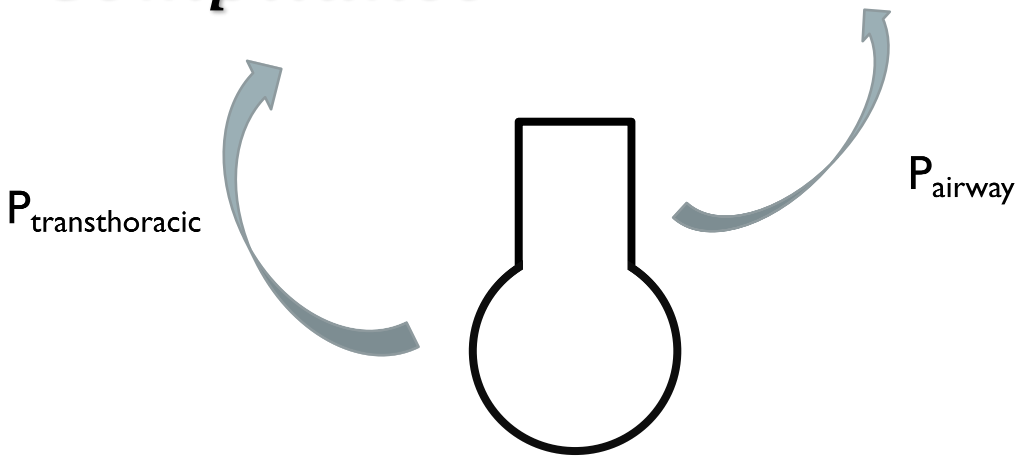
- Widespread use after 1952 polio epidemic in Copenhagen
- Tracheostomy → positive pressure ventilation
- 'Hang bagging'
- 1,500 students manual ventilation for a total of 165,000 hours

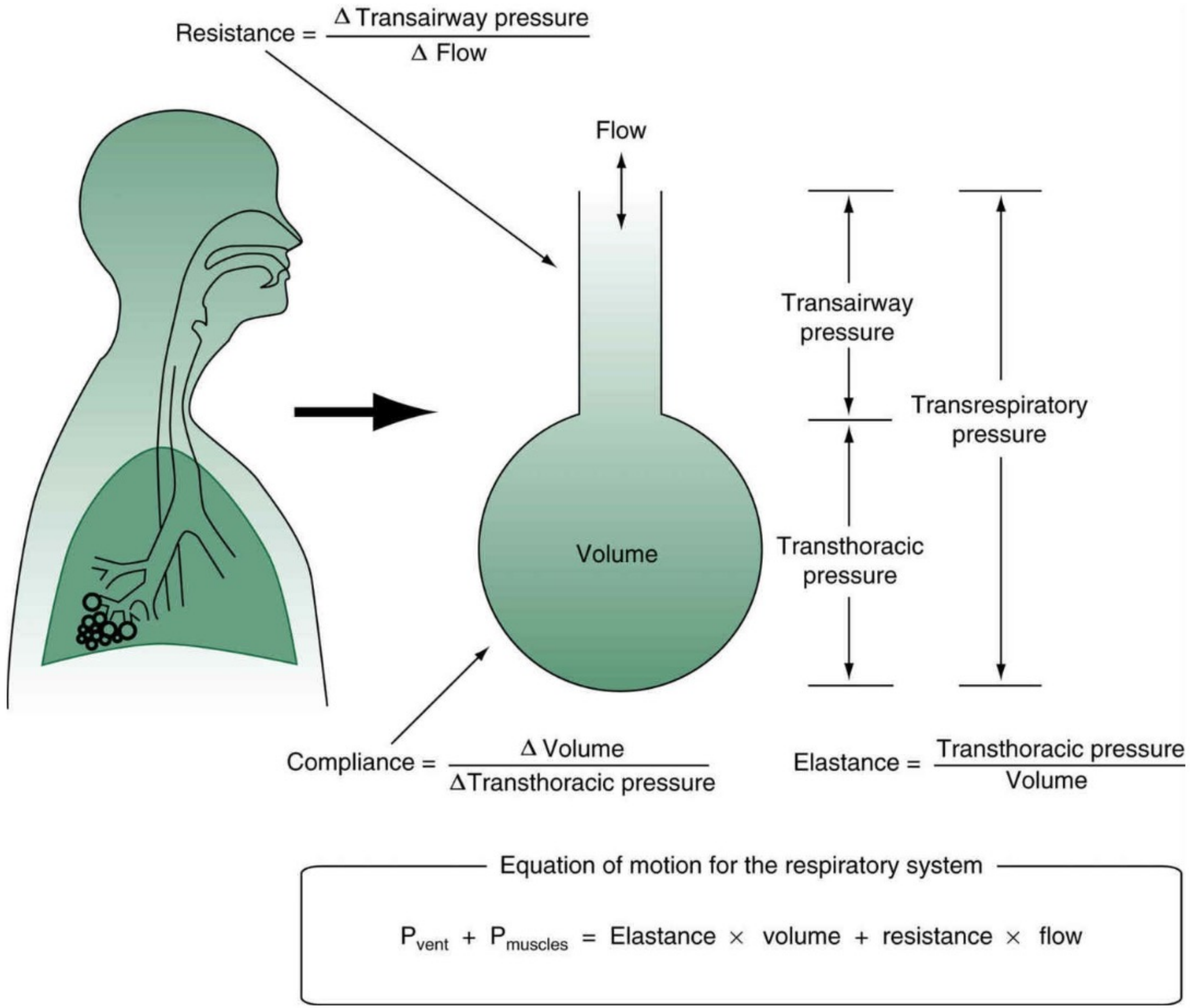
Slutsky AS. History of Mechanical Ventilation. From Vesalius to Ventilator-induced Lung Injury. Am J Respir Crit Care Med. 2015 May 15;191(10):1106-15.

EQUATION OF MOTION

$$P_{machine} + P_{musc} = \frac{Volume}{Compliance} + \text{Flow} \times \text{Resistance} + \text{iPEEP}$$

