VENTILATOR WAVEFORM ANALYSIS

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Seminar Overview

1. Basic Terminology (Types of variables, Breaths, modes of ventilation)
2. Ideal ventilator waveforms (Scalars)
3. Diagnosing altered physiological states
4. Ventilator Patient Asynchrony and its management.
5. Loops (Pressure volume and Flow volume)

Basics phase variables…………..

A. Trigger …….

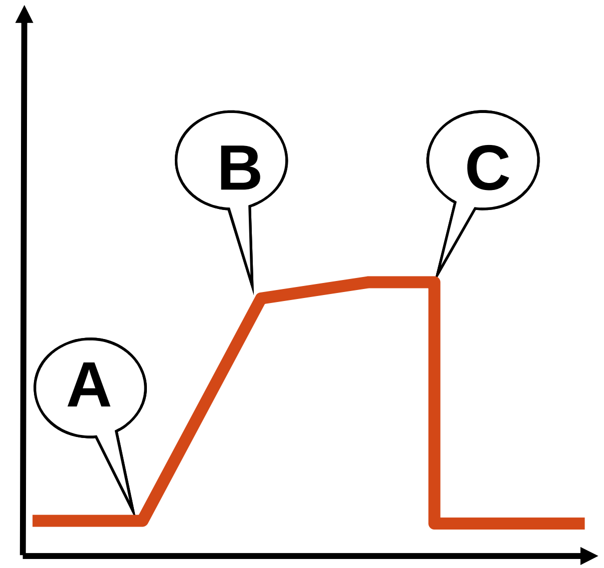
What causes the breath to begin?

B. Limit ……

What regulates gas flow during the breath?

C. Cycle …….

What causes the breath to end?



VARIABLES

1. **TRIGGER VARIABLE** : Initiates the breath
   - Flow (Assist breath)
   - Pressure (Assist Breath)
   - Time (Control Breath)
   - Newer variables (Volume, Shape signal, neural)

Flow trigger better than Pressure trigger.

With the newer ventilators, difference in work of triggering is of minimal clinical significance.

British Journal of Anaesthesia, 2003

2. **TARGET VARIABLE** : Controls the gas delivery during the breath

- Flow (Volume Control modes)
- Pressure (Pressure Control modes)

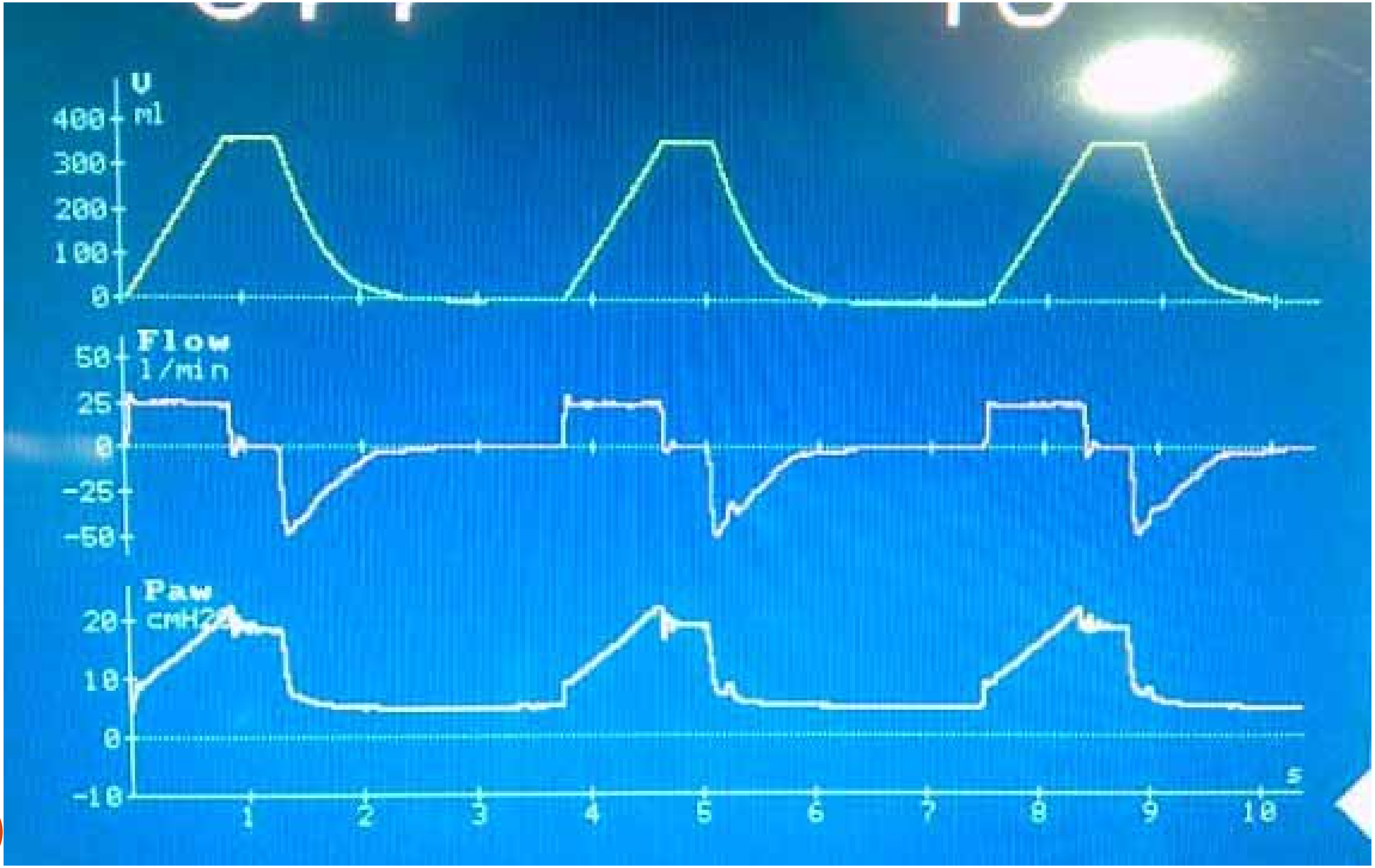
3. **CYCLE VARIABLE** : Cycled from inspiration into expiration

- Volume (Volume control)
- Time (Pressure control)
- Flow (pressure Support)
- Pressure (Safety cycling variable)

Modes of Ventilation

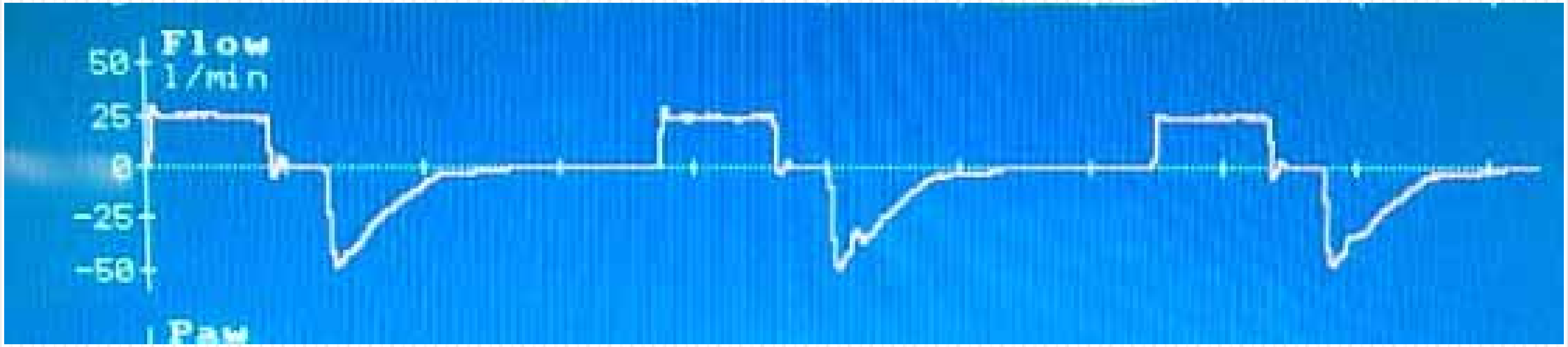
Mode of ventilation	Breath types available
Volume Assist Control	Volume Control, Volume Assist
Pressure Assist Control	Pressure Control, Pressure Assist
Volume SIMV	Volume Control, Volume Assist, Pressure Support
Pressure SIMV	Pressure Control, Pressure Assist, Pressure Support
Pressure Support	Pressure support

SCALARS



V
ml
400
300
200
100
0
Flow
l/min
50
25
0
-25
-50
Paw
cmH2O
20
10
0
-10
1
2
3
4
5
6
7
8
9
10
s

FLOW vs TIME



Flow versus time

Never forget to look at the expiratory limb of the flow waveform

The expiratory flow is determined by the *elastic recoil* of the respiratory system and *resistance* of intubated airways

Types of Inspiratory flow waveforms

a. Square wave flow
b. Ascending ramp flow
c. Descending ramp flow
d. Sinusoidal flow
e. Decay flow

Which form to use??

- Pressure control mode : Always Decelerating or decay flow. Cannot be changed.
- Volume control mode : Flow waveform can be changed depending on the ventilator options.

SQUARE FLOW WAVEFORM :

• Inspiratory time is shortest for Square wave flow form.

• Highest Peak Inspiratory pressures

•Low Mean Inspiratory pressure,, thus better venous return and cardiac output

DESCENDING RAMP FLOW :

• Increases inspiratory time (if not fixed) or peak inspiratory flow rate (if inspiratory time is fixed)

•Least Peak inspiratory pressures (19% decrease).

•High mean airway pressure, helps lung inflation and oxygenation.

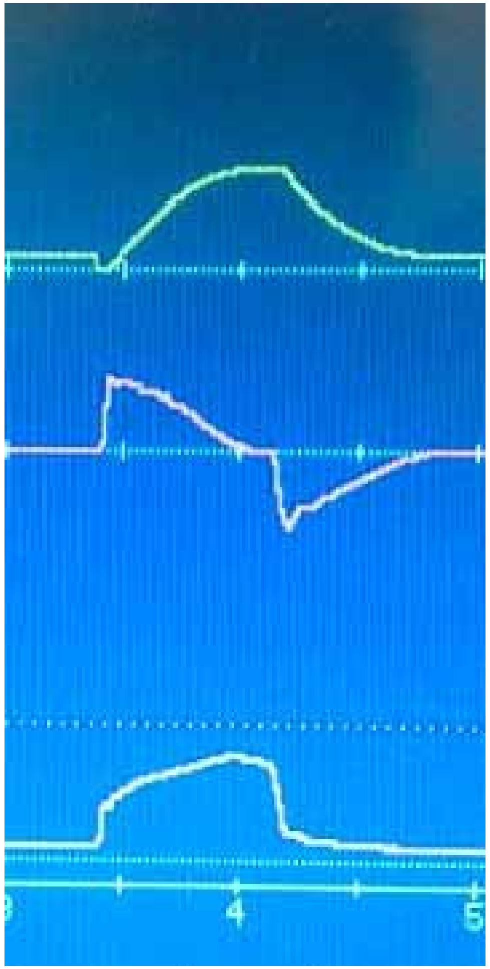
Sinusoidal and ascending ramp flow :

- Initial flow rates are slow and hence cause dyssynchrony – FLOW STARVATION.
- Should not be used in assist modes.

Descending ramp and Square wave flow :

- Usually preferred as the initial flow rate meets the flow demand of the patient. Decreases air hunger.

SQUARE WAVE FLOW



DECSENDING RAMP FLOW

Decelerating flow waveform

- Advantages :
  - Decreases Peak inspiratory pressures
  - Increases oxygenation, decreases A-aDo2
  - Improves patient ventilator synchrony (more physiological)
- Disadvantages :
  - Decreases expiratory time , potential for auto PEEP
  - Increases mean airway pressure, decreases cardiac output
  - Increased intracranial pressures

Egan's Fundamentals of Respiratory Care. 8th ed. 2003:1064.

MechanicalVentilation; Physiological and Clinical Applications.4thed.2006:113.

Intensive Care Med. 1985;11:68-75.

