Ventilator Waveforms: Interpretation

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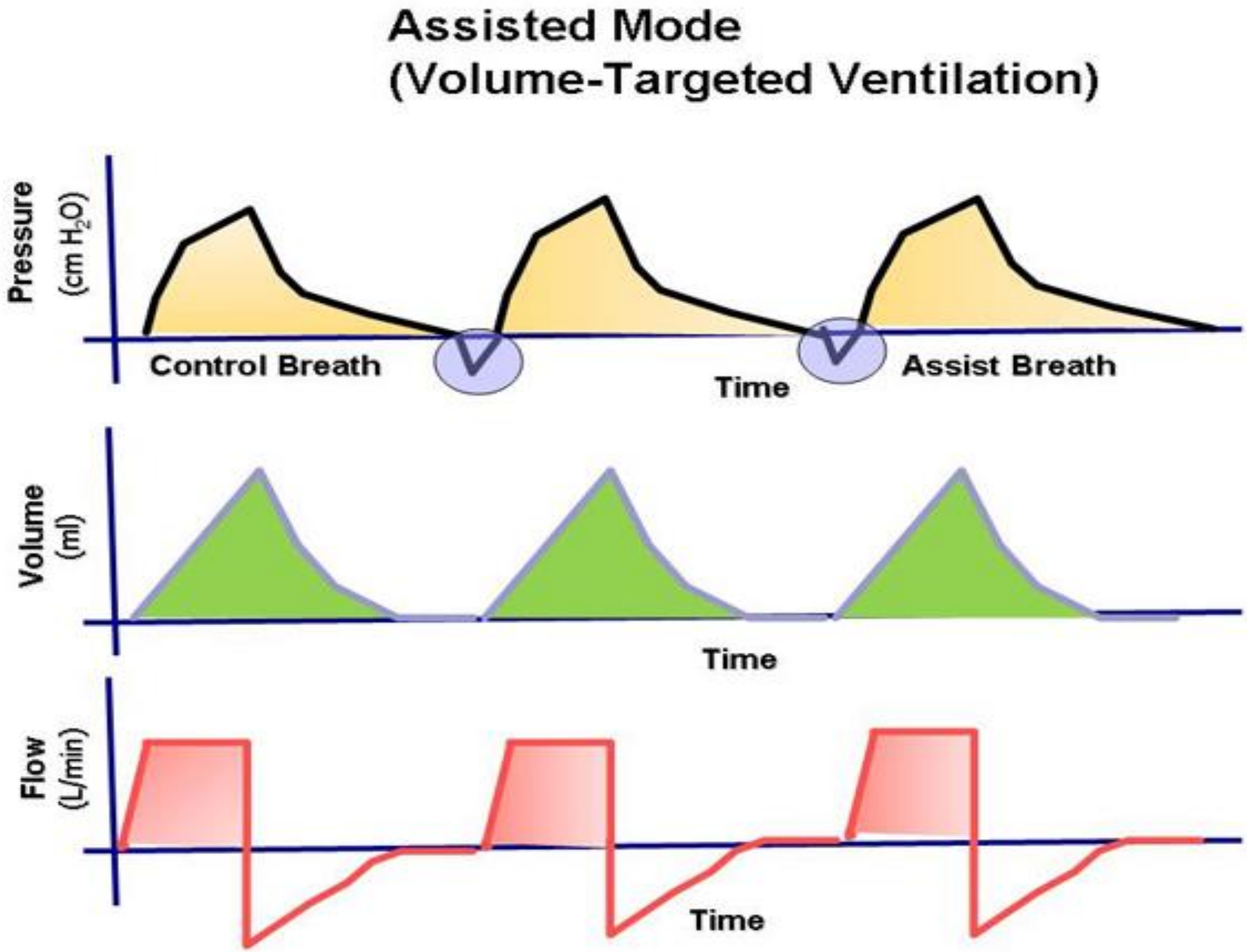
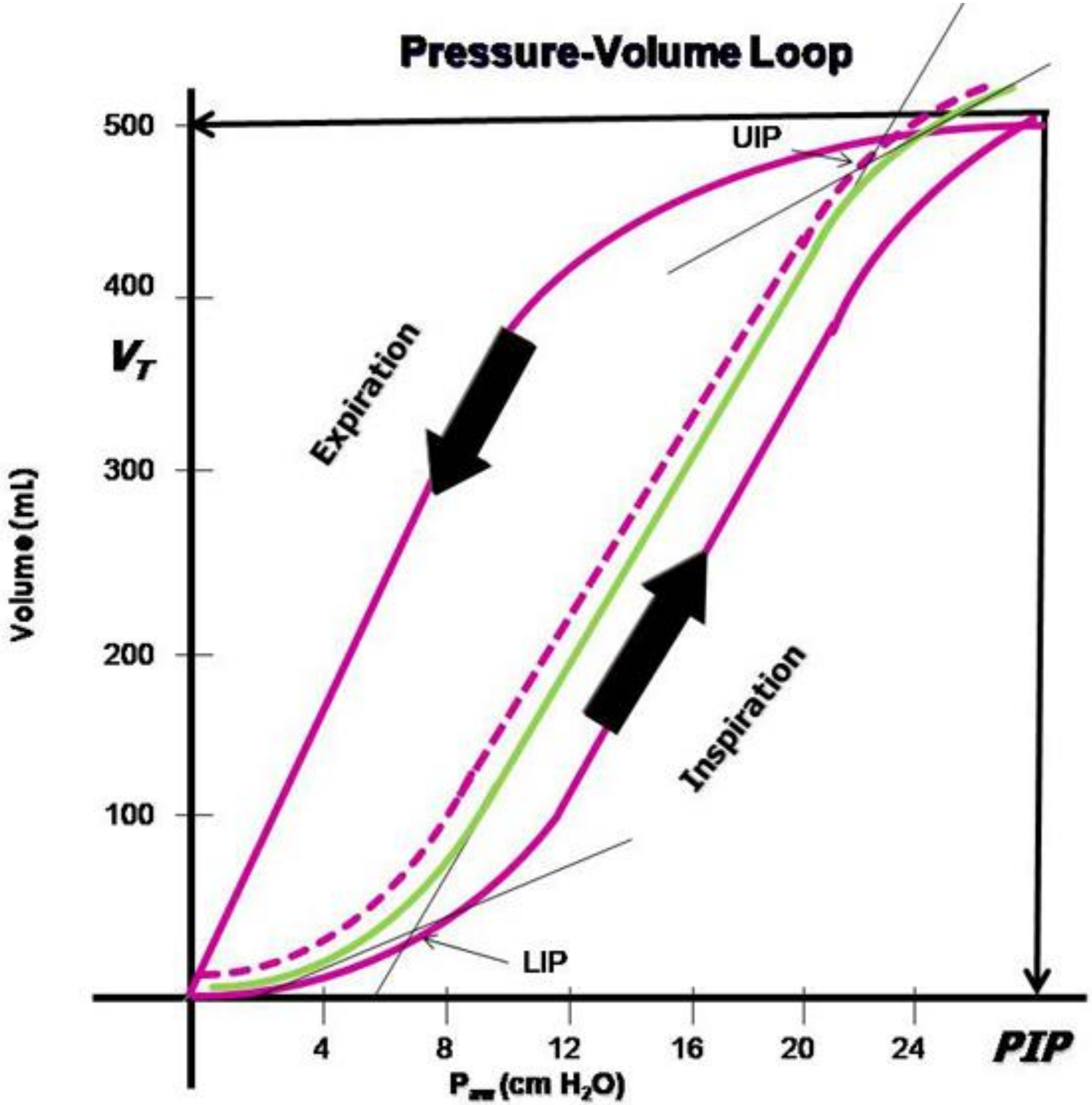
Types of Waveforms