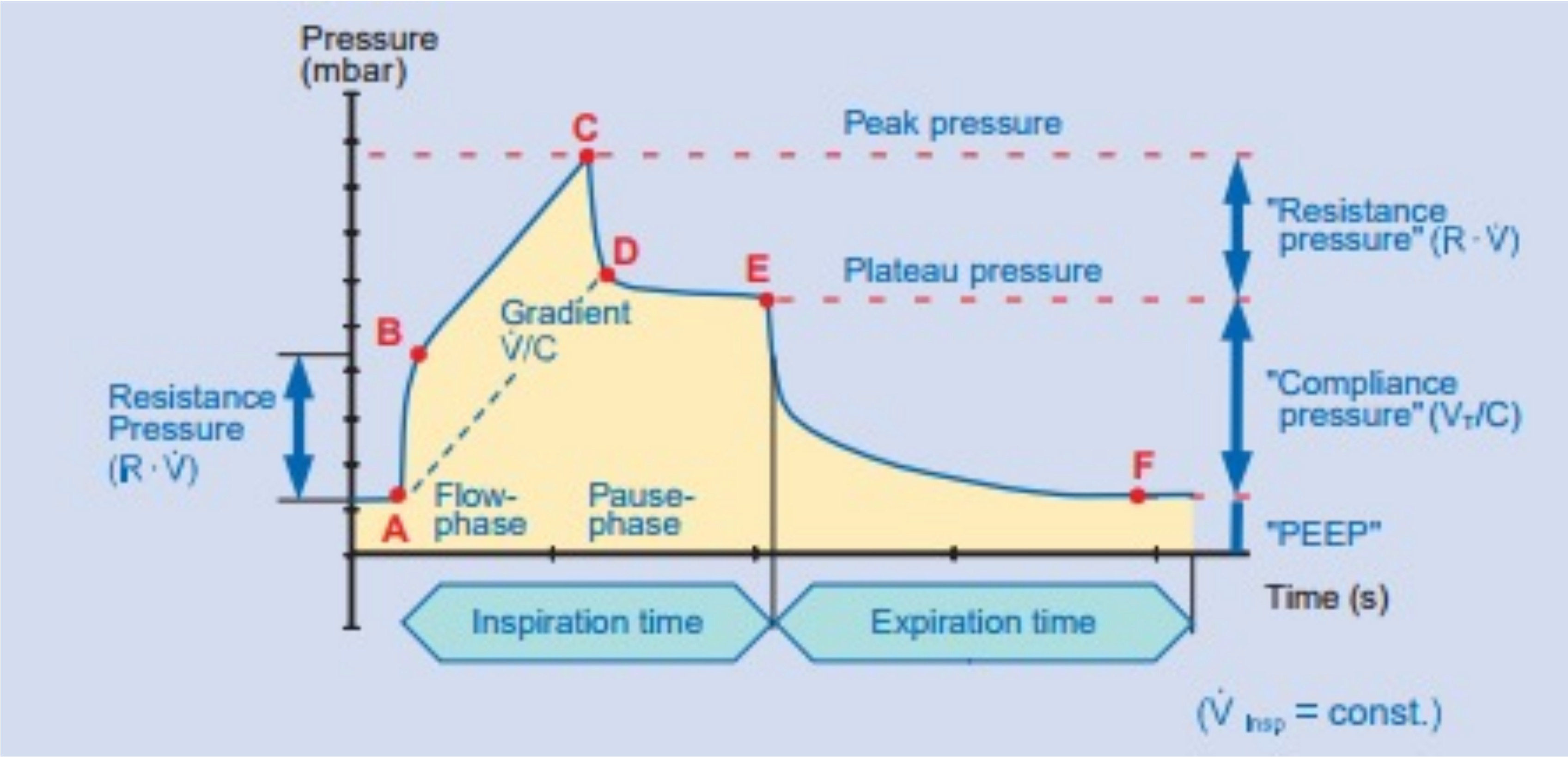




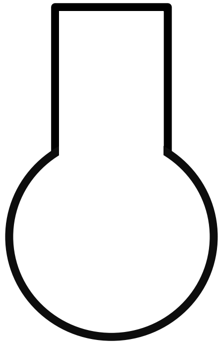


Egan's Fundamentals of Respiratory Care, 11th ed. St. Louis, MO: Elsevier; 2017

PRESSURE TIME GRAPH



DP

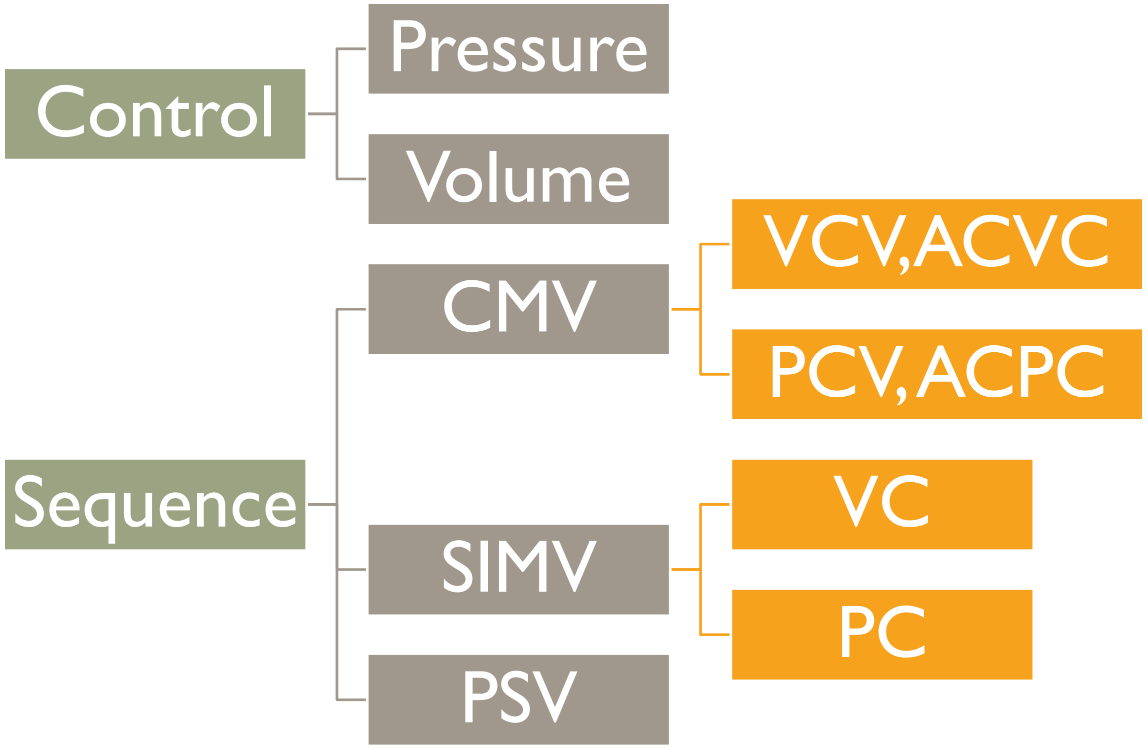


BASIC PHYSIOLOGY

- $Compliance = \frac{Volume}{Pressure}$
- $Compliance = \frac{1}{Elastance}$
- $Cstatic = \frac{VT}{Pplat - PEEP}$
- $Cdynamic = \frac{VT}{PIP - PEEP}$
- Normal static compliance: 50-100 ml/cmH2O

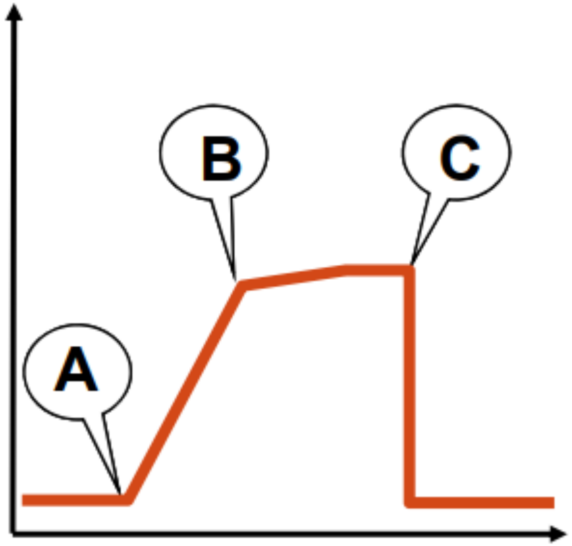
- $Resistance = \frac{Pressure}{Flow}$
- $Resistance = \frac{8nl}{\pi r^4}$
- Normal: 1-8 cmH2O/L/s

MODES OF INVASIVE MECHANICAL VENTILATION



PHASES OF A BREATH

- A = Trigger
- B = Limit
- C = Cycle



TRIGGER

- **Patient triggered**
  - Patient takes a breath
  - Flow trigger: increase in inspiratory flow
  - Pressure trigger: negative deflection in pressure
- **Machine triggered**
  - Controlled by setting the respiratory rate
  - RR = 10 breaths/min: machine delivers a breath every 6 seconds

LIMIT

- What the machine cannot exceed
- **Volume**
  - ACVC
  - If set VT = 400 ml, machine cannot exceed delivering 400 ml
- **Pressure**
  - ACPC, PS
  - If set PC or PS of 10 cmH_2O, the machine cannot give a higher pressure than that

CYCLE

- When to stop inspiration and cycle into expiration
- **Time**
  - ACPC
  - Inspiratory time is set
- **Volume**
  - ACVC
  - Both tidal volume and inspiratory flow are set, thus determining inspiratory time
- **Flow**
  - PS
  - As inspiration continues, flow decreases
  - Once flow decreases to a set threshold, the machine will cycle off into expiration

EXAMPLE: TIME CYCLING

- ACPC
- RR is set at 20 breaths per minute
- Inspiratory time (Ti) is set at 0.9s

- Total cycle time = 60s/RR = 60s/20 = 3s
- Expiratory time (Te) is therefore 3 – 0.9 = 2.1s
- I:E ratio is therefore 1:2:3

EXAMPLE: VOLUME CYCLING

- ACVC
- Set VT 400ml, Flow 50L/min, RR 20 breaths/min
- Ti = Vt/ Flow in minutes
- Ti = 0.008min = 0.48s
- Total cycle time = 60s/RR = 60s/20 = 3s
- Te = 3 - 0.48s = 2.52s
- I:E ratio is 1:5.25

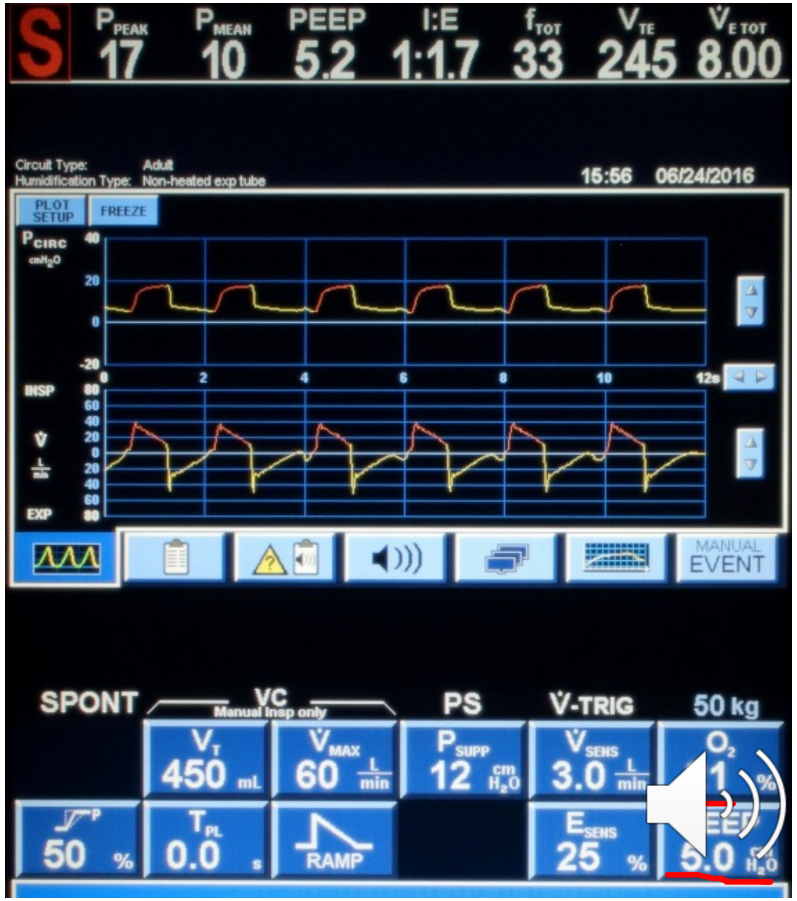
EXAMPLE: FLOW CYCLING

- PS
- Once flow drops below a certain threshold, breath is terminated
- Here, it is set to 25% of peak inspiratory flow rate
- Inspiratory time is thus variable and controlled by the patient's effort

OXYGENATION

HOW TO INCREASE PAO2?