Expiratory flow waveform

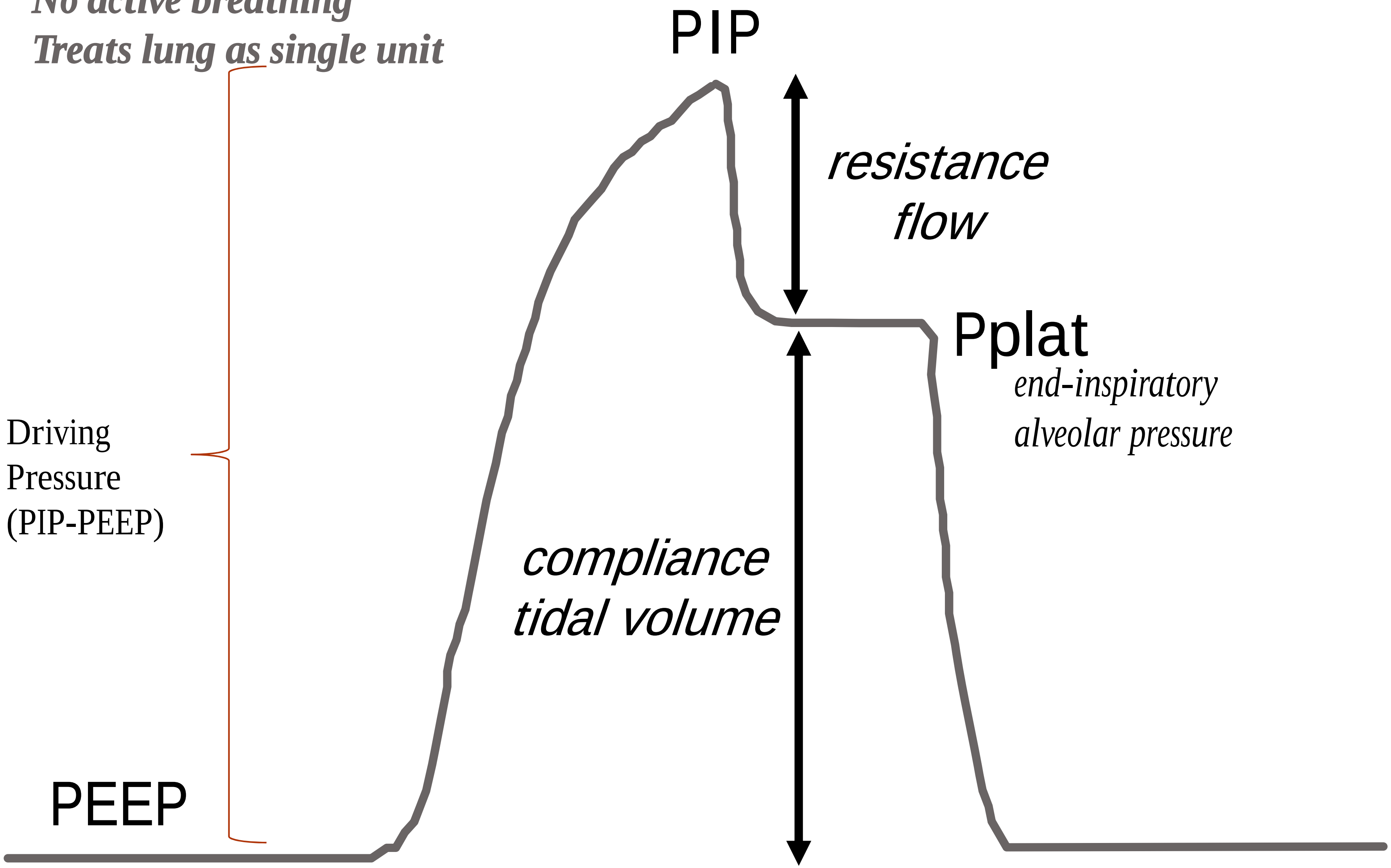
- Passive and determined by compliance of the lung and resistance of the airways.

- Four points to be observed :
  1. Peak Expiratory Flow
  2. Slope of the expiratory limb
  3. Expiratory time
  4. Does the waveform reach the baseline?

PRESSURE vs TIME

Pressu

No active breathing
Treats lung as single unit



$$PIP - PEEP = (Flow \times Resistance) + (Vt / Compliance\ RS)$$

Respiratory System Compliance

$$C = \frac{\text{tidal volume}}{\text{Pplat - PEEP}}$$

Decreased with:

Pulmonary Disorder:

- mainstem intubation
- congestive heart failure
- ARDS
- Atelectasis, consolidation
- fibrosis
- Hyperinflation
- Tension pneumothorax
- pleural effusion

Extra Pulmonary Disorder:

- abdominal distension
- chest wall edema/Obesity
- thoracic deformity

Normal : 100 mL/cm H_2O

Pplat – PEEP = Vt / Compliance

- P plateau increased by
  a) Decreasing compliance of lung : Pulm edema, ARDS, Atelectasis, Pneumonia.
  b) Decreasing compliance of the chest wall : Morbid obesity, ascites, stiff chest wall.
  c) Increasing Tidal volume
  d) Patient ventilator dyssynchrony

Inspiratory Resistance

$$R_i = \frac{PIP - Pplat}{flow}$$

Increased with:

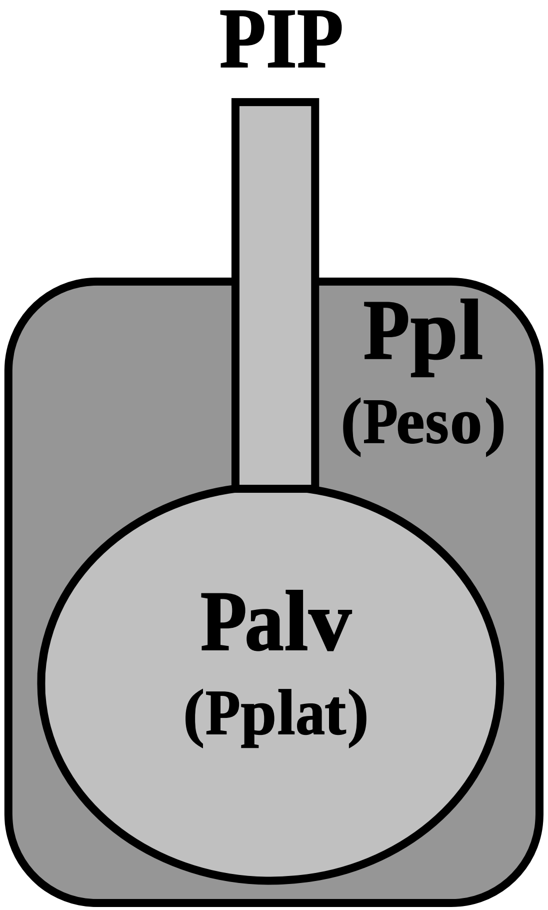
- Airways : Secretions, Mucus plugging, Bronchospasm
- ET tube : Small size, ET block
- Ventilator Circuit: Kinking, Clogged HME

Normal: 5 - 10 cm H_2O/L/s for intubated ventilated adults

measured with 60 L/min (1 L/s) constant flow

P peak – P plat = Flow x Resistance

- Increased by
  a) Increasing resistance : Bronchospasm, Mucus plugging/secretions, ET block , Biting the ET tube, Tube kinking, Clogged HME.
  b) Increasing flow : Increasing Vt, Increasing Insp.pause, Increasing I:E ratio



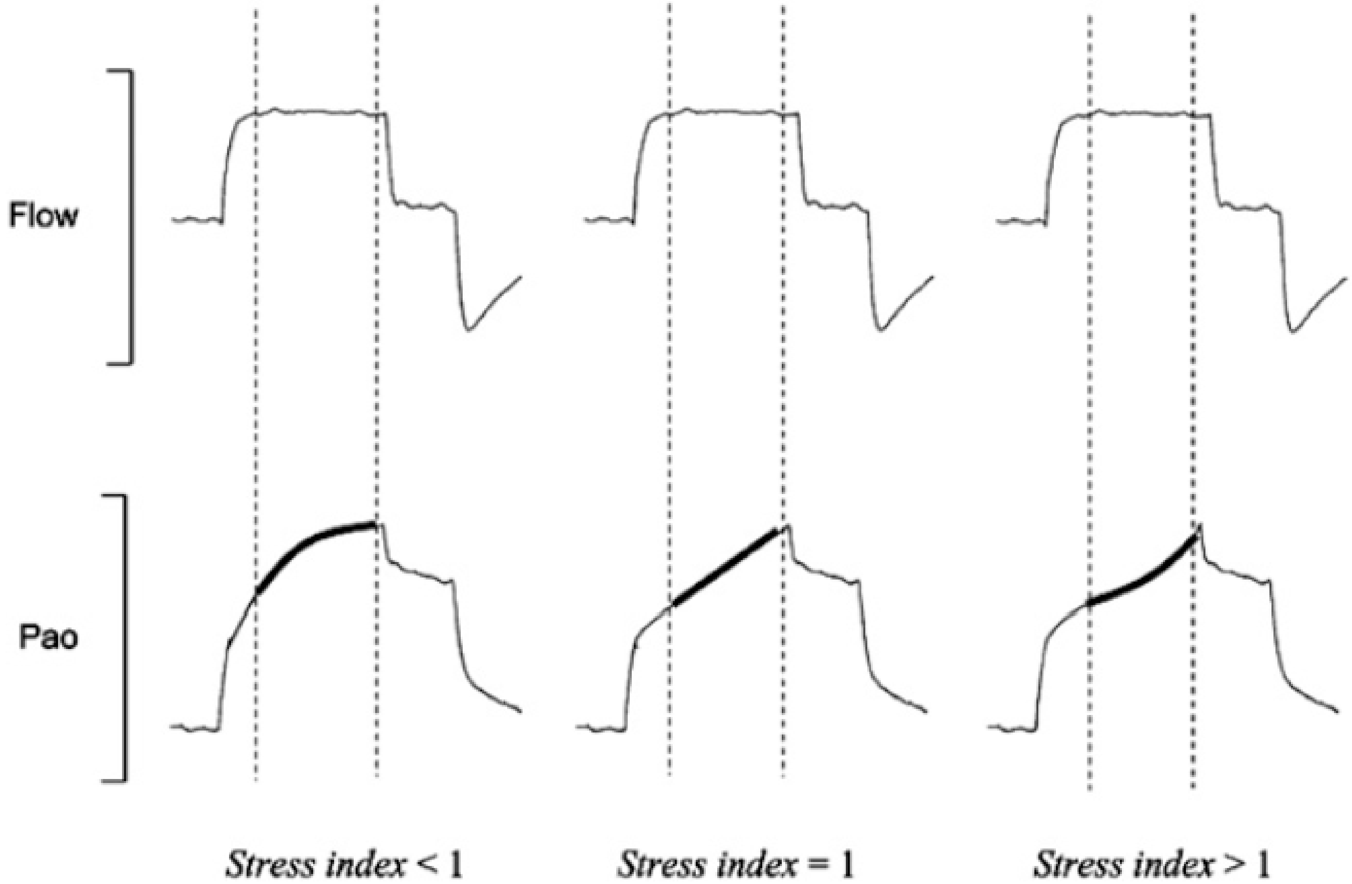
$$Crs = \frac{\text{tidal volume}}{\text{Pplat - PEEP}}$$

$$Ccw = \frac{\text{tidal volume}}{\Delta \text{Peso}}$$

$$C_L = \frac{\text{tidal volume}}{(\text{Pplat} - \text{PEEP}) - \Delta \text{Peso}}$$

$$R_i = \frac{\text{PIP - Pplat}}{\text{flow}}$$

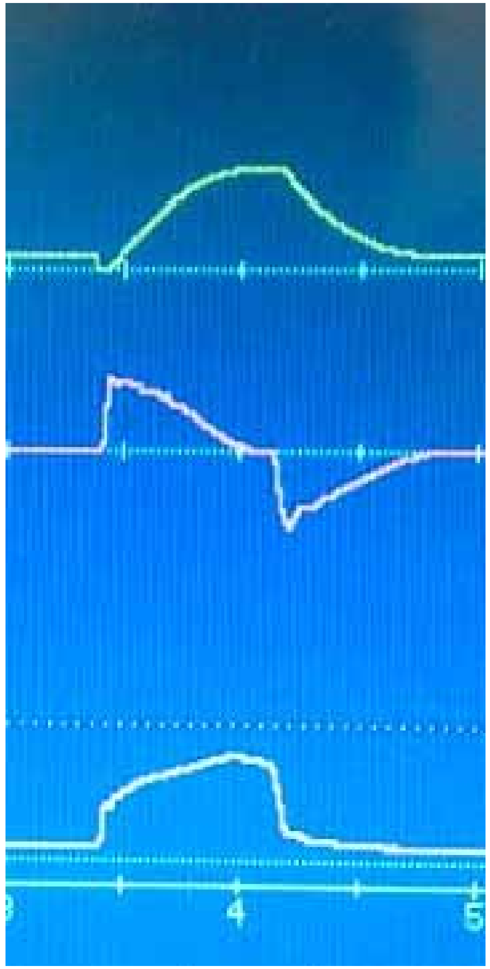
STRESS INDEX (ARDS)