- **Scalars** are waveform representations of pressure, flow or volume on the y axis vs time on the x axis
- **Loops** are representations of pressure vs volume or flow vs volume

Scalar Waveforms



Loop



Pressure-Volume Loop
500
400
300
200
100
V_T
Volume (mL)
UIP
LIP
Expiration
Inspiration
4
8
12
16
20
24
PIP
P_{aw} (cm H_2O)

Common problems that can be diagnosed by analyzing Ventilator waveforms

Abnormal ventilatory Parameters/ lung mechanics
E.g.. Overdistension,
Auto PEEP
COPD

Patient-ventilator Interactions
E.g. flow starvation,
Double triggering,
Wasted efforts
Active expiration

Ventilatory circuit related problems
E.g. auto cycling and Secretion build up in the Ventilatory circuit

Lung Mechanics

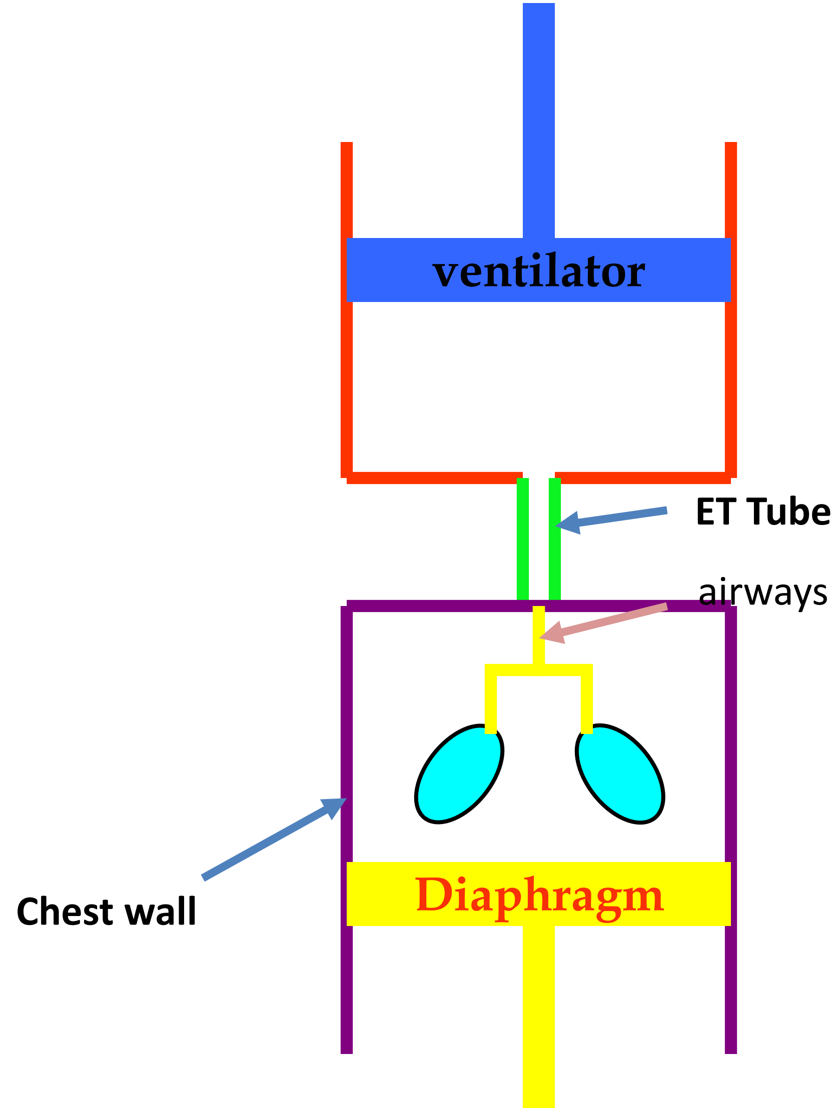
- Use Scalar
- Pressure Time Waveform with a square wave flow pattern

Understanding the basic ventilator circuit diagram

Essentially the circuit diagram of a mechanically ventilated patient can be broken down into two parts. These two systems are connected by an endotracheal tube which we can consider as an extension of the patient's airways.