- FiO2
  - Percentage of oxygen within oxygen-air mixture
- PEEP
  - Ventilator maintains positive airway pressure at the end of expiration to prevent alveolar collapse
  - Oxygenation is improved by reducing V/Q mismatch
- FiO2 and PEEP are titrated to maintain PaO2 60-100mmHg, SpO2 92-98%
  - O2 targets for general ICU population based on LOCO2, ICU-ROX, HOT-ICU



COMMON MODES

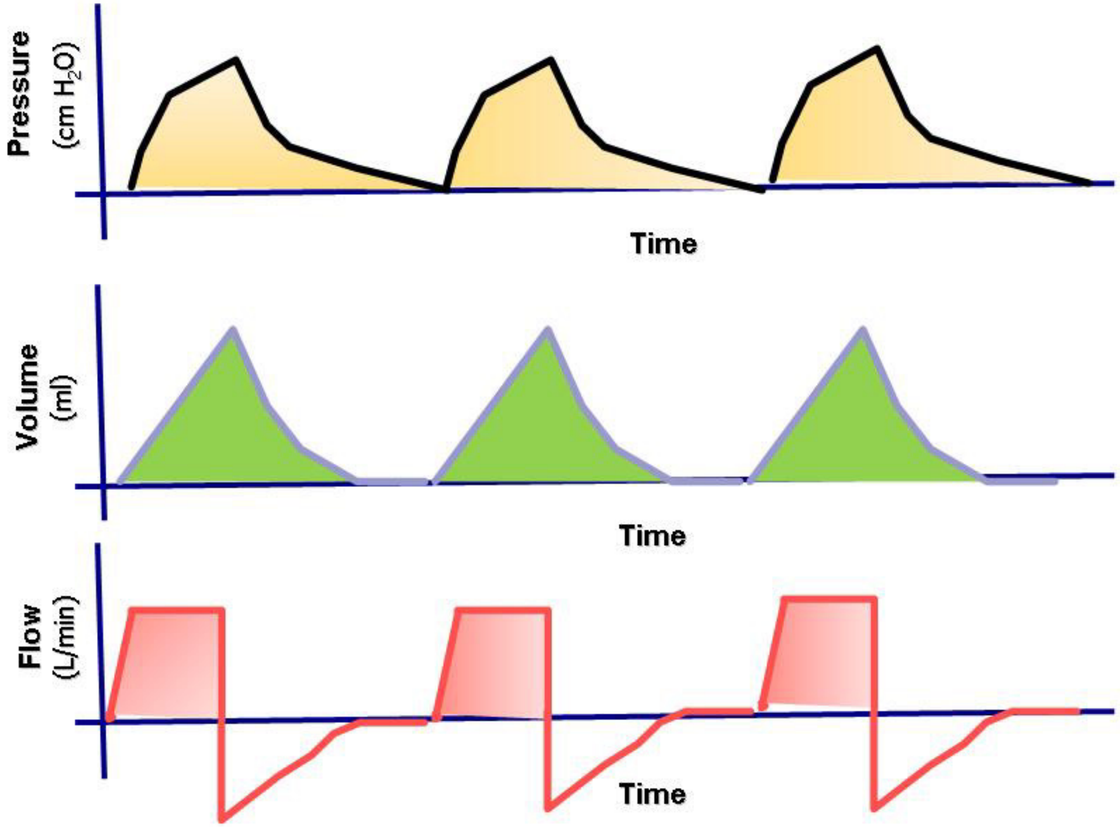
VOLUME CONTROL VENTILATION

- Ventilator will deliver a fixed tidal volume at a fixed rate
  - Regardless of lung compliance and in the absence of spontaneous breath
  - Volume is guaranteed unless pressure alarm reached (safety mechanism)
- Operator sets the following
  - Tidal volume (6-8ml/kg ideal body weight)
  - Rate (10-15)
  - I:E ratio through inspiratory flow rate (40-70L/min, I:E ratio of 1:2– 1:3)
- Minute ventilation = Tidal Volume x RR
- Variables adjusted based on pH and pCO2

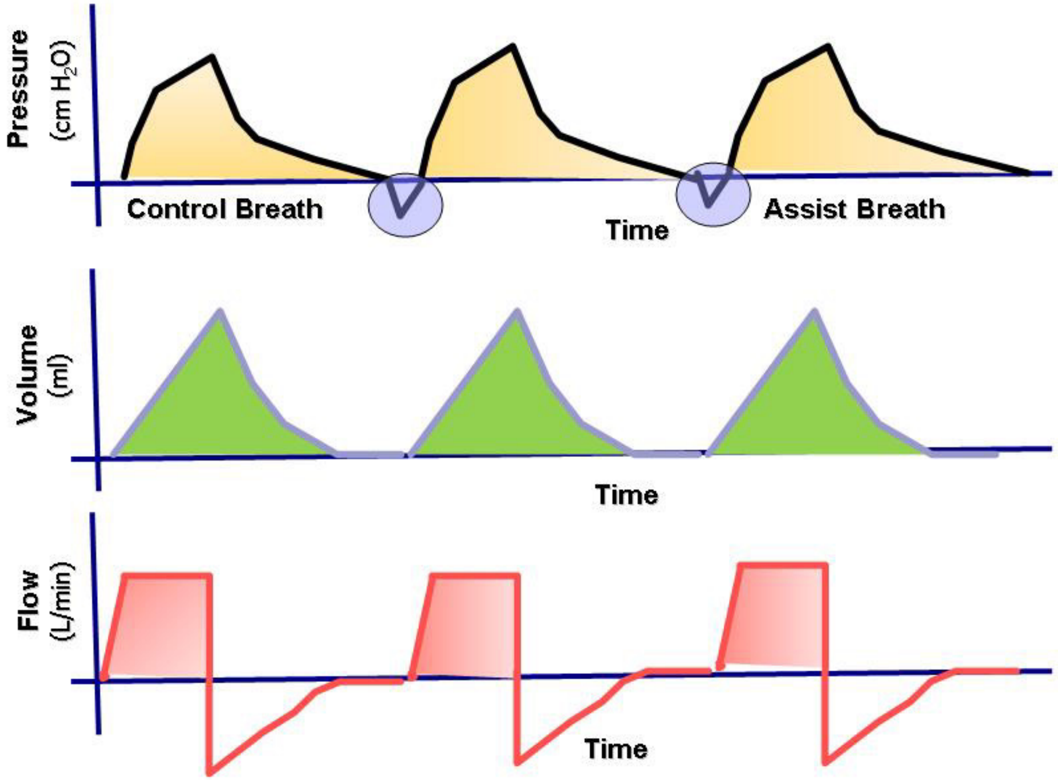
VOLUME CONTROL VENTILATION

- **Controlled mode**
  - **Continuous mandatory ventilation 'VCV'**
  - All breaths are triggered by the machine
- **Synchronized mode**
  - **Assist control 'ACVC'**
    - Breaths can be triggered by patient (assisted breaths) or machine (controlled breaths)
  - **Synchronized intermittent mandatory ventilation 'SIMV-VC'**
    - Ventilator will deliver set rate of breaths if patient is breathing slower than set RR
    - If patient breaths above set RR, the rest of the breaths are delivered via pressure support ventilation

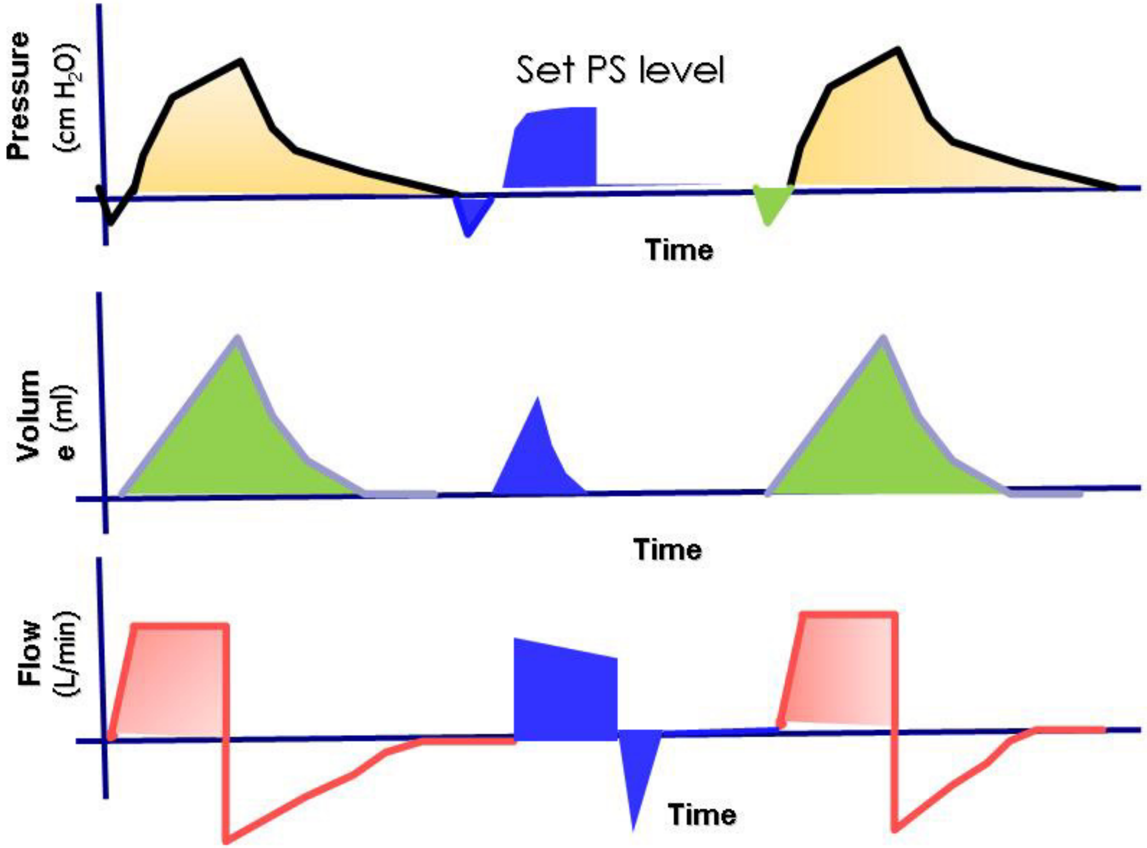
VOLUME CONTROL VENTILATION (VCV)



ASSIST CONTROL VOLUME CONTROL (ACVC)



SIMV-VC + PS


Pressure
(cm H_2O)
Set PS level
Time
Volum
e (ml)
Time
Flow
(L/min)
Time

PRESSURE CONTROL VENTILATION

- Ventilator delivers tidal volume based on positive pressure set
- Operator sets the following
  - Inspiratory pressure (‘PC15’ refers to a pressure of 15cmH2O above PEEP)
  - Inspiratory time
  - Rate
- Tidal volume is the dependent variable
  - Depends on compliance and resistance of the lung
  - Tidal volume will decrease if lung compliance decreases at a given pressure