Increase PEEP (Recruitment) | Ideal PEEP | Decrease PEEP (Overdistension)

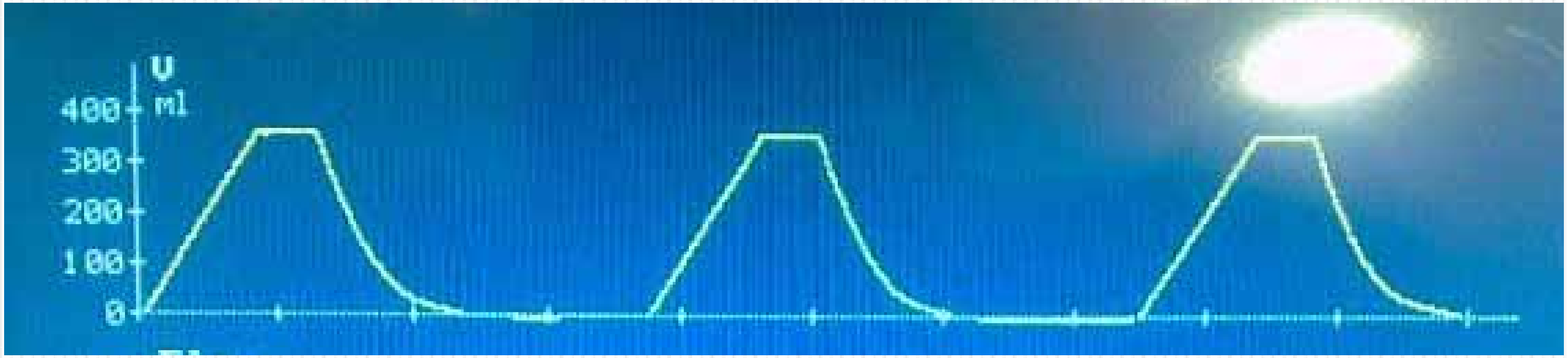
Chest 2010;137;1203-1216

SQUARE WAVE FLOW



DECSENDING RAMP FLOW

VOLUME vs TIME



Information derived from Volume Time Scalar

Tidal Volume	Volume on y axis
Air leak	Expiratory limb fails to return to x axis
Active Expiration	Tracing continues beyond the baseline
Auto PEEP	Expiratory limb fails to reach the baseline

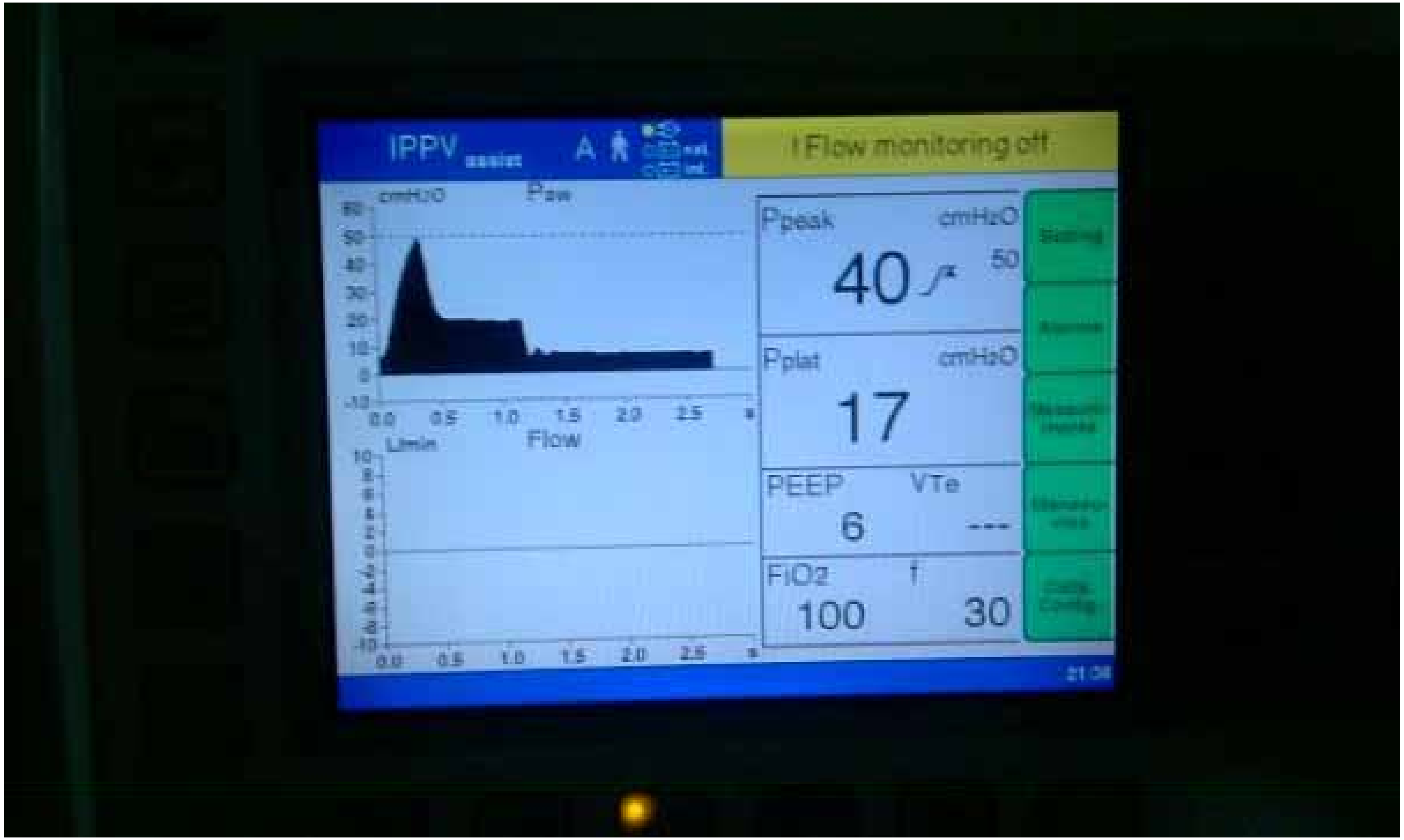
HOW TO USE THE GRAPHS FOR DIAGNOSIS OF DISEASE STATES ?

Which waveforms to monitor ?

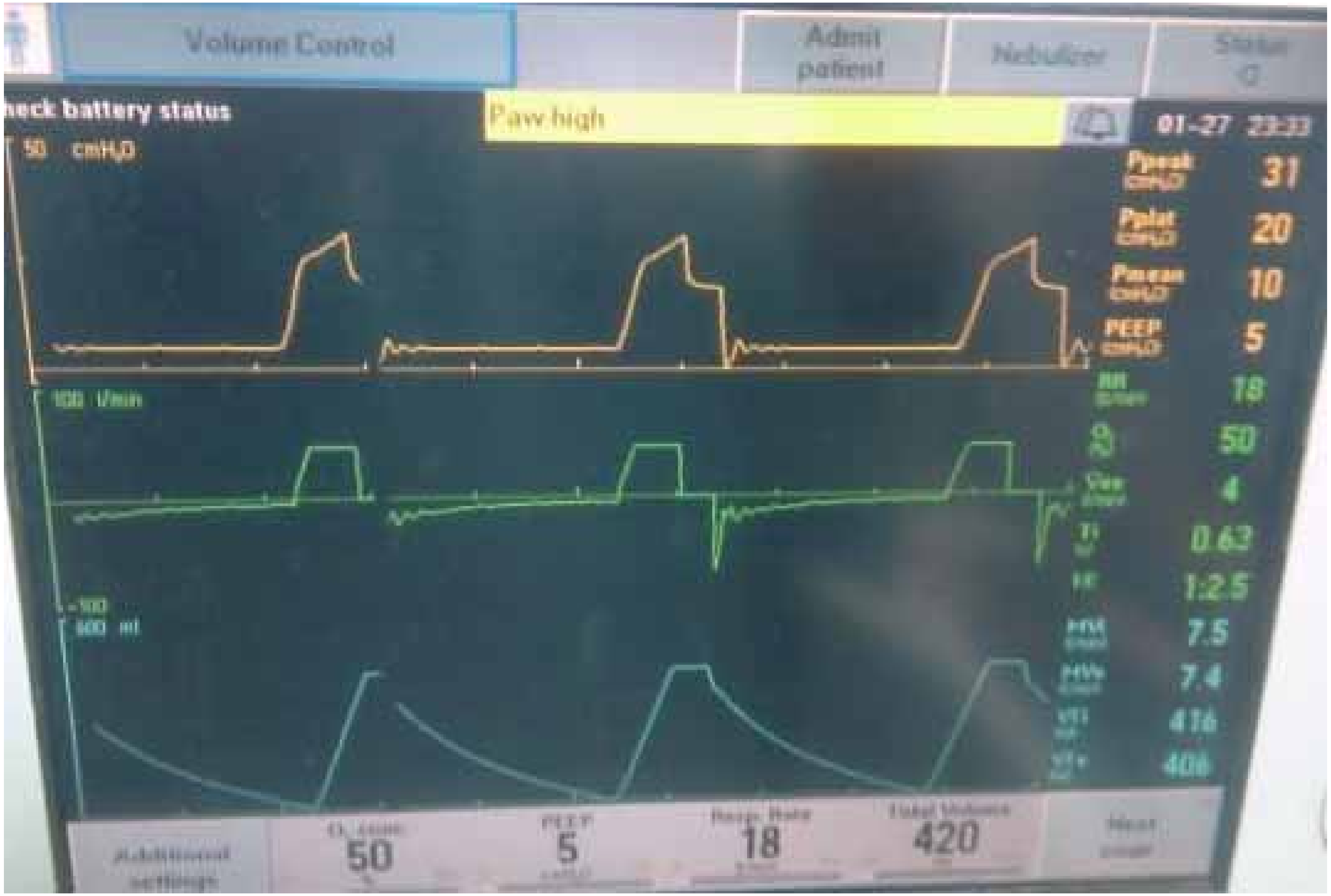
Mode of ventilation	Independent variables	Dependent variables	Waveforms that will be useful	Waveforms that normally remain unchanged
Volume Control/ Assist-Control	Tidal volume, RR, Flow rate, PEEP, I/E ratio	P_{aw}	**Pressure-time:** Changes in P_{ip}, P_{plat} **Flow-time (expiratory):** Changes in compliance **Pressure-volume loop:** Overdistension, optimal PEEP	Volume-time Flow time (inspiratory)
Pressure Control	P_{aw}, Inspiratory time (RR), PEEP and I/E ratio	$V_{t,\ flow}$	**Volume-time and flow-time**: Changes in V_t and compliance **Pressure-volume loop:** Overdistension, optimal PEEP	Pressure-time
Pressure support/ CPAP	PS and PEEP	V_t, and RR, flow, I/E Ratio	**Volume- time** **Flow- time** (for V_t and V_E)	

Increased airway resistance (ACMV- VC)

- Pressure Time Waveform :
  - Increased difference between Ppeak and Pplat
  - Normal P plat
- Expiratory flow waveform :
  - Decreased PEFR
  - Increased expiratory time
  - Scooped out appearance of expiratory limb
  - Potential for auto PEEP
  - Loss of peak (emphysema)
- Volume Time Waveform :
  - Expiratory limb long



A patient with Endotracheal Tube block (When received from Dialysis room)



A patient with acute severe asthma on ventilator

Decreased Compliance of Respiratory System

- Pressure Time Waveform :
  - Increased P plat and Ppeak.
  - Normal P peak – Pplat