The ventilator makes up the first part of the circuit. It is depicted schematically as a piston that moves in a reciprocating fashion during the respiratory cycle.

The patient's own respiratory system makes up the 2nd part of the circuit. The diaphragm is also shown as a 2nd piston, causing air to be drawn into the lungs during contraction.



Understanding airway pressures

The respiratory system can be thought of as a mechanical system consisting of resistive (airways +ET tube) and elastic (lungs and chest wall) elements in series

THUS P_{aw} = Flow X Resistance **+** Volume x 1/Compliance

ET tube + Airways
(resistive element)

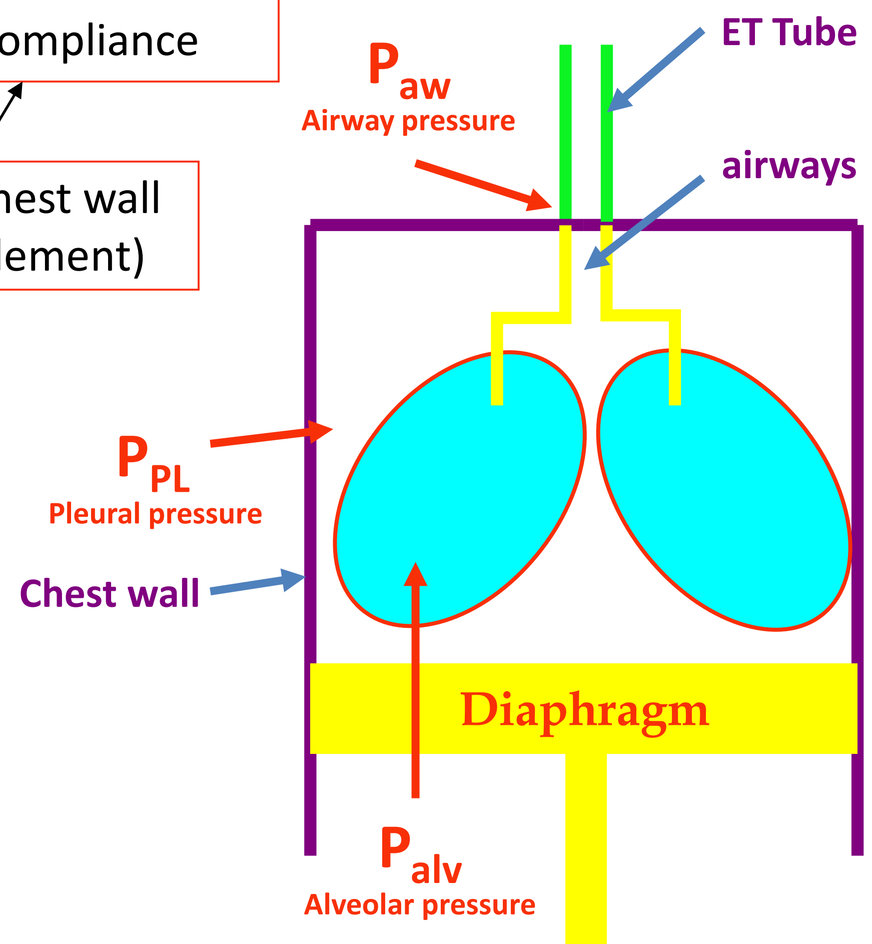
Airways + ET tube / **Chest wall**
(resistive element) / **(elastic element)**

Lungs + Chest wall
(elastic element)

Resistive pressure varies with airflow and the diameter of ETT and airways.

The elastic pressure varies with volume and stiffness of lungs and chest wall.