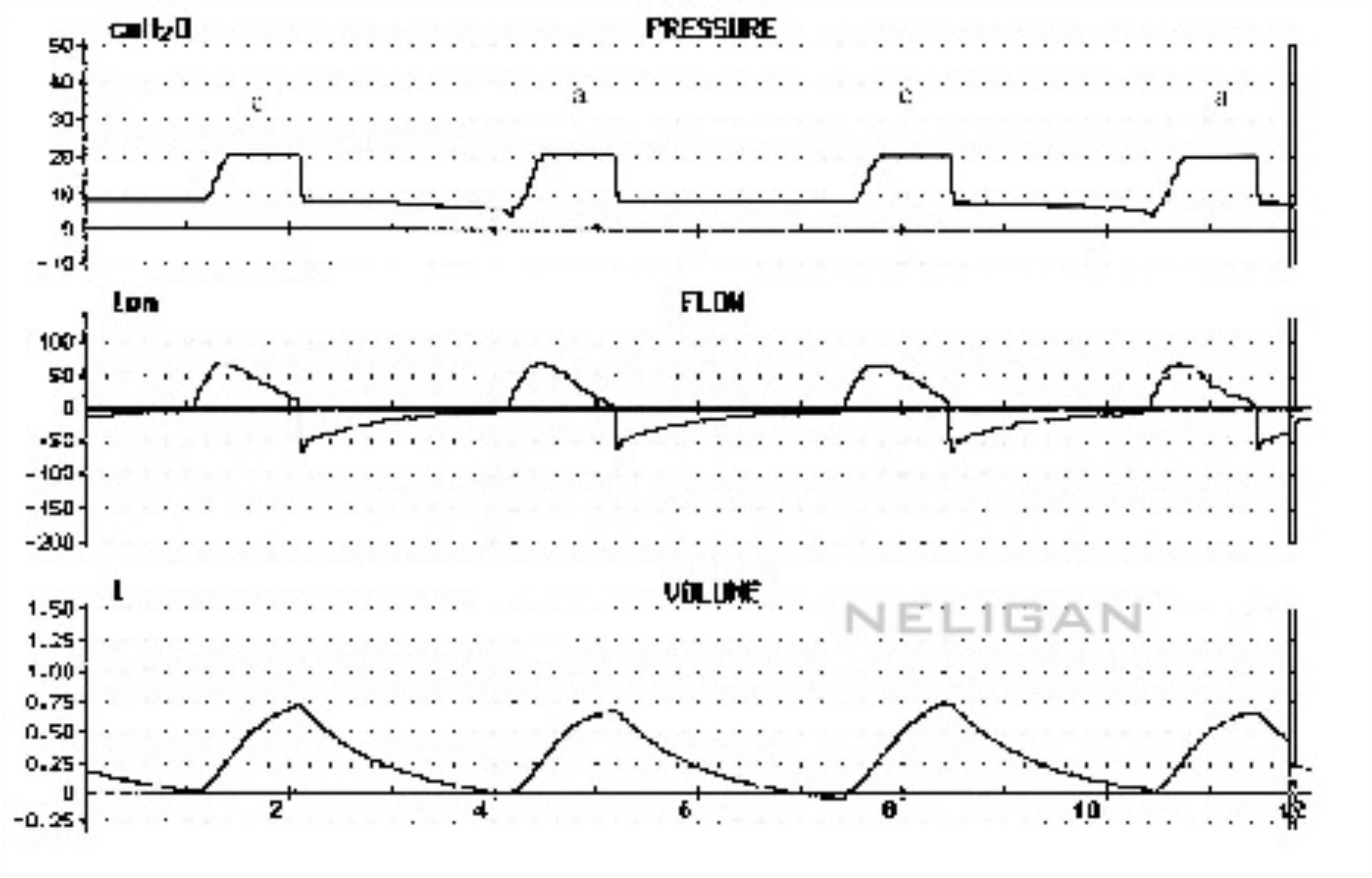
PRESSURE CONTROL VENTILATION

- **Controlled mode**
  - Controlled mandatory ventilation ‘PCV’
- **Synchronized mode**
  - Assist control ‘ACPC’
  - Synchronized intermittent mandatory ventilation ‘SIMV-PC’

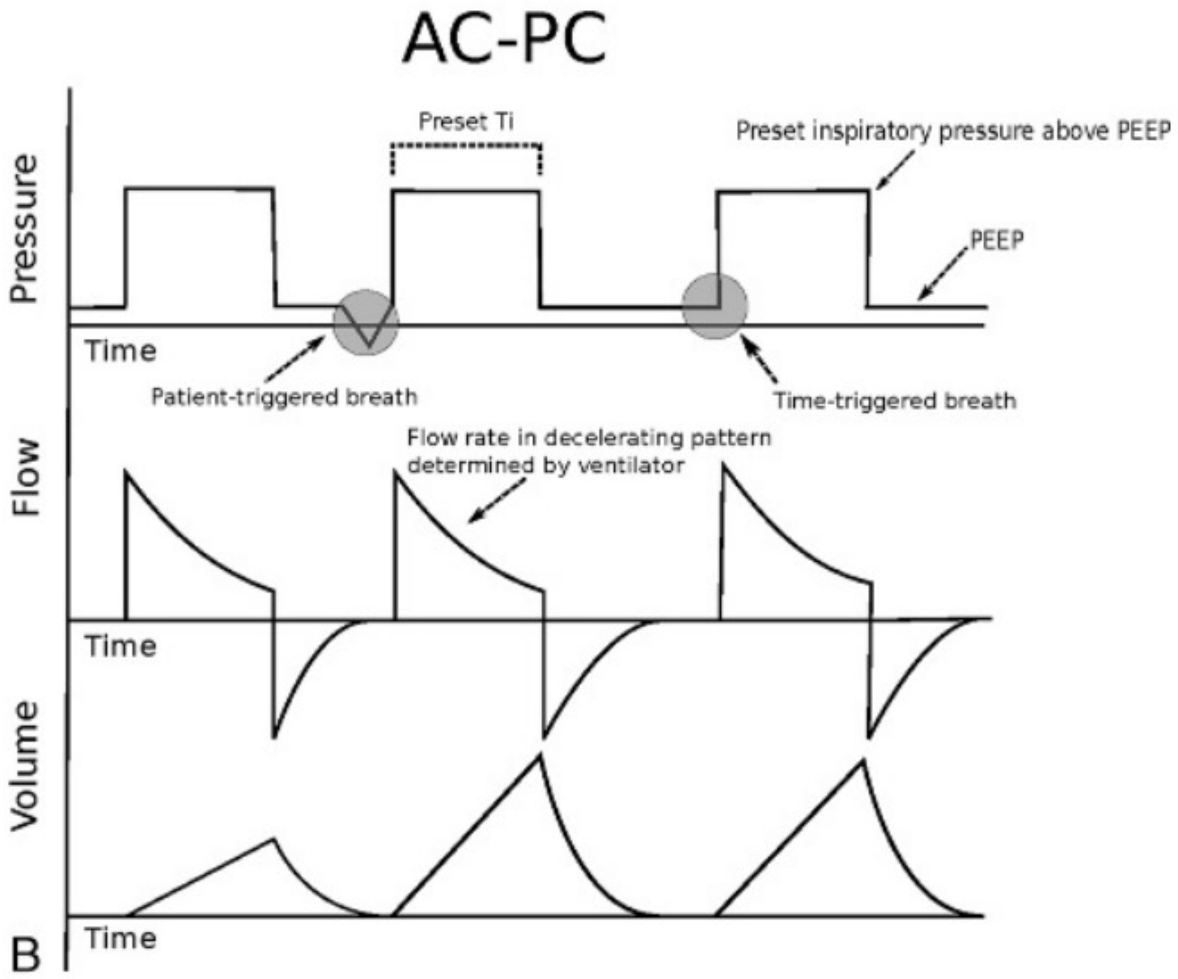
PRESSURE CONTROL VENTILATION

- Advantages
  - Limits inspiratory pressure: prevents barotrauma
  - If patient is breathing spontaneously, it allows the patient to influence the tidal volume
    - Favourable in metabolic acidosis where high minute ventilation is required
    - Patient can take a larger breath as long as it is within the inspiratory time
  - Better patient-ventilator synchrony
- Disadvantages
  - Variable tidal volume: risk of volutrauma, cannot guarantee minute ventilation
  - Fixed inspiratory time may result in patient-ventilator asynchrony

PRESSURE CONTROL VENTILATION (PCV)



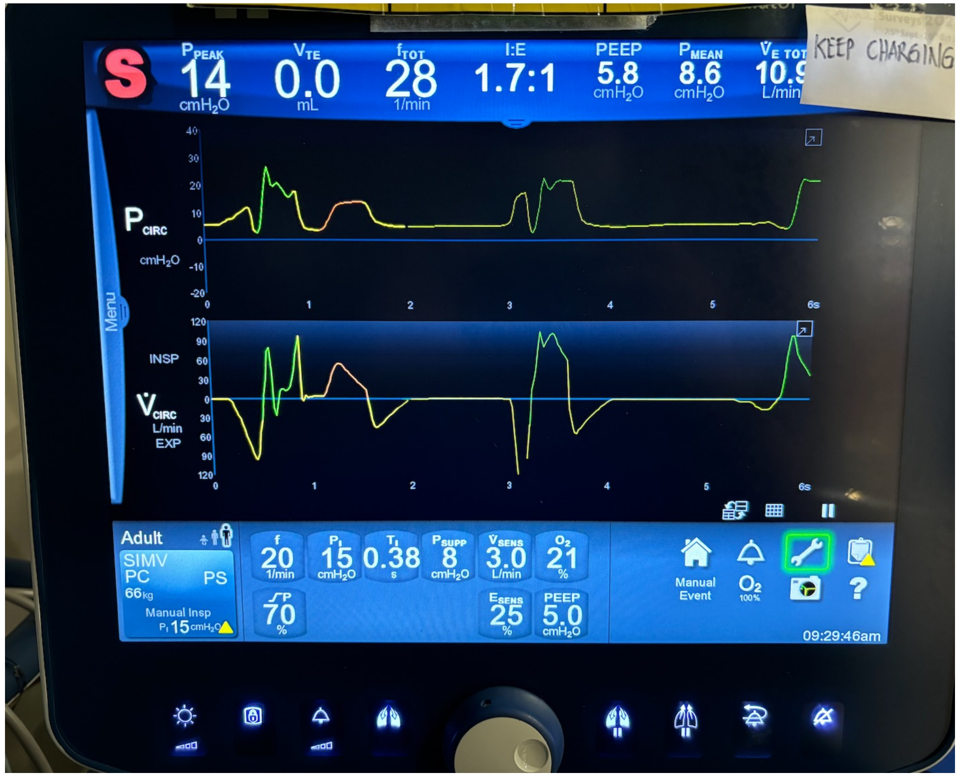
ASSIST CONTROL PRESSURE CONTROL (ACPC)