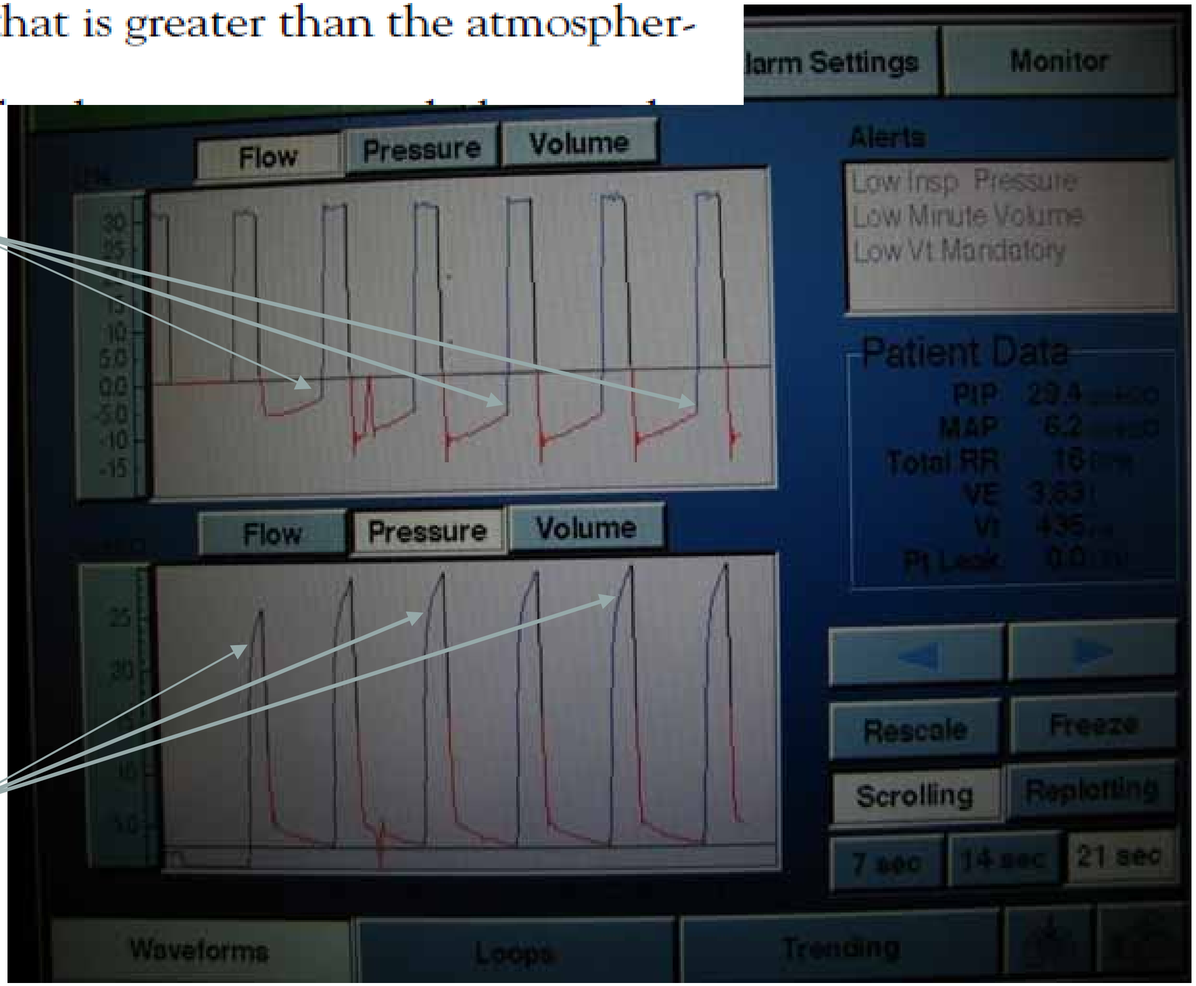
- Flow Time Waveform :
  - Increased PEFR
  - Shortened expiratory time

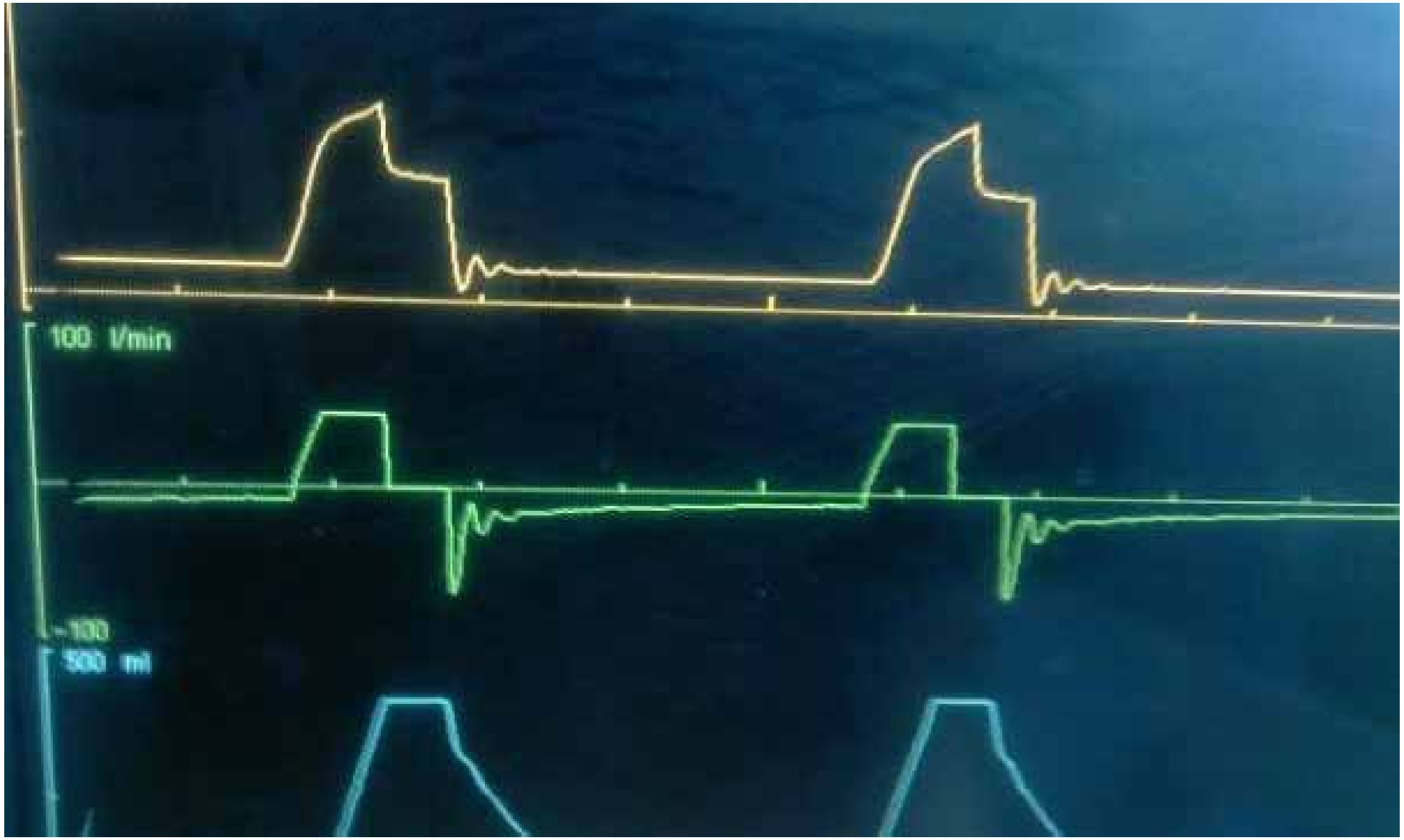
Auto PEEP/Intrinsic PEEP

Positive end-expiratory pressure (PEEP) is defined as pressure in the alveoli at the end of exhalation that is greater than the atmospheric pressure.

Notice how the expiratory flow fails to return to the baseline indicating air trapping (Auto PEEP)

Also notice how air trapping causes an increase in airway pressure due to increasing end expiratory pressure and end inspiratory lung volume.





A patient of acute severe asthma. Note failure of expiratory limb to return to baseline

Physiologic mechanisms of auto-positive end-expiratory pressure

Dynamic hyperinflation
plus intrinsic expiratory flow limitation

- Chronic obstructive pulmonary disease

Dynamic hyperinflation
without intrinsic expiratory flow limitation

- Breathing pattern and ventilator settings
  - Rapid breaths
  - High tidal volume
  - Inspiration greater than expiration
  - End-inspiratory pause
- Added flow resistance
  - Fine-bore endotracheal tube
  - Ventilator tubing and devices

Without dynamic hyperinflation

- Recruitment of expiratory muscles

AUTO- PEEP : Consequences

- Increases the work of Triggering
- Ineffective triggering
- Worsens Oxygenation
- Lung Hyperinflation- barotrauma
- Hemodynamic Compromise

AUTO PEEP : Recognition

- Analysis of ventilator graphics:
  - Pressure wave: while performing an expiratory hold, the waveform rises above baseline.
  - Flow wave: the expiratory flow doesn't return to baseline before the next breath begins.
  - Volume wave: the expiratory portion doesn't return to baseline.
  - Flow/Volume Loop: the loop doesn't meet at the baseline
  - Pressure/Volume Loop: the loop doesn't meet at the baseline
- Delay between start of Inspiratory effort and Pressure drop
- No increase in P peak with increase in Applied PEEP

Treatment of auto-positive end-expiratory pressure

Change ventilator settings
- Increase expiratory time
- Decrease respiratory rate
- Decrease tidal volume

Reduce ventilatory demand
- Reduce anxiety, pain, fever, shivering
- Reduce dead space
- Give sedatives and paralytics

Reduce flow resistance
- Use large-bore endotracheal tube
- Suction frequently
- Give bronchodilators

Counterbalance expiratory flow limitation
- External positive end-expiratory pressure

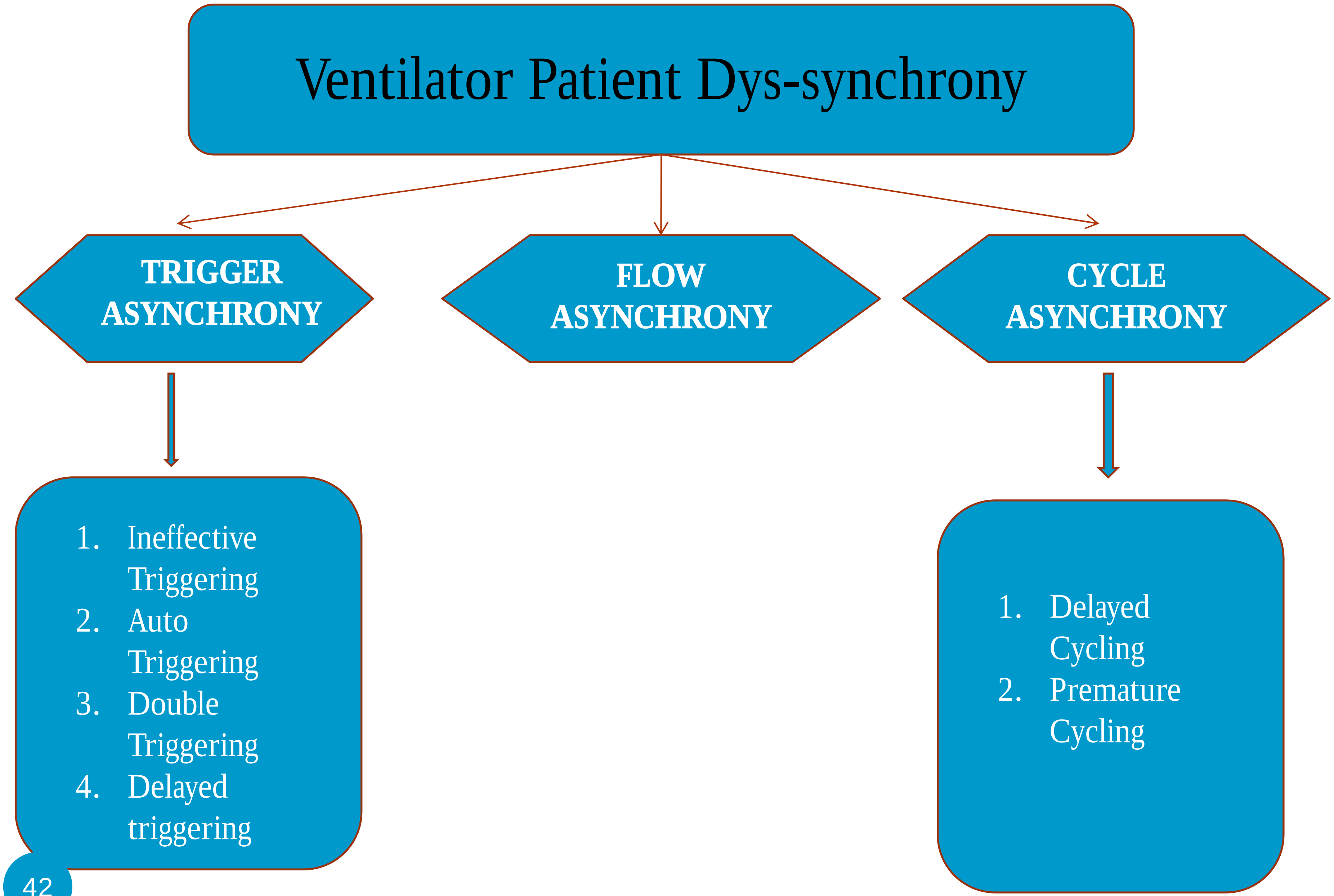
VENTILATOR PATIENT SYNCHRONY

VS

DYS-SYNCHRONY

What is Ventilator Patient Synchrony?