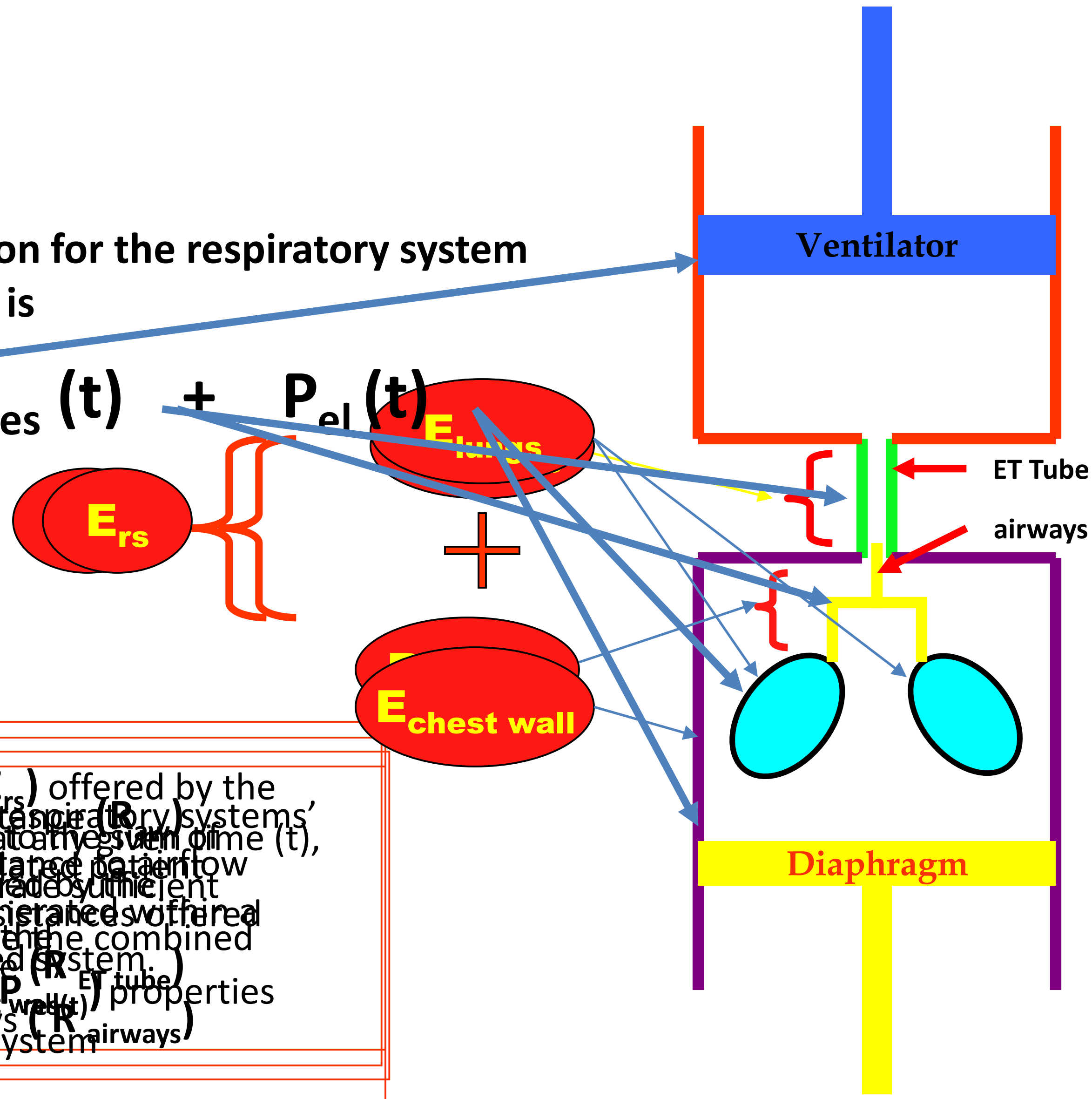
Pel = Volume x 1/Compliance



Understanding basic respiratory mechanics

Thus the equation of motion for the respiratory system is

$$P_{aw}(t) = P_{res}(t) + P_{el}(t)$$



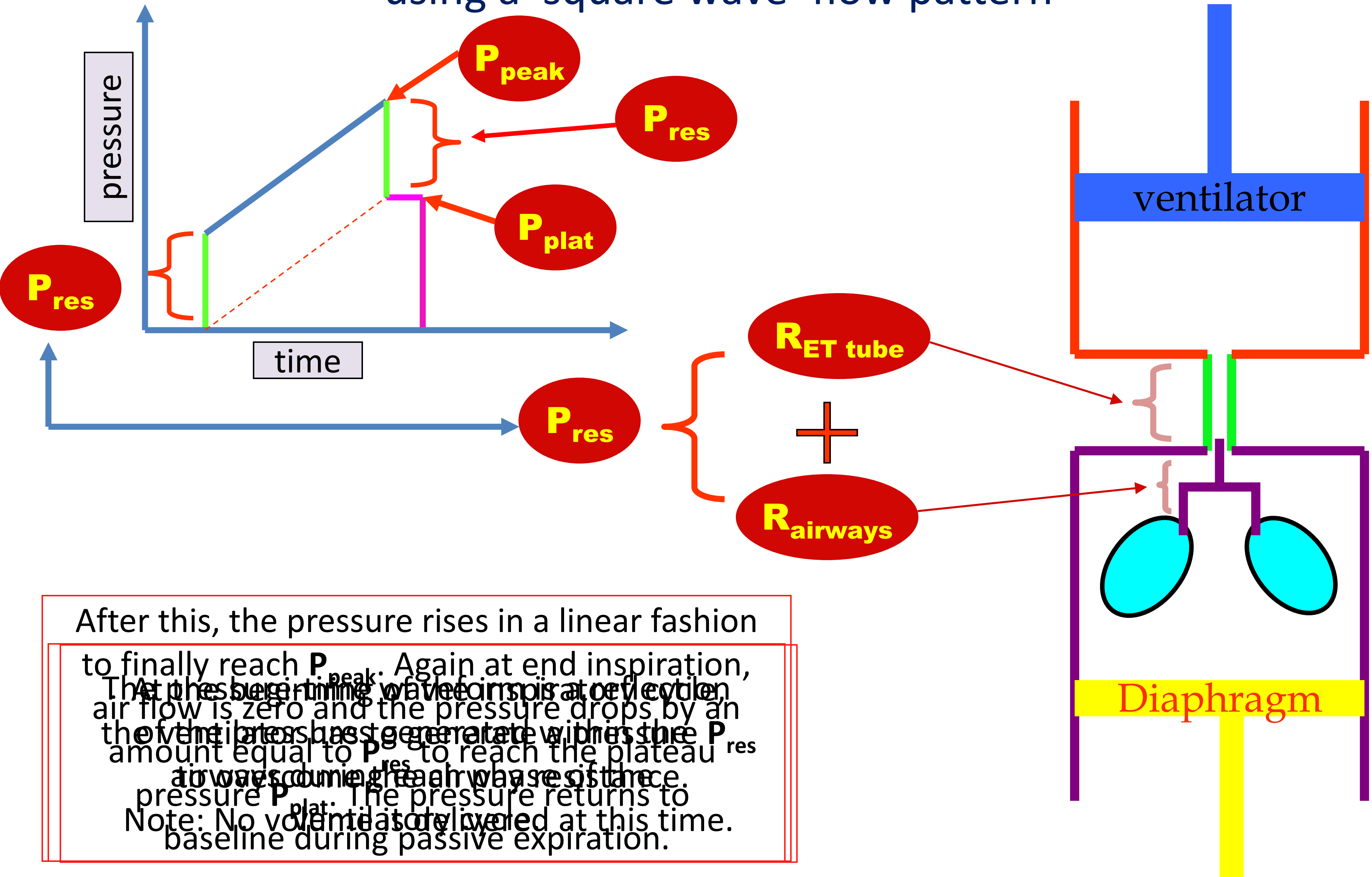
The total '***elastic***' resistance **(E_{rs})** offered by the respiratory system is equal to the sum of the elastances offered by the Lung **(E_{lungs})** and the chest wall **($E_{chest\ wall}$)**

Let us now understand how the respiratory systems' inherent elastance and resistance to airflow determines the pressure generated within a mechanically ventilated system.