Walter JM, Corbridge TC, Singer BD. Invasive Mechanical Ventilation. South Med J. 2018 Dec;111(12):746-753

SIMV-PC + PS

KEEP CHARGING
PPEAK 21 cmH2O
VTE 445 mL
fTOT 19 1/min
I:E 1:2.3
PEEP 4.8 cmH2O
PMEAN 9.6 cmH2O
VE TOT 8.28 L/min
PCIRC cmH2O
INSP
VCIRC L/min
EXP
Menu
Adult
SIMV PC PS
66kg
Manual Insp
PI 15 cmH2O
f 20 1/min
PI 15 cmH2O
TI 0.90 s
PSUPP 8 cmH2O
VSENS 3.0 L/min
O2 21 %
70 %
ESENS 25 %
PEEP 5.0 cmH2O
Manual Event
O2 100%
09:13:25am

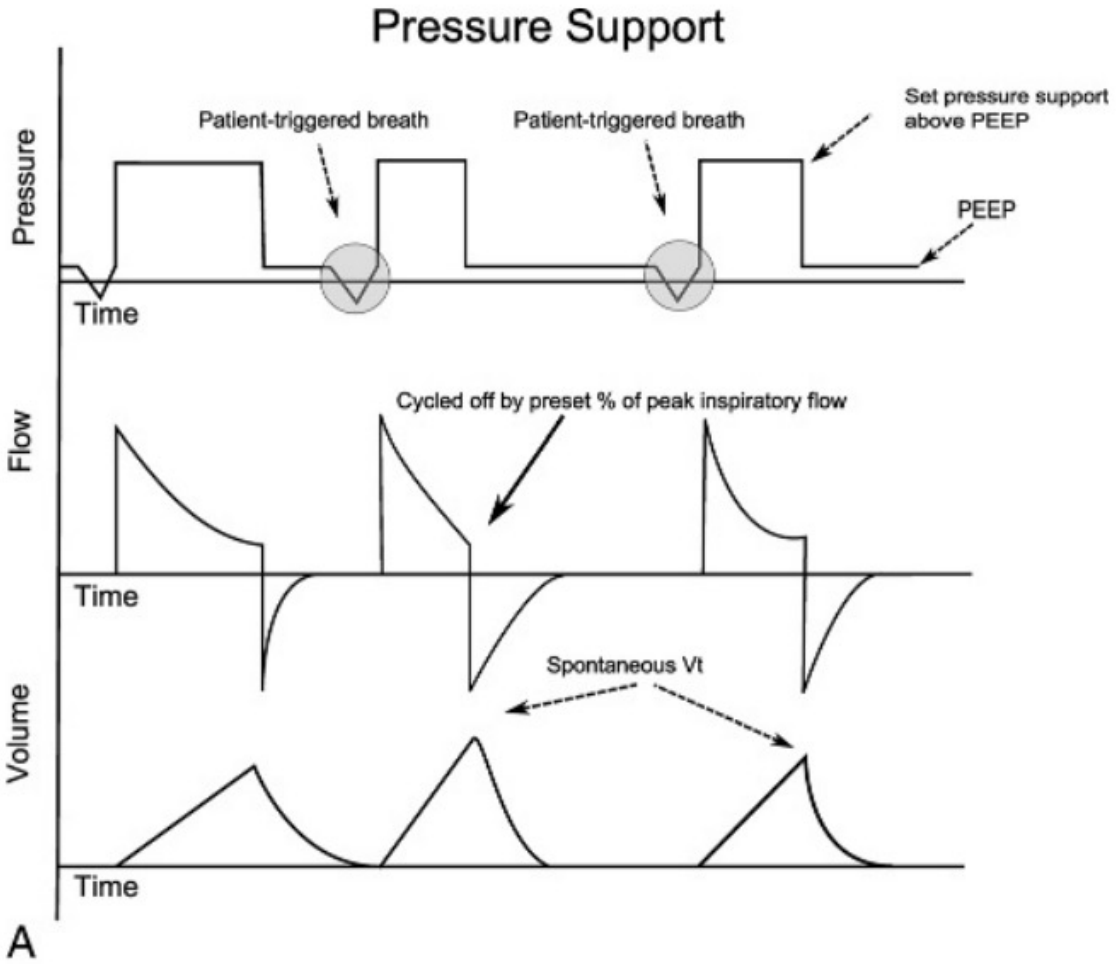


KEEP CHARGING
S
PPEAK 14 cmH2O
VTE 0.0 mL
fTOT 28 1/min
I:E 1.7:1
PEEP 5.8 cmH2O
PMEAN 8.6 cmH2O
VE TOT 10.9 L/min
PCIRC cmH2O
INSP
VCIRC L/min
EXP
Menu
Adult
SIMV PC PS
66kg
Manual Insp
PI 15 cmH2O
f 20 1/min
PI 15 cmH2O
TI 0.38 s
PSUPP 8 cmH2O
VSENS 3.0 L/min
O2 21 %
70 %
ESENS 25 %
PEEP 5.0 cmH2O
Manual Event
O2 100%
09:29:46am

PRESSURE SUPPORT VENTILATION

- Patient triggered, pressure-limited breath
- Patient has influence on
  - Rate
  - Inspiratory time
  - Tidal volume
- Weaning mode – gradual decrease in the amount of pressure support given to patient until extubation

PRESSURE SUPPORT VENTILATION



- Unlike ACPC, inspiratory time is variable

Walter JM, Corbridge TC, Singer BD. Invasive Mechanical Ventilation. South Med J. 2018 Dec;111(12):746-753

OTHER MODES OF VENTILATION

- Volume support ventilation
- Pressure regulated volume control (PRVC)
- Airway pressure release ventilation (APRV)
- High frequency oscillatory ventilation (HFOV)
- Proportional assist ventilation (PAV)
- Adaptive servoventilation (ASV)
- Neurally adjust ventilatory assistance (NAVA)

AIRWAY PRESSURE RELEASE VENTILATION (APRV)

- Open-lung, pressure controlled, inverse ratio (I > E time) mode of ventilation
- Promotes oxygenation (increased mean airway pressure but lower peak airway pressure)
- Allows spontaneous breathing (less need for sedation)
- Different names with different ventilators
  - BiVent (Servo-I Maquet), BiLevel (PB840 Covidien), DuoPAP (C-1 Hamilton)
- Drawbacks: Breath stacking (short exp time), barotrauma and haemodynamic compromise (long periods of inspiration at high pressure), hypercapnia

APRV

- Components of APRV include
  - P-high (25-30cmH2O) – Affects oxygenation
  - P-low (0-5cmH2O) – PEEP equivalent
  - T-high (4-6s) – Affects oxygenation
  - T-low – Time spent in T-low allows for ventilation
    - Pressure should not reach 0 to prevent de-recruitment (some amount of autoPEEP is desired)
    - Termination of expiratory flow occurs at 25% PEFR

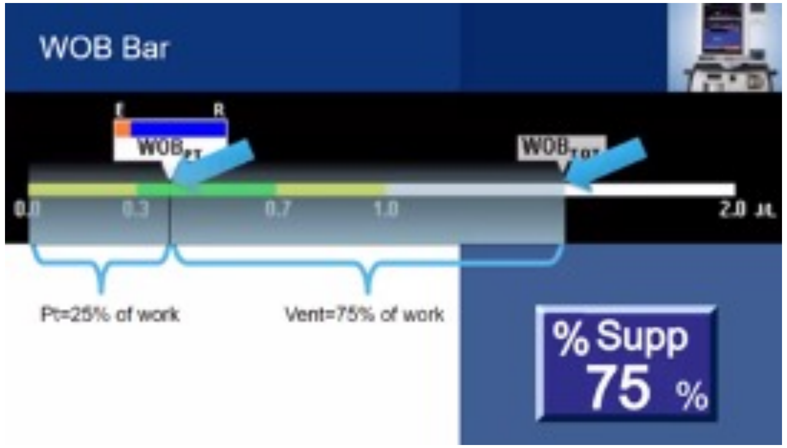
APRV

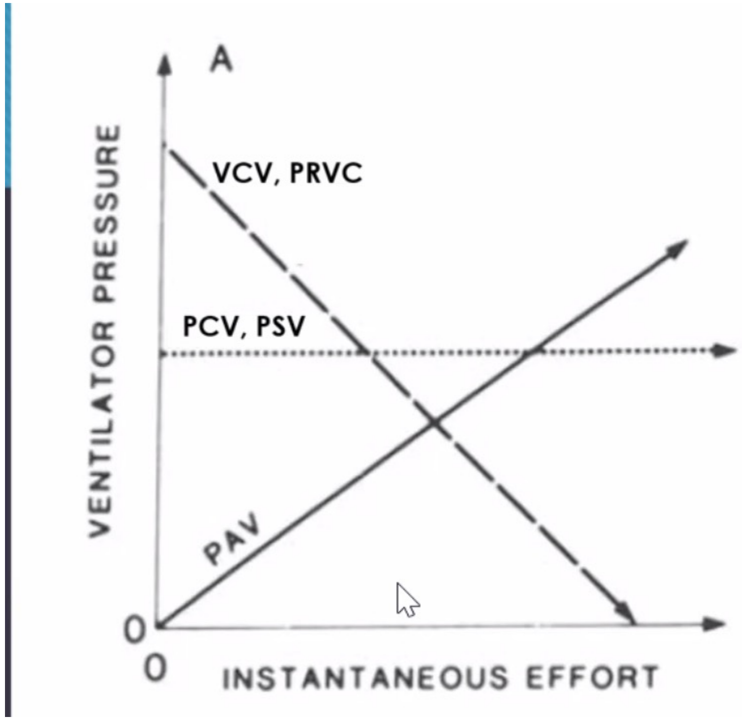
- Inverse ratio ventilation
- (Insp. > Exp. Time)