- The ventilator should start inspiration at the time of onset of patients inspiration.
- The flow provided by the ventilator should meet the flow demand of the patient.
- The Ventilator Inspiratory time should match with the patients inspiratory time.


Ventilator Patient Dys-synchrony
TRIGGER ASYNCHRONY
FLOW ASYNCHRONY
CYCLE ASYNCHRONY
1. Ineffective Triggering
2. Auto Triggering
3. Double Triggering
4. Delayed triggering
1. Delayed Cycling
2. Premature Cycling

INEFFECTIVE TRIGGGERING

- One of the most common asynchronies
- Failure of the patients inspiratory effort to initiate a ventilator breath.
- Identified by
  - Visual inspection of patients expanding thoracic volume but without delivery of ventilator breath.
  - Ventilator graphics which show a decrease in airway pressure with an increase in flow but no initiation of breath.

Ineffective triggering

- What causes this?
  - Improper sensitivity of trigger threshold
  - Respiratory muscle weakness (disease related, critical illness neuromyopathy, electrolyte imbalances)
  - Intrinsic PEEP in COPD patients
  - Decreased respiratory drive (Excessive sedatives)
  - Alkaline pH
  - External nebulizers
  - High Tidal volumes / High Pressure support decrease respiratory drive.

AUTO TRIGGERING

Definition : Ventilator delivers an assisted breath that was not initiated by the patient

Causes :

1. Circuit leaks (ET cuff, ICTD with BPF etc)
2. Fluid in the circuit
3. Cardiac oscillations (High cardiac output states)
4. Very low trigger threshold

.

DOUBLE TRIGGERING

- Patients inspiration continues after the ventilator inspiration and triggers another breath immediately after the inspiration.
- Also called Breath Stacking

Causes :

1. High Ventilatory demand of the patient (ARDS)
2. Inappropriate settings (Low tidal volume, Short inspiratory time, High cycle threshold)

A case of Morbid Obesity with Obesity hypoventilation syndrome.
Note the low tidal volumes generated on PSV mode

DELAYED TRIGGERING

Components of Triggering :

- Trigger threshold : The pressure / flow that must be attained by the patients breath to trigger the ventilator.
- Inspiratory Trigger Time (ITT) : Time from the initiation of effort to the Trigger threshold .
- Rise Time to Baseline Pressure (RTBP)

Inspiratory Delay Time (IDT) = ITT + RTBP

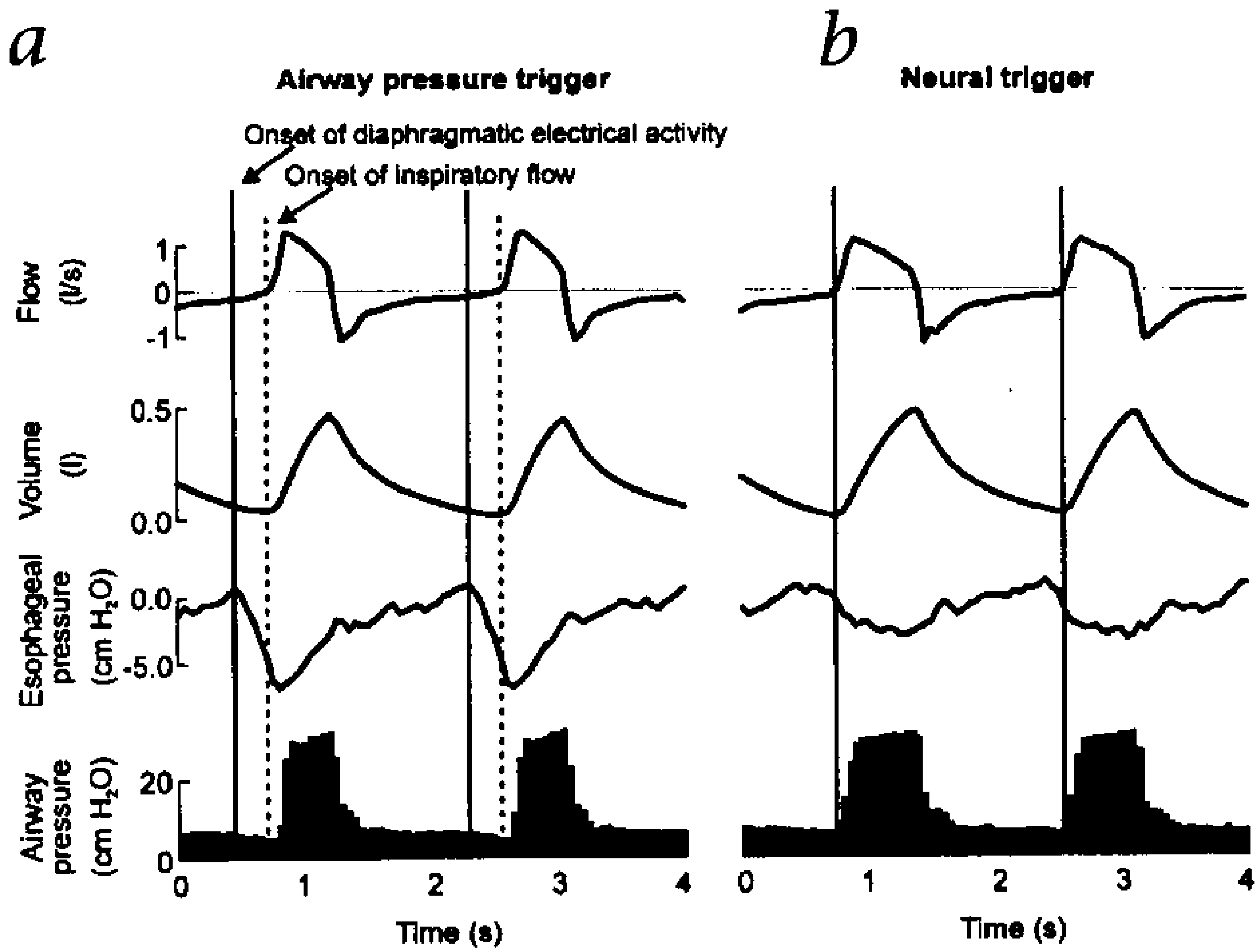
DELAYED TRIGGERING

- An Inherent problem with all the conventional modes of ventilation
- Can be overcome by
  - Newer modes of ventilation (NAVA)
  - Newer methods of triggering (Shape signal triggering)

Neurally Adjusted Ventilatory Assist (NAVA)

Diaphragmatic Electrical activity is sensed by an electrode placed in the esophagus and is used to trigger the breath and cycle into expiration.

Sinderby C et al. Nat Med 1999;5(12):1433-1436.



Sinderby Nature Med 1999;5:1433
NEJM 2001;344 : 1986-1996

FLOW ASYNCHRONY

Causes :

- High Ventilatory demand (ALI / ARDS)
- Low ventilatory settings (Flow rate, Tidal volume, Pramp)

What to do :

- Treat reversible causes of air hunger (fever, acidosis)
- Increase the tidal volume (if feasible)
- Increase the flow rate (directly, or by decreasing inspiratory time, increasing pause)
- Change to pressure control mode with variable flow
- Sedate / Paralyze the patient (last resort)

Patient of ARDS being ventilated using ARDS Network strategy
(Tidal volume = 6 ml/kg, Body weight = 66 kg)

Tidal volume increased to 440 ml from 400 ml to improve the flow synchrony

Same patient during a spike of fever 39.2 C showing severe flow dyssynchrony

CYCLING ASYNCHRONY

- **Delayed Cycling** : Ventilator Ti > Patient Ti

  Ventilator continues Inspiration when actually expiration has started.

- **Premature Cycling** : Ventilator Ti < Patient Ti

  Patients inspiratory effort continue into the expiratory phase of ventilator breath.

DELAYED CYCLING

Patient while weaning . Expiratory trigger sensitivity of 25 %

How to Manage :

- Decrease Inspiratory time
- Decrease Tidal volume (SCMV mode)
- Increase Expiratory Trigger Sensitivity (PSV mode)

Expiratory trigger sensitivity increased to 60 % to improve cycling synchrony.

A case of Acute severe asthma on SCMV mode.
I : E ratio kept at 1: 3.3 to avoid auto PEEP.
Ventilator shows double triggering

I : E ratio decreased to 1 : 2.5 along with control of bronchospasm.
None of the other parameters changed. No further double triggering.
Illustrates double triggering due to short inspiratory time and premature cycling

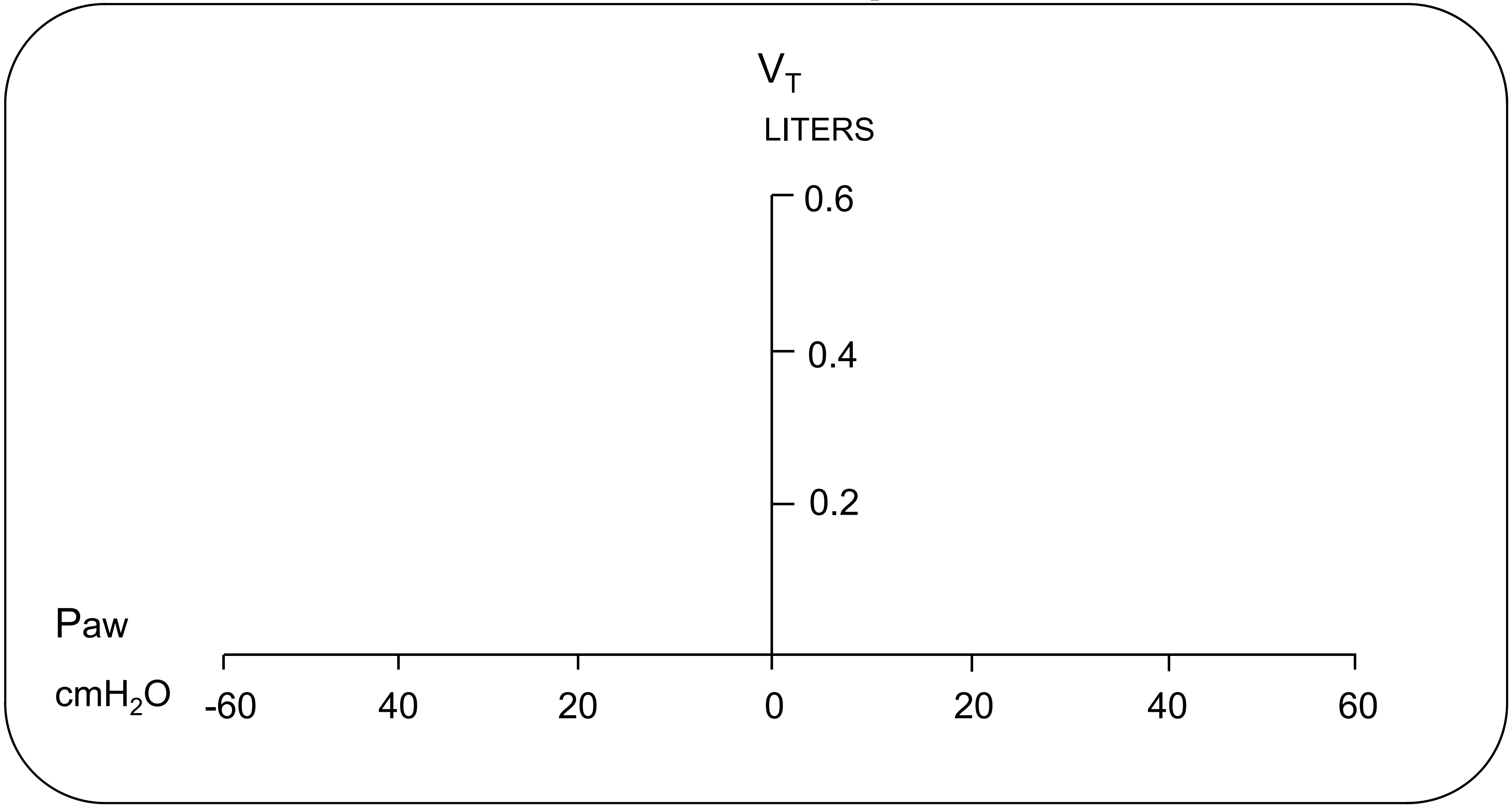
PATIENT VENTILATOR DYS-SYNCHRONY CLINICAL SIGNIFICANCE ??