The total '***airway***' resistance **(R_{aw})** in the mechanically ventilated patient is equal to the sum of the resistances offered by the endotracheal tube **($R_{ET\ tube}$)** and the patient's airways **($R_{airways}$)**

Thus to move air into the lungs at any given time (t), the ventilator has to generate sufficient pressure **(P_{aw})** to overcome the combined elastic **($P_{el(t)}$)** and resistance **($P_{res(t)}$)** properties of the respiratory system

Understanding the pressure-time waveform using a 'square wave' flow pattern



The pressure-time waveform is a reflection of the pressures generated within the airways during each phase of the ventilatory cycle.

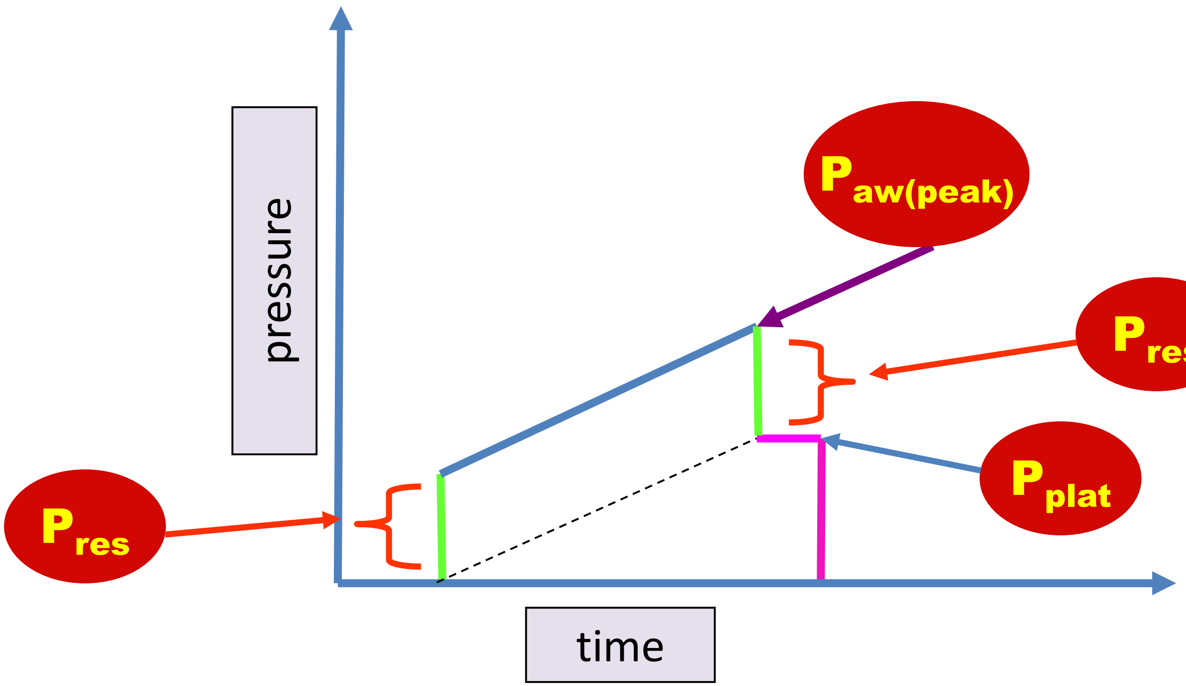
At the beginning of the inspiratory cycle, the ventilator has to generate a pressure P_{res} to overcome the airway resistance. Note: No volume is delivered at this time.

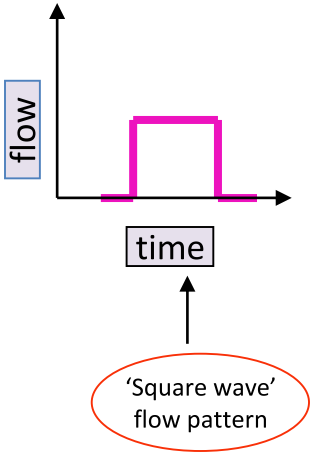
After this, the pressure rises in a linear fashion to finally reach P_{peak}. Again at end inspiration, air flow is zero and the pressure drops by an amount equal to P_{res} to reach the plateau pressure P_{plat}. The pressure returns to baseline during passive expiration.