- **Set:**
- P-high=25-30cm$H_2$0 (Pplat)
- P-low = 0-5 cm$H_2$0 (PEEP)
- T-high = 5.5 sec
- T-low = 0.5 sec

PAV

- PAV – Proportional assist ventilation
  - Delivers amount of support proportional to patient effort
  - Calculates respiratory mechanics every 4-10 breaths by applying a short end inspiratory pause;
  - Determines the pressure needed in each breath
  - % support is set on the ventilator to determine how much work the ventilator and patient does respectively





OTHER MODES: NEWER WEANING MODES

- ASV (Adaptive support ventilation)/ AVM (Adaptive mechanical ventilation)
  - Closed-loop controlled mode of ventilation
  - Automatically adjusts settings based on patient's requirements to optimize work of breathing
  - Input parameters: IBW, % of minute volume, PEEP, FiO2
  - Output parameters: RR, tidal volume, I:E ratio
- NAVA – Neurally adjusted ventilatory assistance
  - Mode of ventilation that utilizes electrical activity of diaphragm (using a special NGT) to generate appropriate breaths and assist ventilation
  - Amount and timing of support tailored to diaphragm activity

WHAT TO MONITOR?

- Cardiac monitor, blood pressure
- SpO_2
- End-tidal CO_2
- Arterial blood gas
  - Usually done 30 minutes to 1 hour after initiation/ adjustment of mechanical ventilation
  - Determine if PaO_2 and $PaCO_2$ correlate with SpO_2 and end-tidal CO_2
- Ventilator parameters:
  - Peak inspiratory pressure, Plateau pressure, Tidal volume, Respiratory rate

COMMON ALARMS

PEAK PRESSURE ALARM

- Usually when **peak inspiratory pressure exceeds 40 cmH2O**
  - *May need to increase Ppeak alarm limit if main problem is thought to be increased resistance in status asthmaticus*
- Check ventilator circuit and ETT for any kinks
- Attempt to pass in-line suction through and suction to check patency
- Auscultate for unequal breath sounds, wheeze, crepitations
- Differentiate between increased Resistance versus Compliance
- Check plateau pressure
  - If Ppeak - Pplat difference is large (>5 cmH2O) = increased airway resistance
    - ETT obstruction
    - Bronchospasm
  - If Ppeak - Pplat is small = decreased lung compliance
    - Lung collapse, PTX, pneumonia, ARDs, pulmonary edema, raised IAP

LOW MINUTE VENTILATION

- Usually occurs in PC or PSV as tidal volume is not guaranteed
- If occurs in ACVC, consider
  - Leak: cuff, circuit, pneumothorax – VTexpired < VTset
  - Ventilator dysynchrony
  - Peak pressure limit being hit resulting in premature termination of breath

OTHERS

- RR alarm
  - Usually capped at 30-35 breaths/min
  - Occurs when the patient is breathing above set rate
- Apnea alarm
  - Occurs in PSV
  - As safety mechanism, the machine will deliver a breath when patient has not triggered a breath for a specified duration

VENTILATOR INDUCED LUNG INJURY

- Inappropriate stress and strain to the lung
- Stress = k (specific elastance) x strain

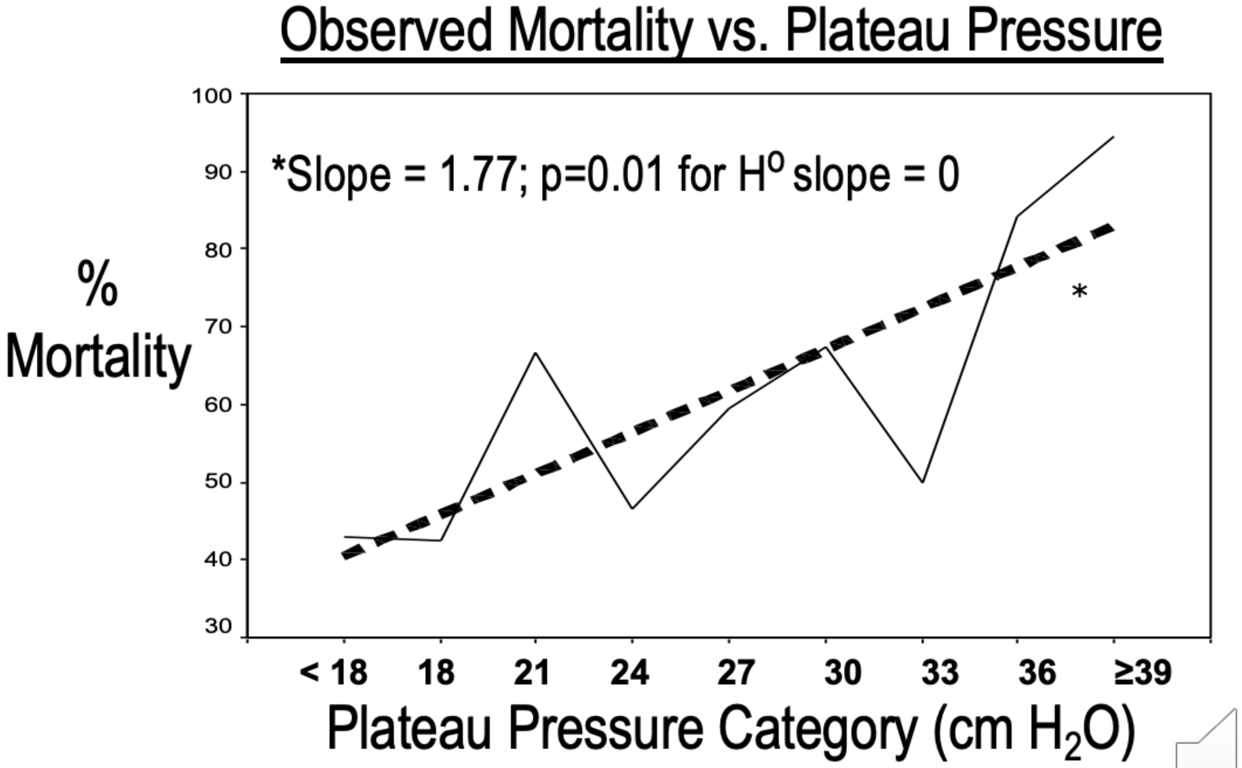
Barotrauma	Due to increase in transalveolar pressure with regional lung overdistension Related to end-inspiratory stress May result in pneumothorax
Volutrauma	Overdistension of alveoli by volume Related to end-inspiratory strain at the alveolar level
Atelectotrauma	Repeated opening and closing of alveoli causes a shearing force
Biotrauma	Due to cytokine and inflammatory mediator release

BAROTRAUMA

Plateau pressure

- Measure of pressure alveoli are exposed to by removing pressure due to airflow resistance
- Measured using an end inspiratory pause

Target <30cmH2O



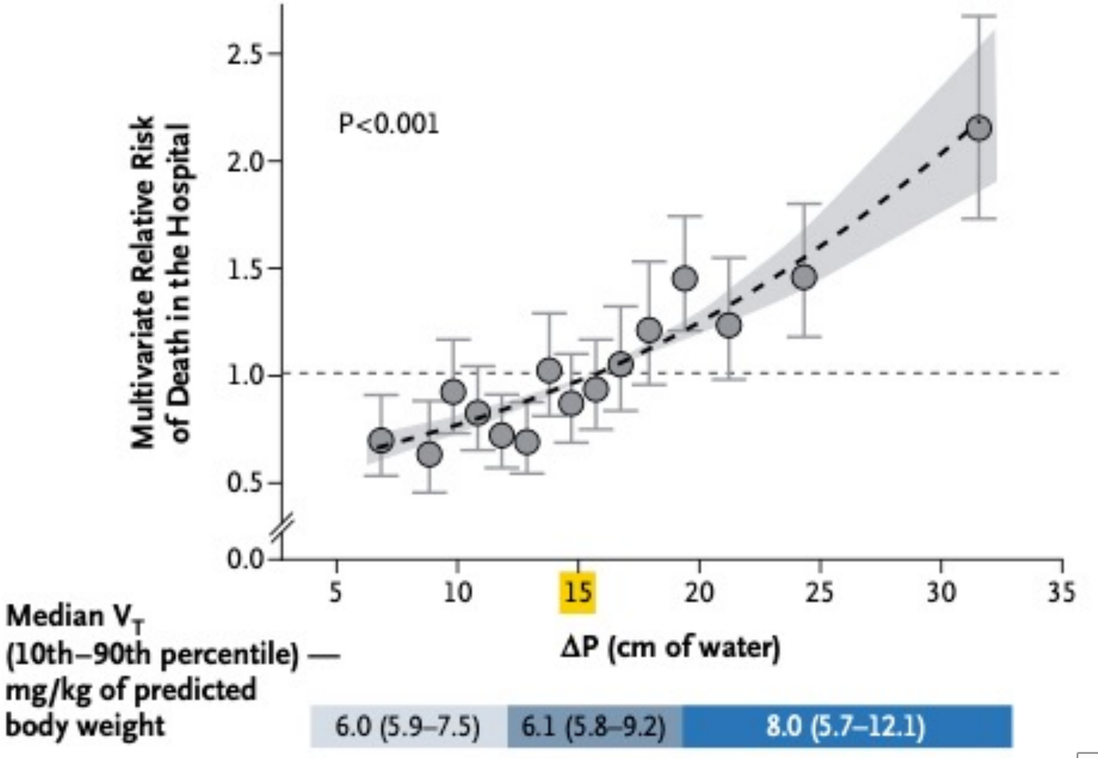
Crit Care Med 2005; 33:21-30

BAROTRAUMA

Driving pressure

- Pplat – PEEP or V_T/C_{RS}
- Normalises tidal volume to compliance of the respiratory system (surrogate to the functional size of the 'baby lung')