- Increases Work Of Breathing
- Causes Ultra structural damage to the respiratory muscles.
- Worsens Respiratory mechanics (Auto PEEP)
- Alters gas exchange (Auto, double triggering – lower CO2)
- Increased need for sedation
- Longer duration of mechanical ventilation
- Difficulty in weaning
- Confounds lung protective ventilation (Double breaths)
- Sleep Fragmentation
- Inability to tolerate NIV

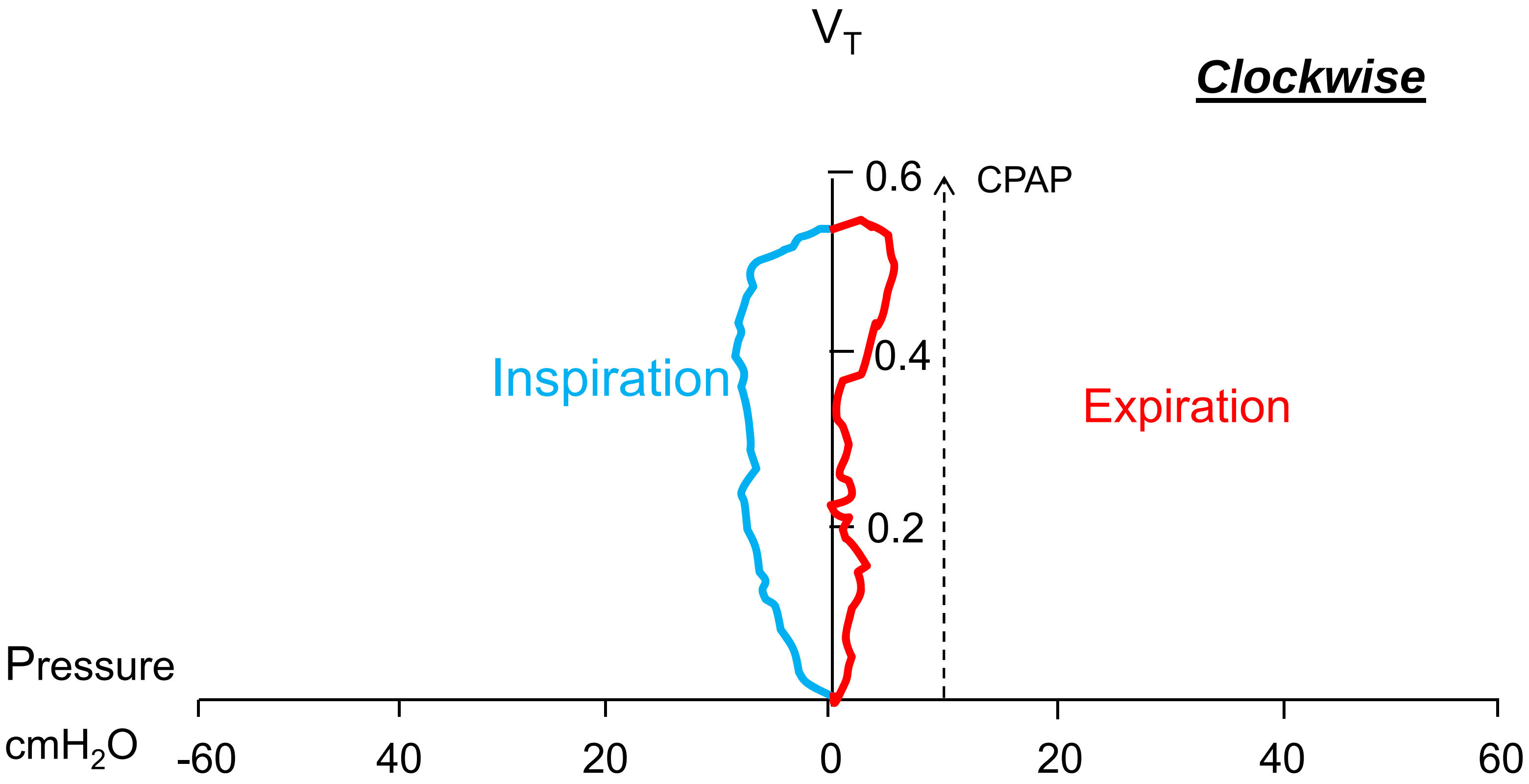
Loops

- **Pressure-Volume Loops**