Pressure-time waveforms using a 'square wave' flow pattern

$P_{aw(peak)}$ = Flow x Resistance **+** Volume x 1/ Compliance

Scenario # 1

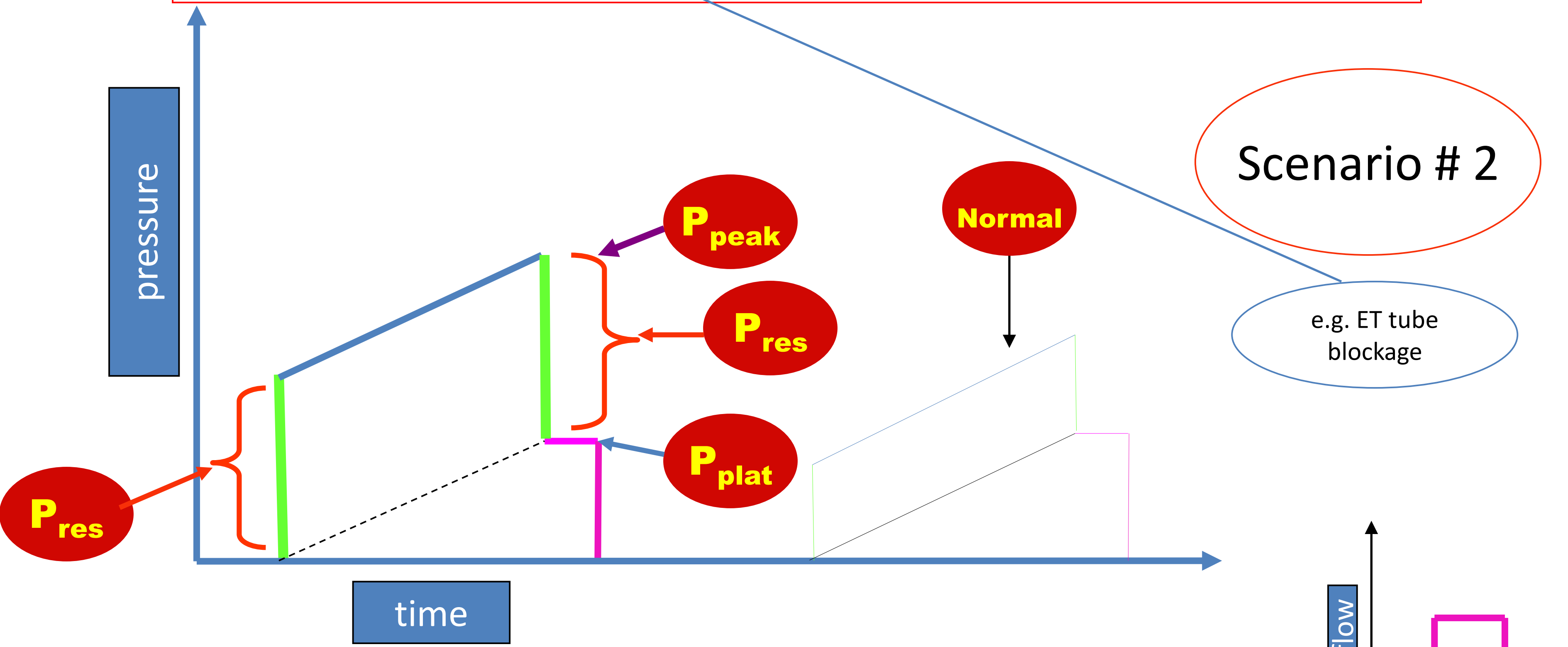


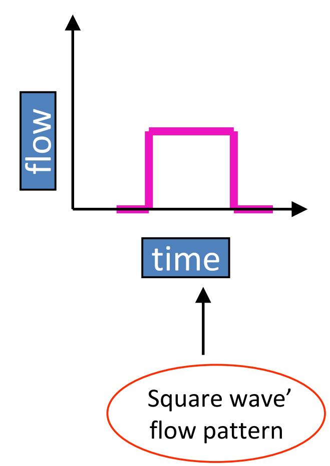


This is a **normal** pressure-time waveform
With normal peak pressures **(** P_{peak}**)** ;
plateau pressures **(**P_{plat})and
airway resistance pressures **(**P_{res}**)**

Waveform showing high airways resistance

$$P_{aw(peak)} = \text{Flow x Resistance} + \text{Volume x 1/ Compliance} + \text{PEEP}$$