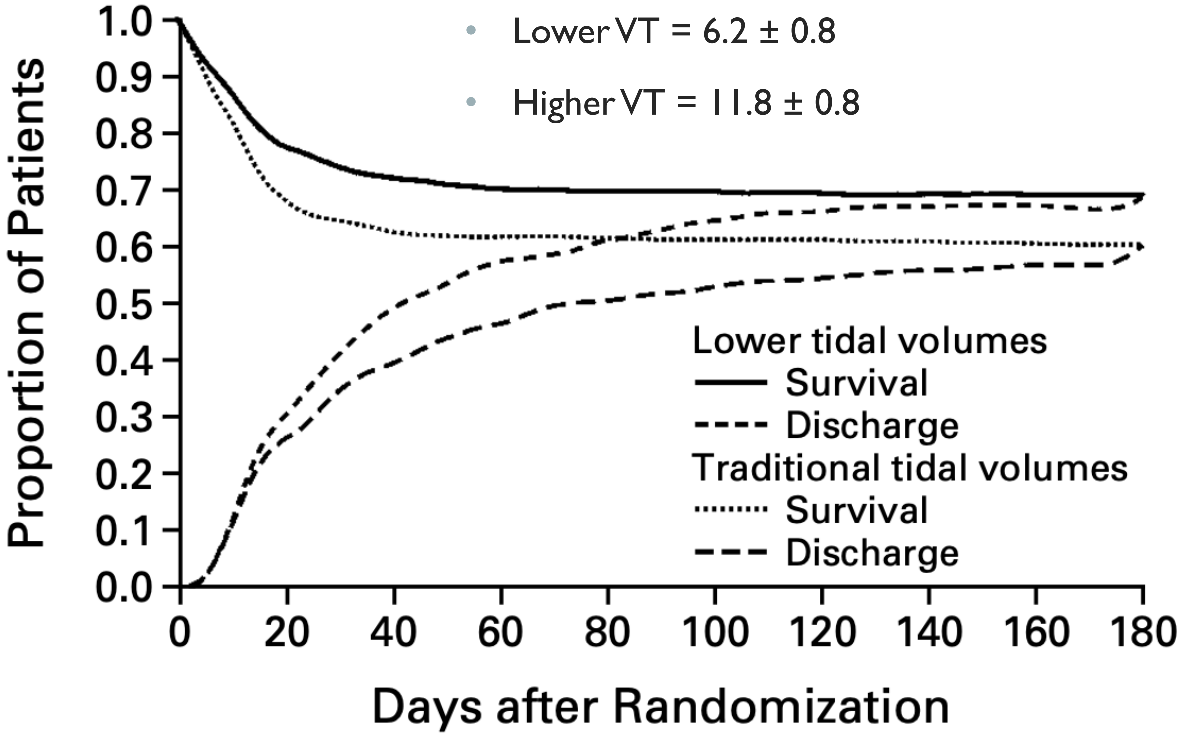
Target <15 cmH2O



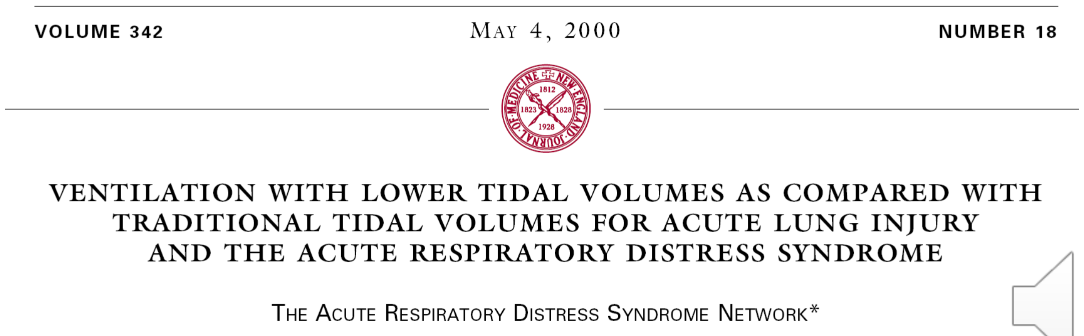
Amato MB. Driving pressure and survival in the acute respiratory distress syndrome. N Engl J Med. 2015 Feb 19;372(8):747-55.

VOLUTRAUMA

- Lower VT = 6.2 ± 0.8
- Higher VT = 11.8 ± 0.8



- Keep tidal volumes at 6ml/kg IBW
- ARDSNET trial, lower tidal volume strategy had mortality reduction of 9% (p = 0.005)

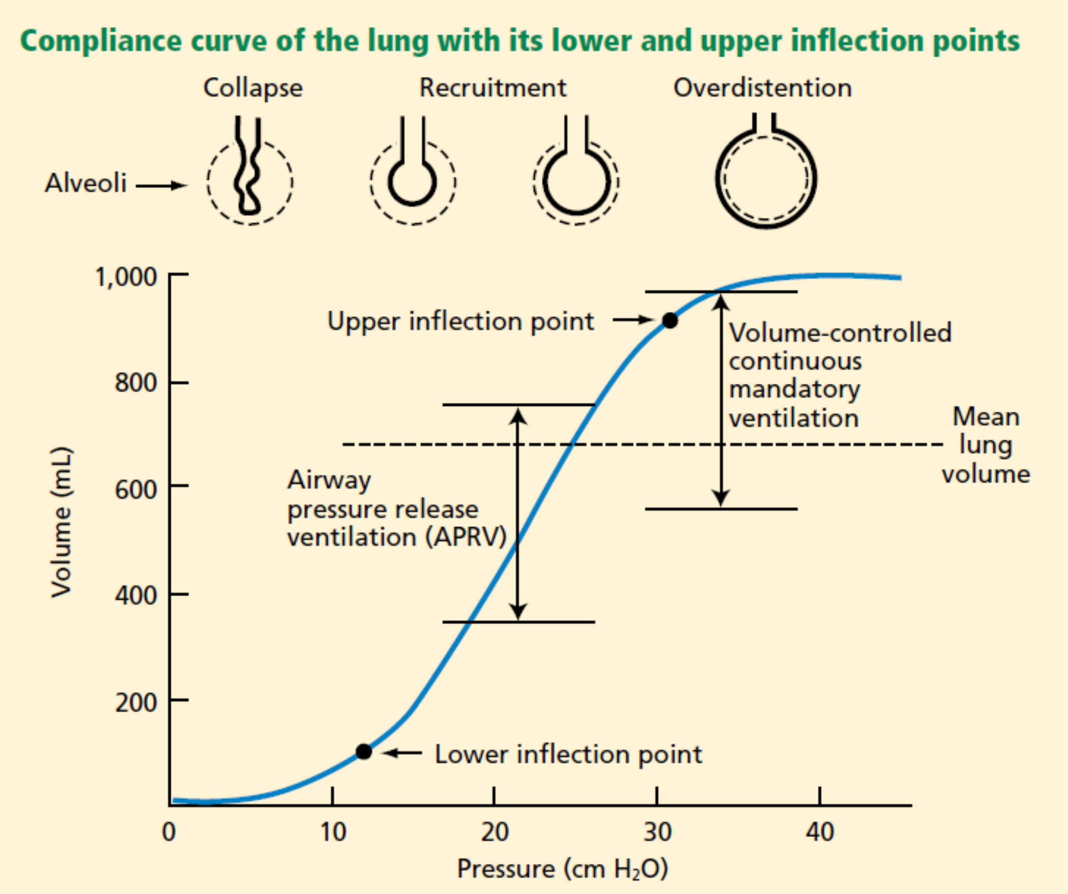

VOLUME 342 | MAY 4, 2000 | NUMBER 18

VENTILATION WITH LOWER TIDAL VOLUMES AS COMPARED WITH TRADITIONAL TIDAL VOLUMES FOR ACUTE LUNG INJURY AND THE ACUTE RESPIRATORY DISTRESS SYNDROME

THE ACUTE RESPIRATORY DISTRESS SYNDROME NETWORK*

ATELECTOTRAUMA

- Keep lungs open with optimal PEEP



REPRINTED FROM PAPADAKOS PJ, LACHMANN B. THE OPEN LUNG CONCEPT OF MECHANICAL VENTILATION: THE ROLE OF RECRUITMENT AND STABILIZATION. CRIT CARE CLIN 2007; 23:241–250, WITH PERMISSION FROM ELSEVIER.