- **Flow-Volume Loops**

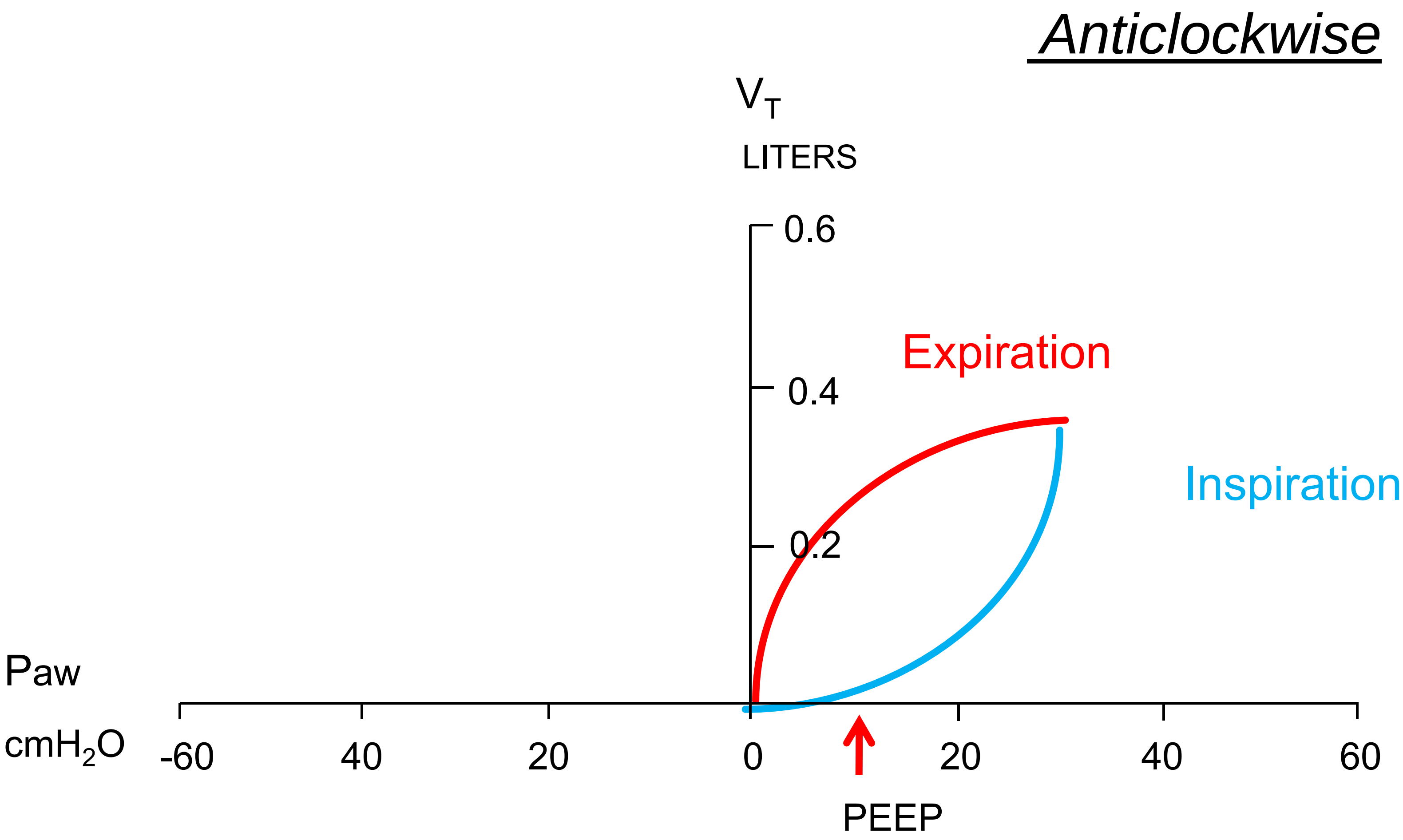
Pressure-Volume Loop



Spontaneous Breath

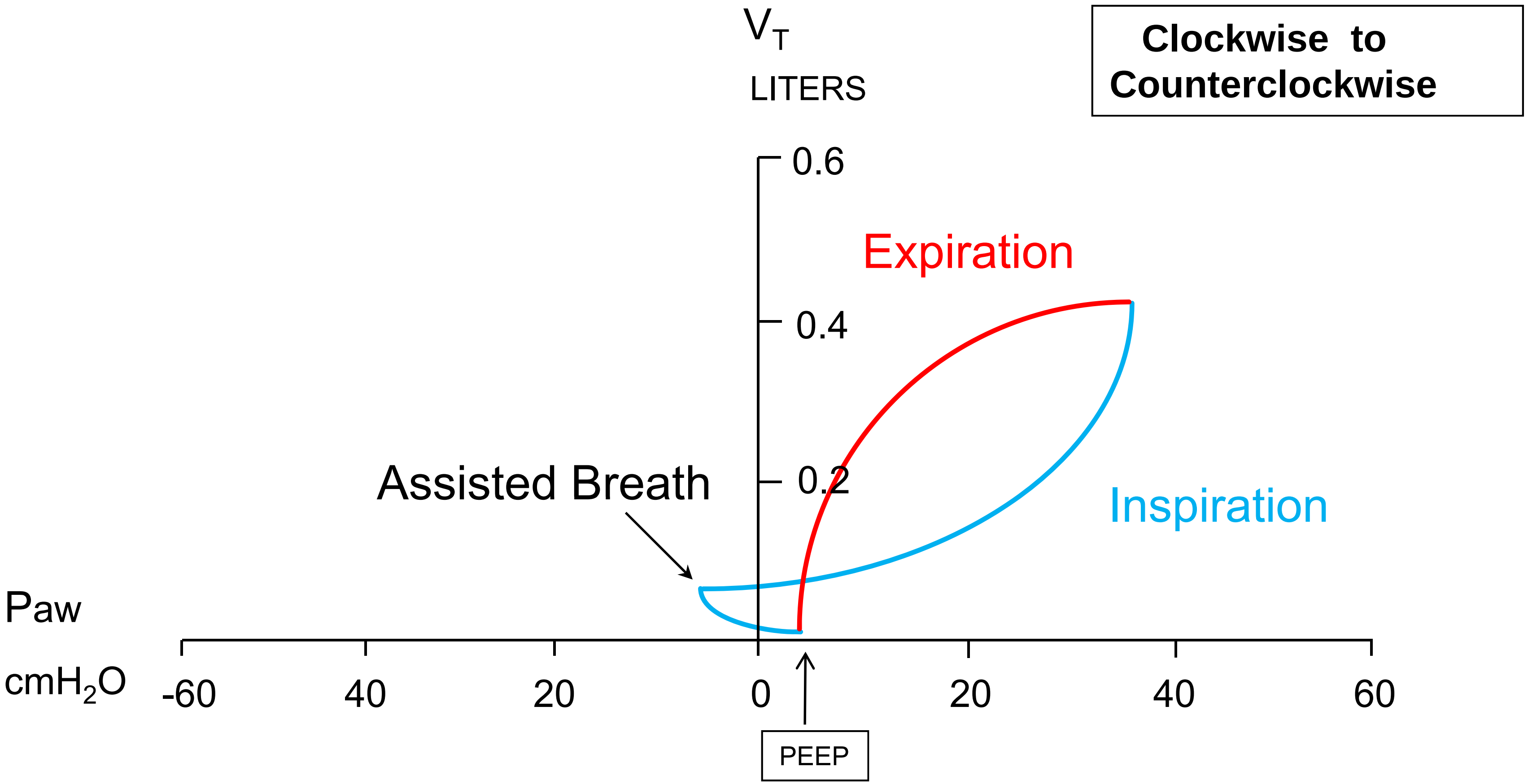


Controlled Breath

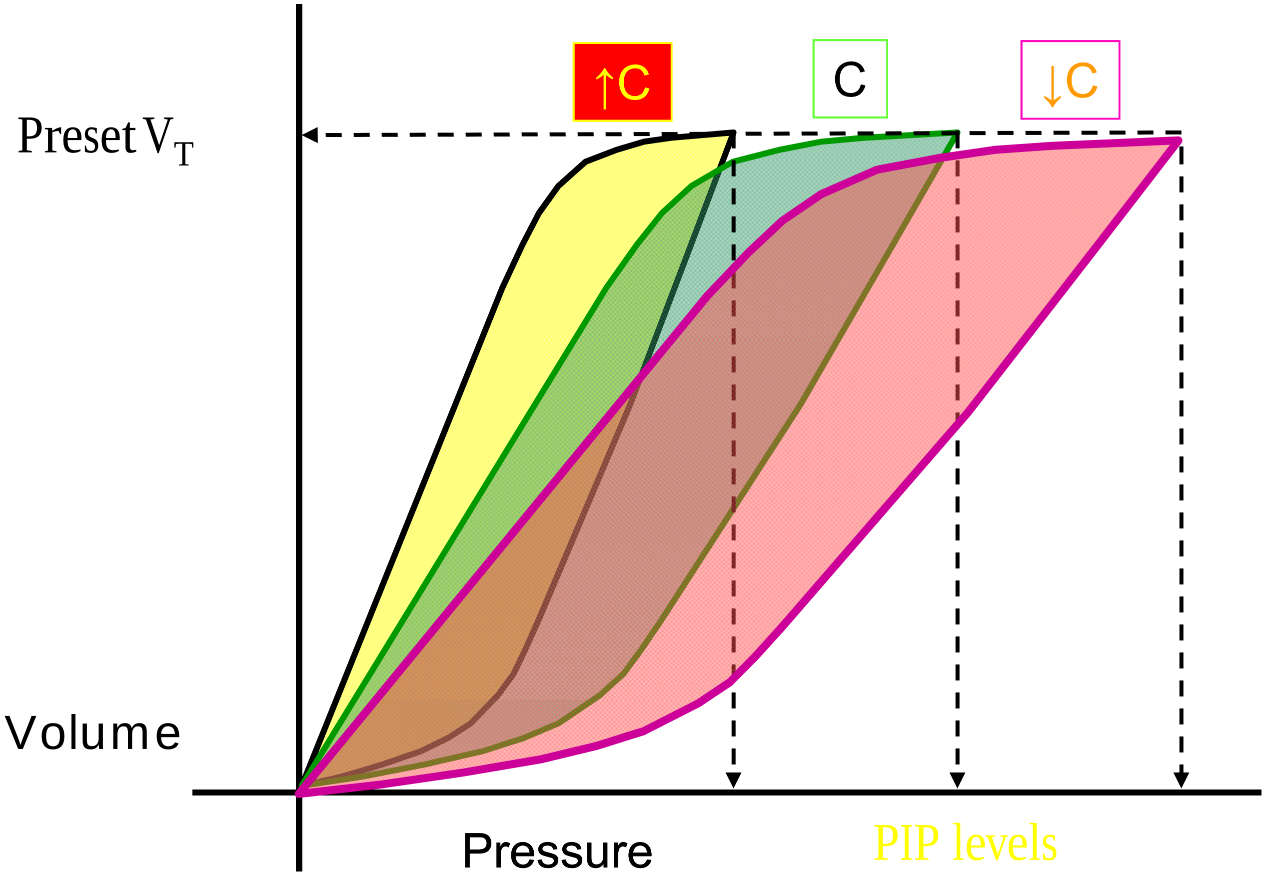


P-V loop and PEEP…..

Assisted Breath

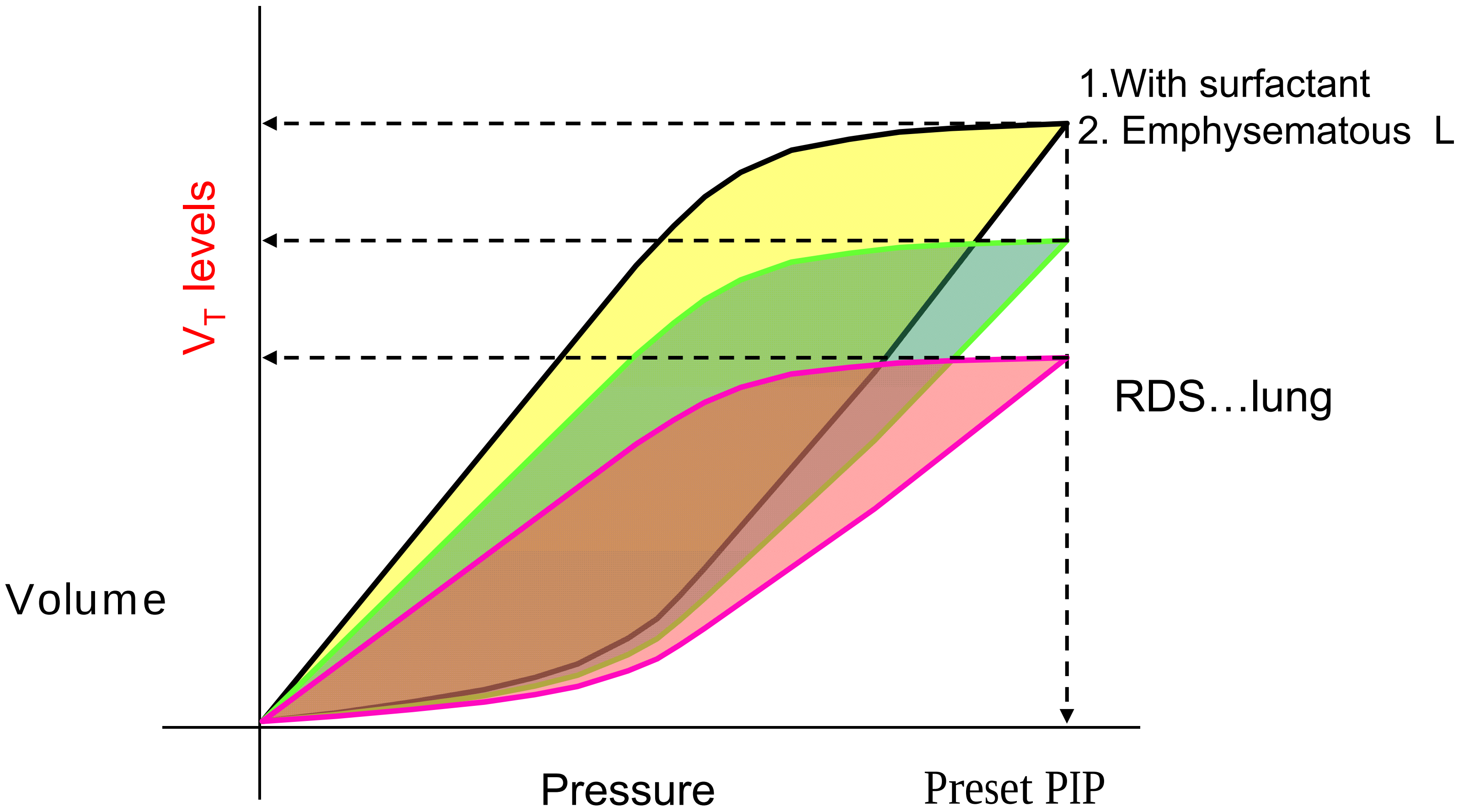


Lung Compliance Changes and the P-V Loop.... (Volume mode)



Constant V_T………. Variable Pressure

Lung Compliance Changing in P-V Loop (pressure mode)............