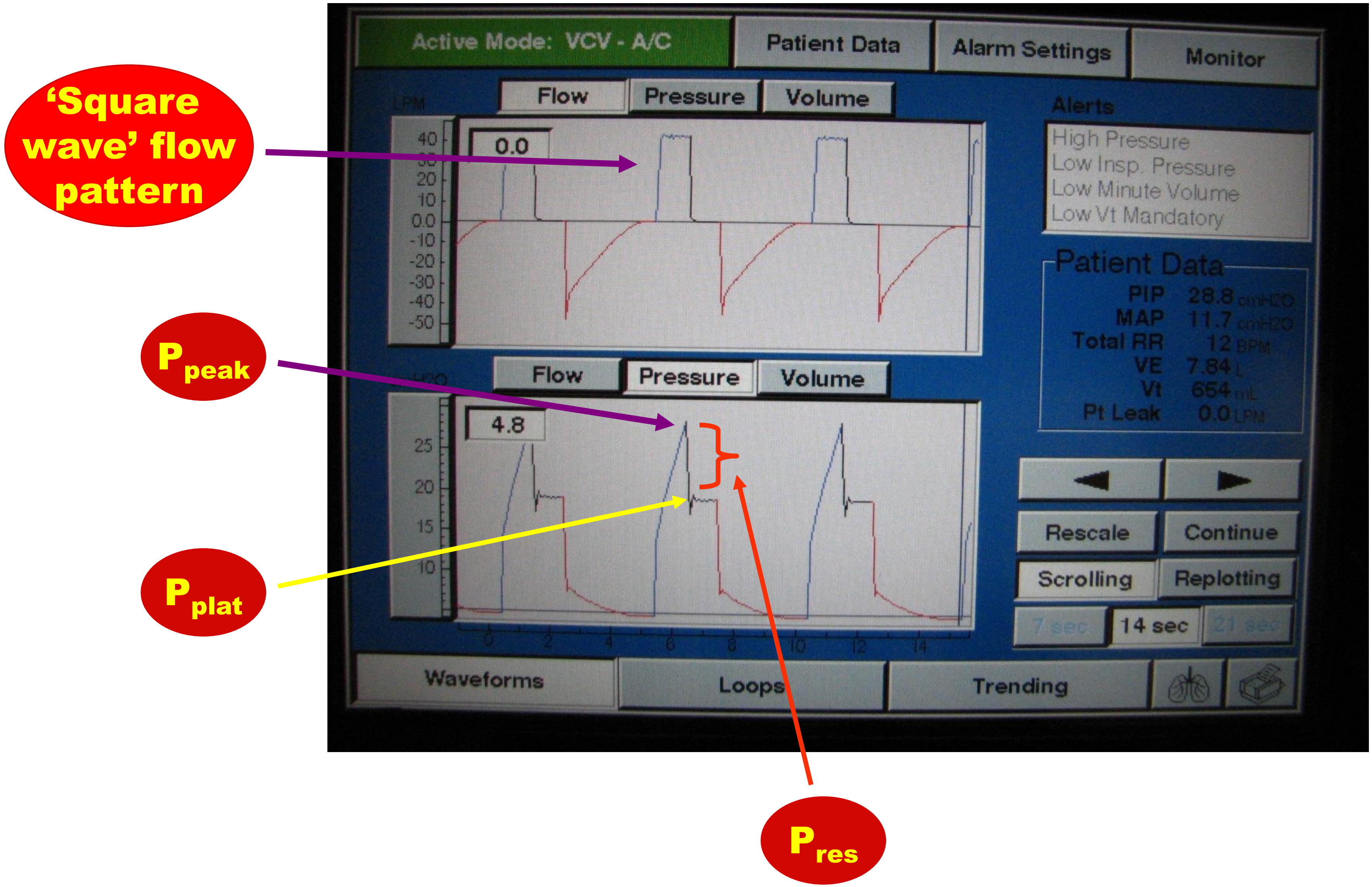




This is an **abnormal** pressure-time waveform

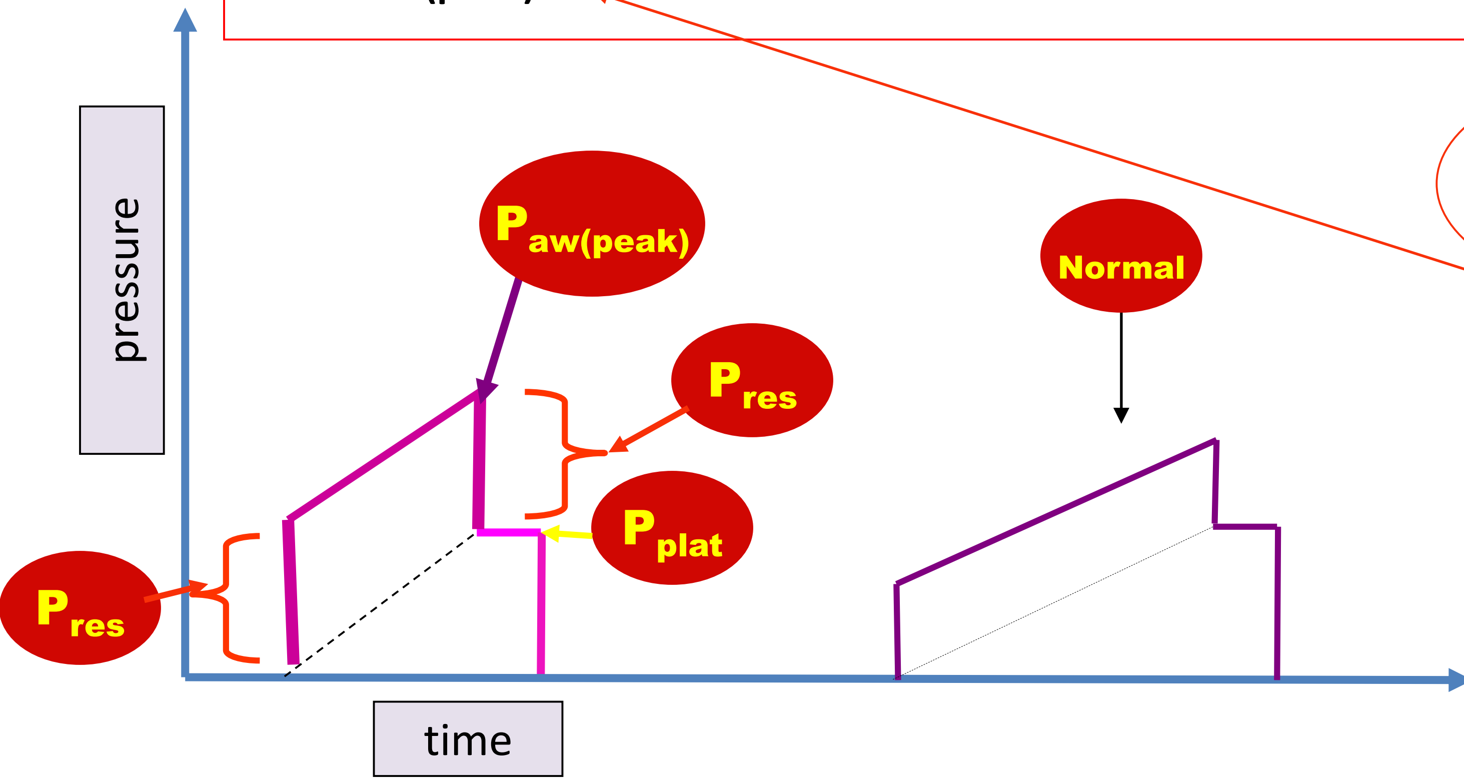
The increase in the peak airway pressure is driven entirely by an **increase** in the airways resistance pressure. Note the **normal** plateau pressure.