FIGURE 1

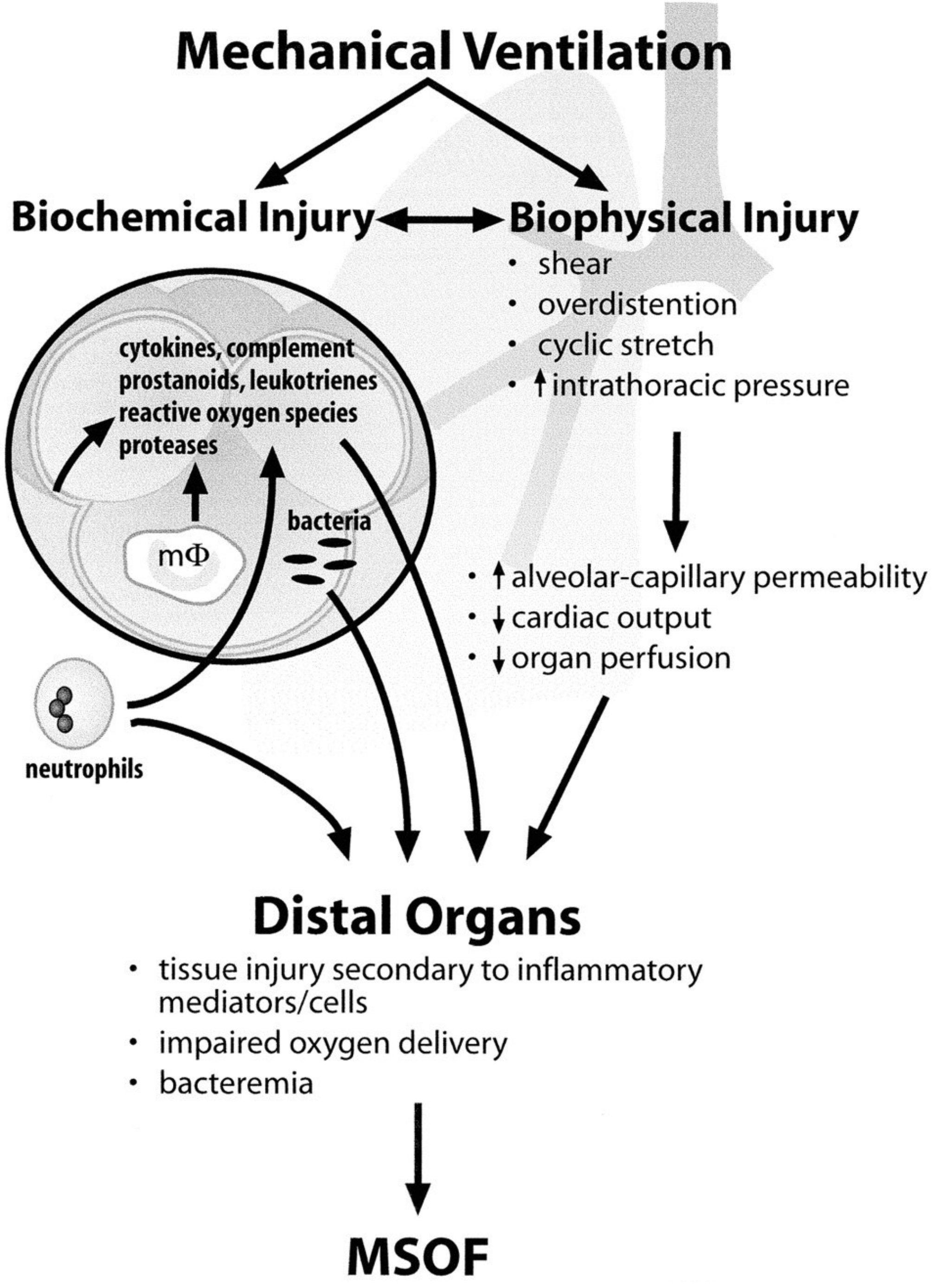
HOW TO SELECT OPTIMUM PEEP?

FiO_2	0.3	0.4	0.4	0.5	0.5	0.6	0.7	0.7
PEEP	5	5	8	8	10	10	10	12

FiO_2	0.7	0.8	0.9	0.9	0.9	1.0
PEEP	14	14	14	16	18	18-24

- Selection of PEEP according to the ARDSNET PEEP FiO2 table should suffice for most patients
- No difference in mortality between low or high PEEP FiO2 table
- In moderate-severe ARDs: high PEEP FiO2 table had better oxygenation with signal for reduced mortality (subgroup analysis)
- Other strategies exist, 'individualized PEEP' – not yet shown to demonstrate superiority

BIOTRAUMA


Mechanical Ventilation
Biochemical Injury
Biophysical Injury
• shear
• overdistention
• cyclic stretch
• ↑ intrathoracic pressure
cytokines, complement
prostanoids, leukotrienes
reactive oxygen species
proteases
mΦ
bacteria
neutrophils
• ↑ alveolar-capillary permeability
• ↓ cardiac output
• ↓ organ perfusion
Distal Organs
• tissue injury secondary to inflammatory mediators/cells
• impaired oxygen delivery
• bacteremia
MSOF

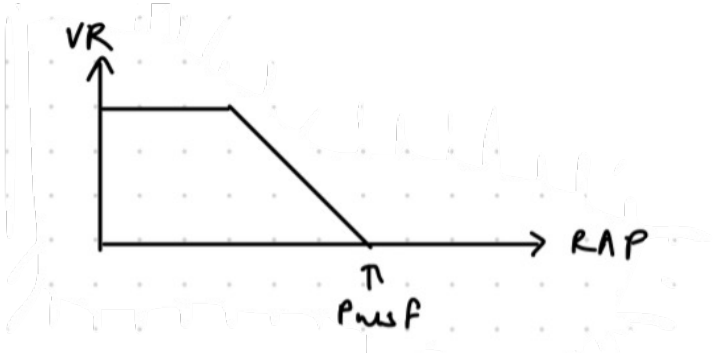
HEART LUNG INTERACTIONS

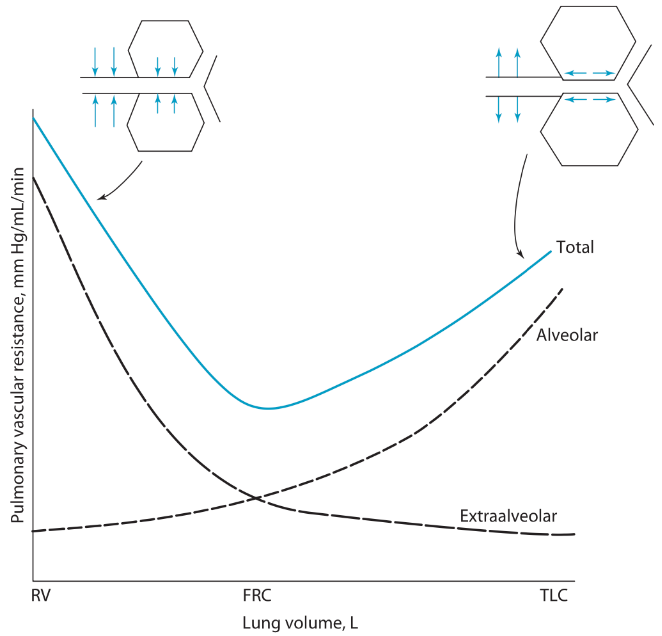
RV preload ↓

- During inspiration, intrathoracic pressure ↑
- Pleural pressure ↑ and is transmitted to the RA
- RA pressure ↑ leading to a ↓ in venous return

RV afterload ↑

- Increase in alveolar pressure is transmitted to the intra-alveolar vessels, leading to ↑ in PVR and RV afterload





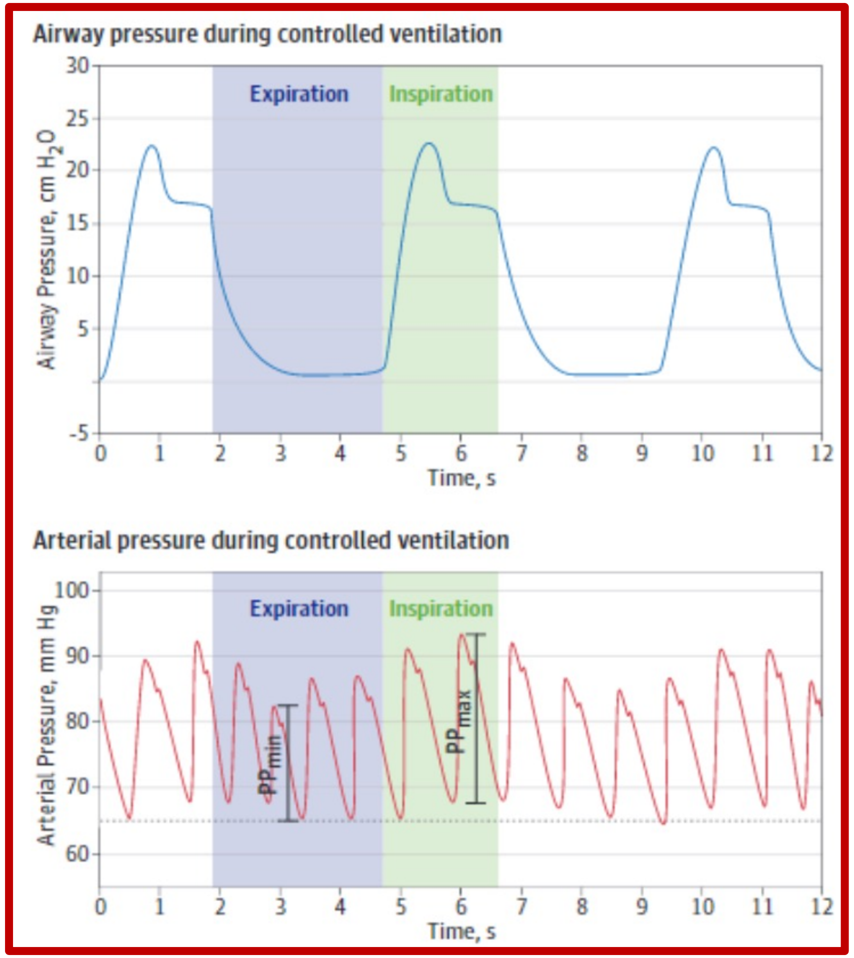
HEART LUNG INTERACTIONS

LV preload: variable

- Initially ↑ as blood is pushed out of the pulmonary circulation
- In the next beat, ↓ due to decreased RV preload

LV afterload ↓

- Due to increased transmural pressure (Ppl - LVEDP) from increased intrathoracic pressure



FURTHER READING

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- Walter JM. Invasive Mechanical Ventilation. South Med J. 2018 Dec 111;(12):746-753
- Slutsky AS, Ranieri VM. Ventilator-induced lung injury. N Engl J Med. 2013 Nov 28;369(22):2126-36
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