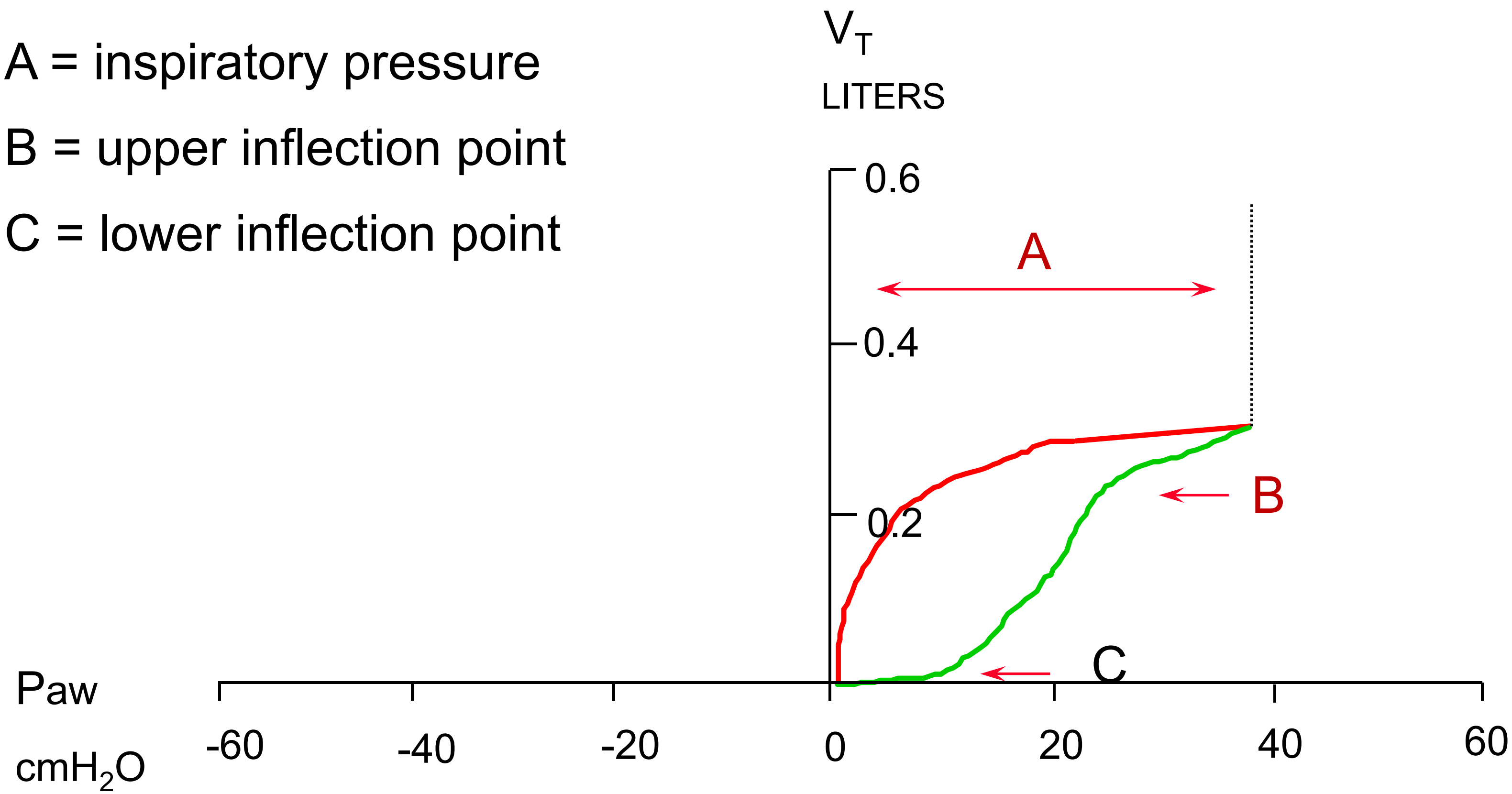
Constant PIP……… variable V_T

Overdistension

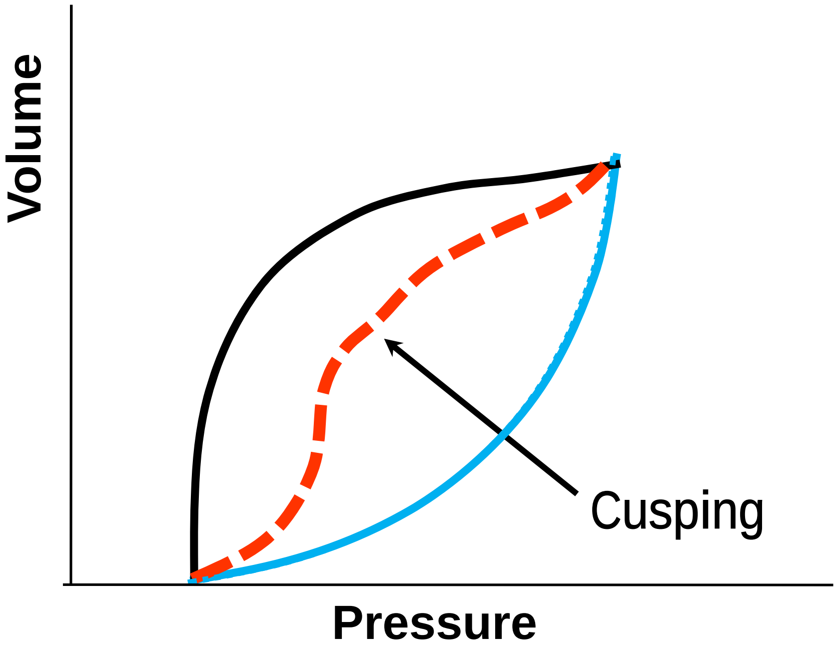
A = inspiratory pressure

B = upper inflection point

C = lower inflection point



Insufficient flow

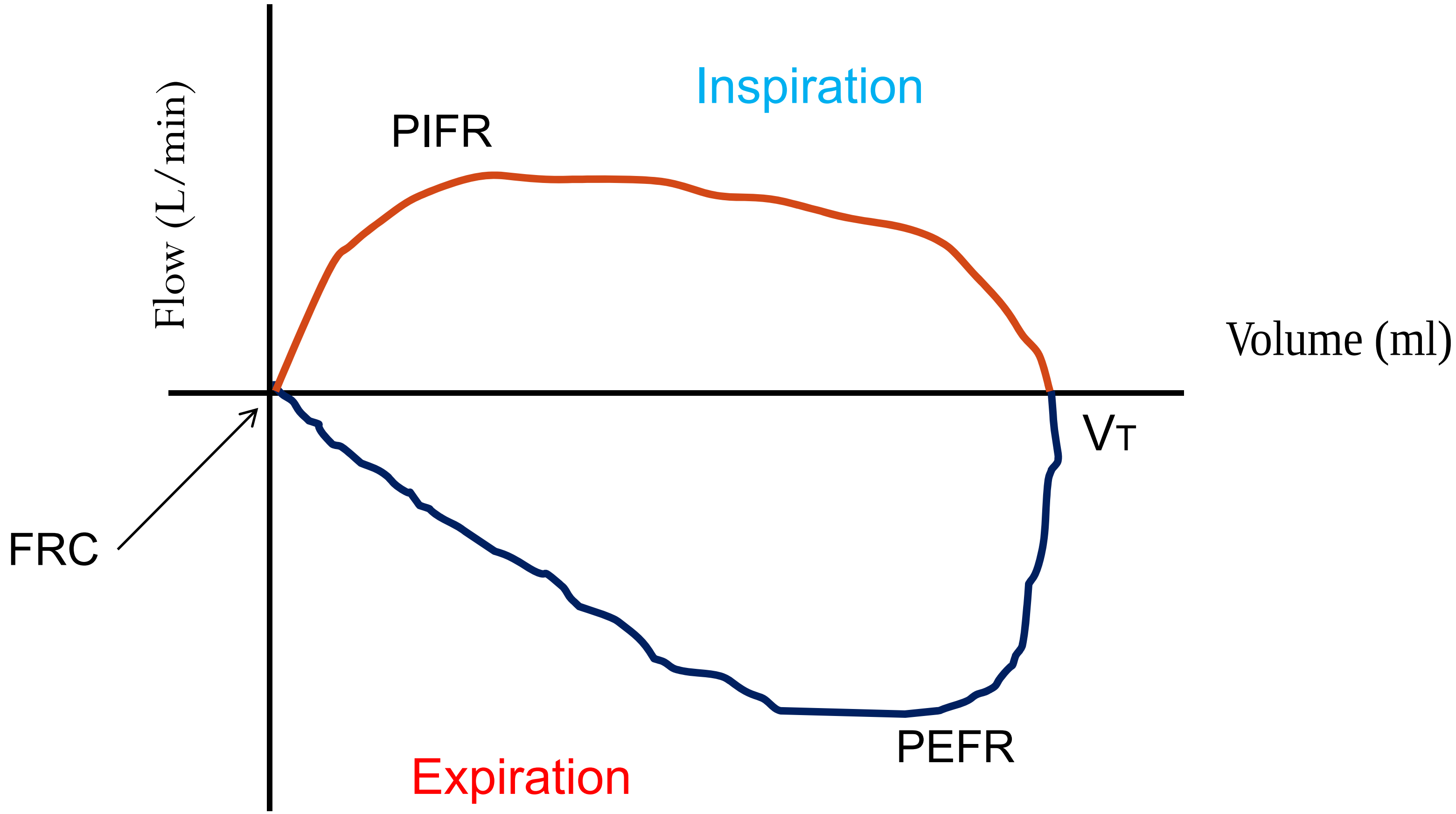


Normal

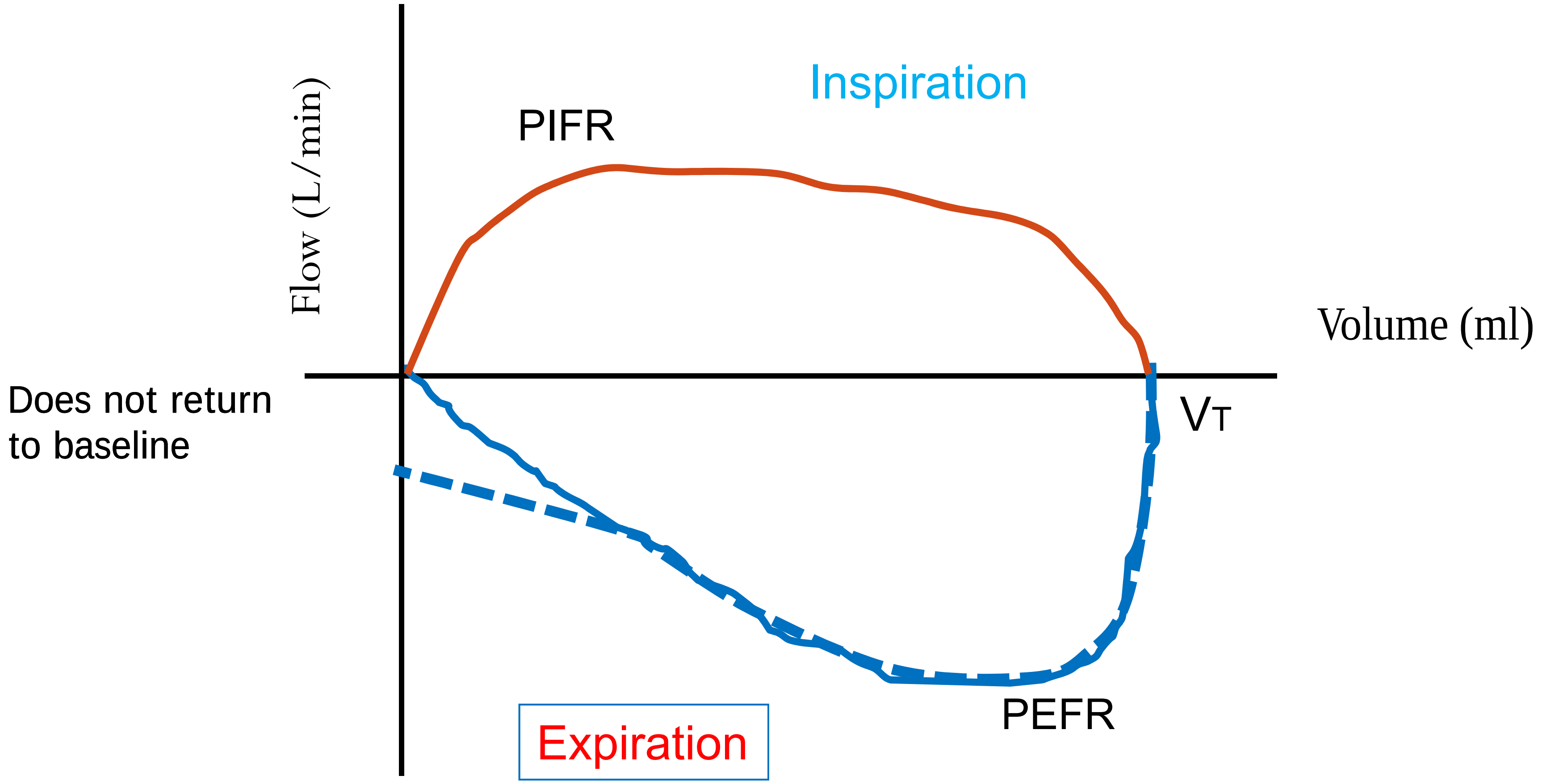
Insufficient Flow

Flow –Volume Loops……

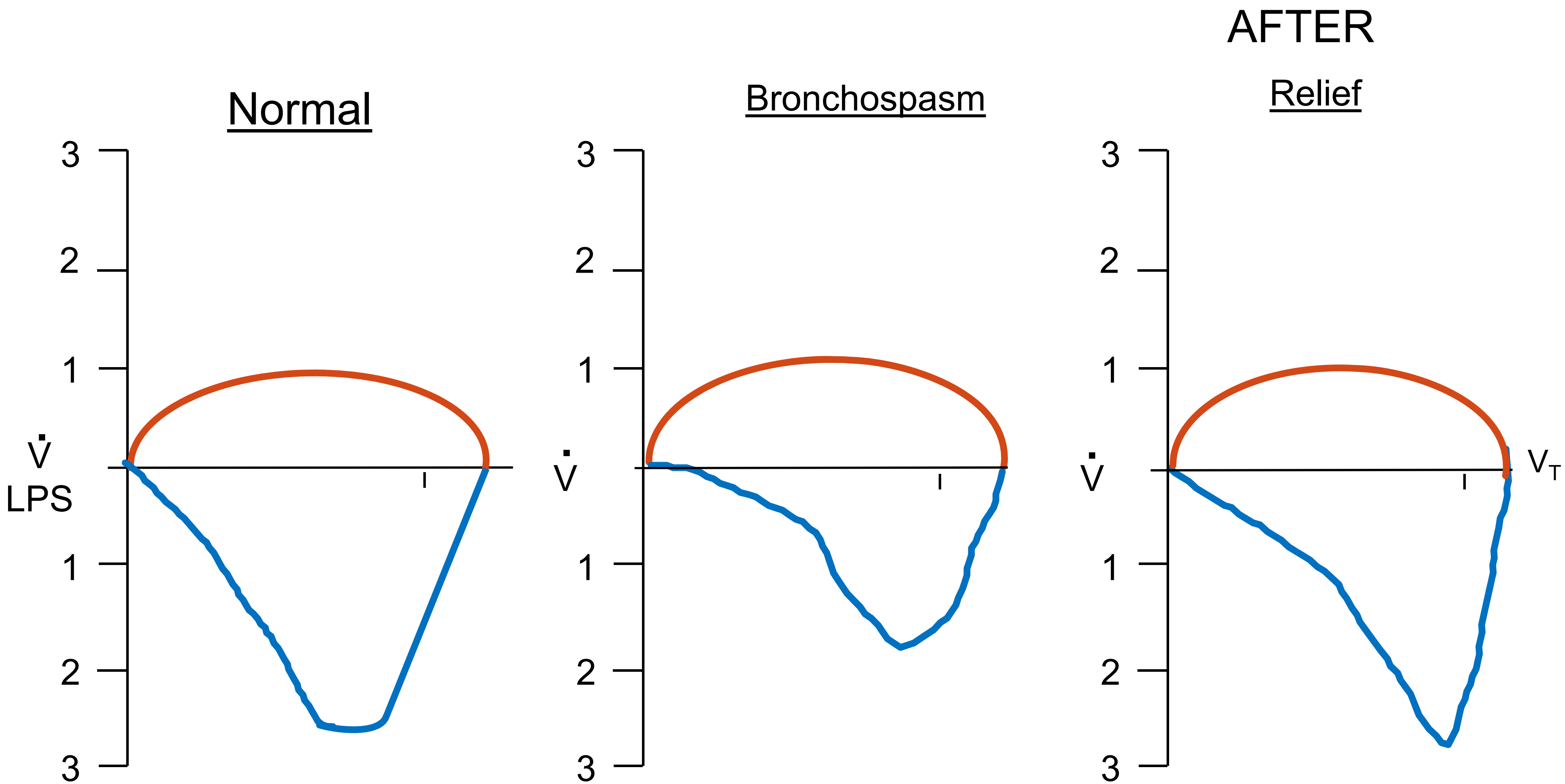
Flow-Volume Loop



Air Trapping



Bronchodilator Response….. F-V loop



SUMMARY

- Identify the correct waveforms to monitor
- Spend more time at the bedside
- Never Ignore any ventilator alarm

- Monitor P peak, P plat and expiratory limb of flow volume loop to diagnose changes in lung resistance or compliance.

- Identify Dys synchrony early and correct the cause.