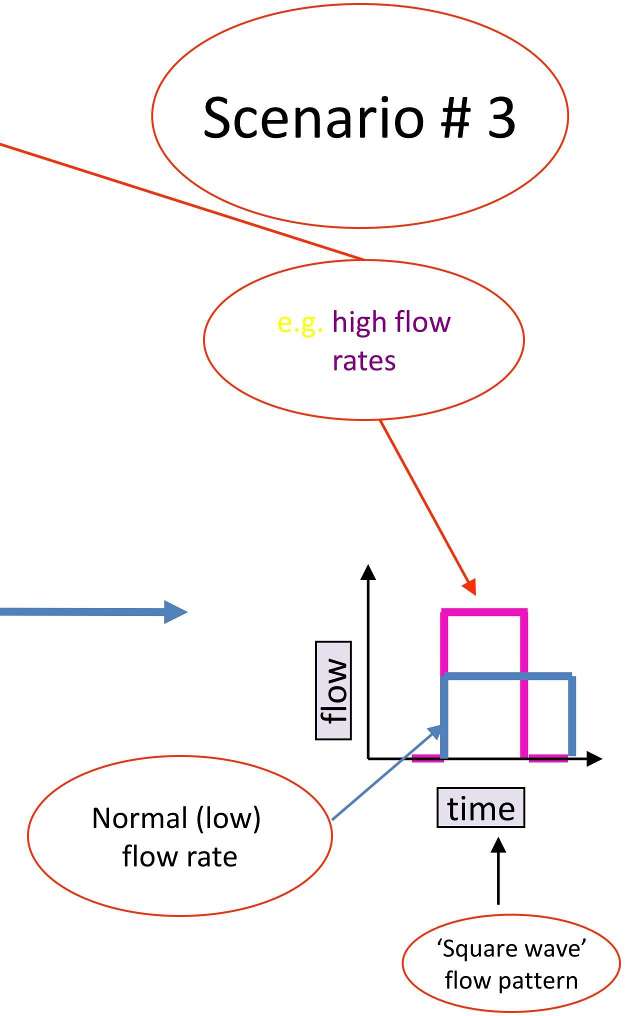
Waveform showing increased airways resistance



Waveform showing high inspiratory flow rates

$P_{aw(peak)}$ = **Flow** x Resistance + Volume x 1/compliance + PEEP





The increase in the peak airway pressure is caused by high inspiratory flow rate and airways resistance.

This is an **abnormal** pressure-time waveform

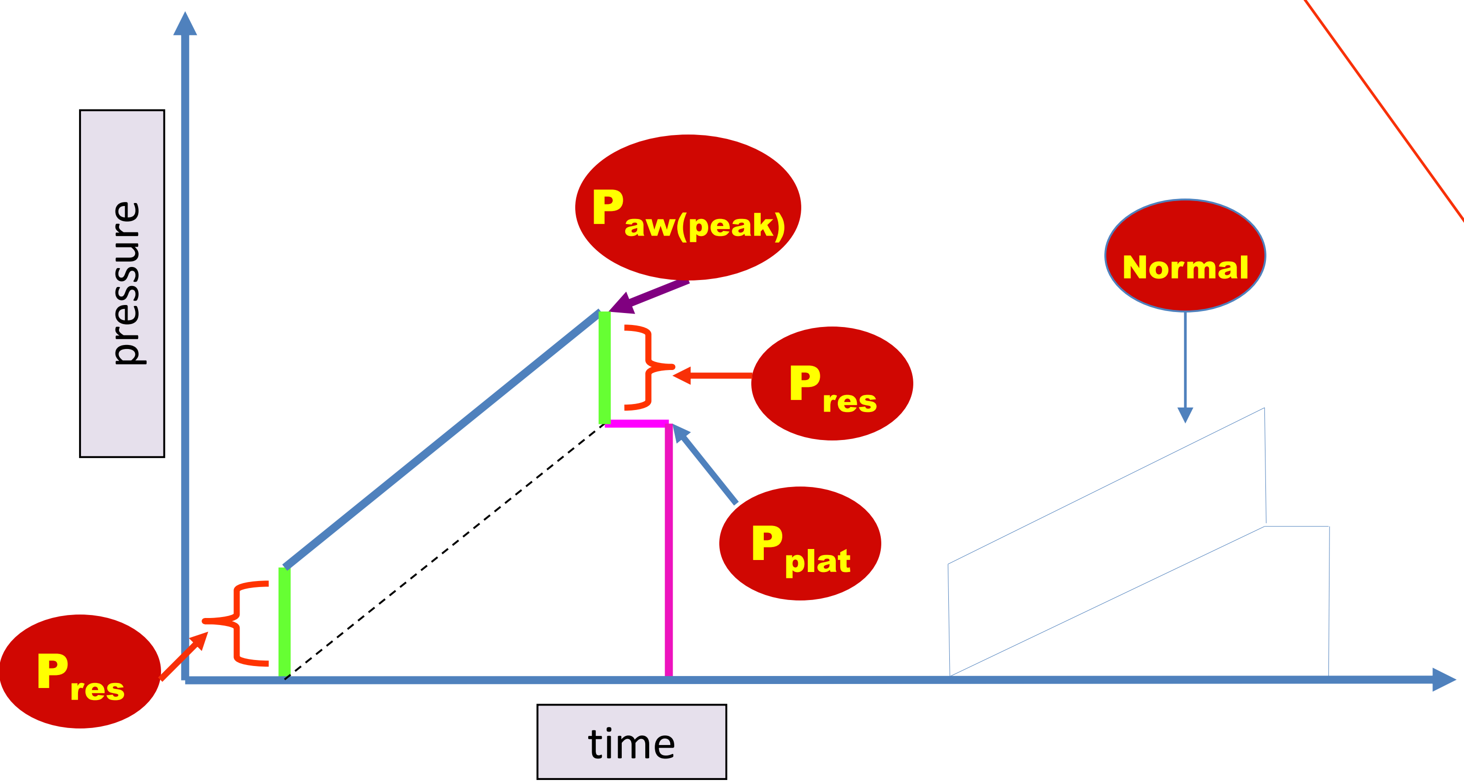
Note the **shortened** inspiratory time and high flow

Waveform showing decreased lung compliance

$P_{aw(peak)}$ = Flow x Resistance + Volume x 1/ Compliance + PEEP

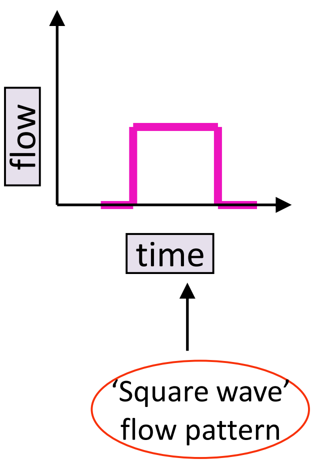
Scenario # 4

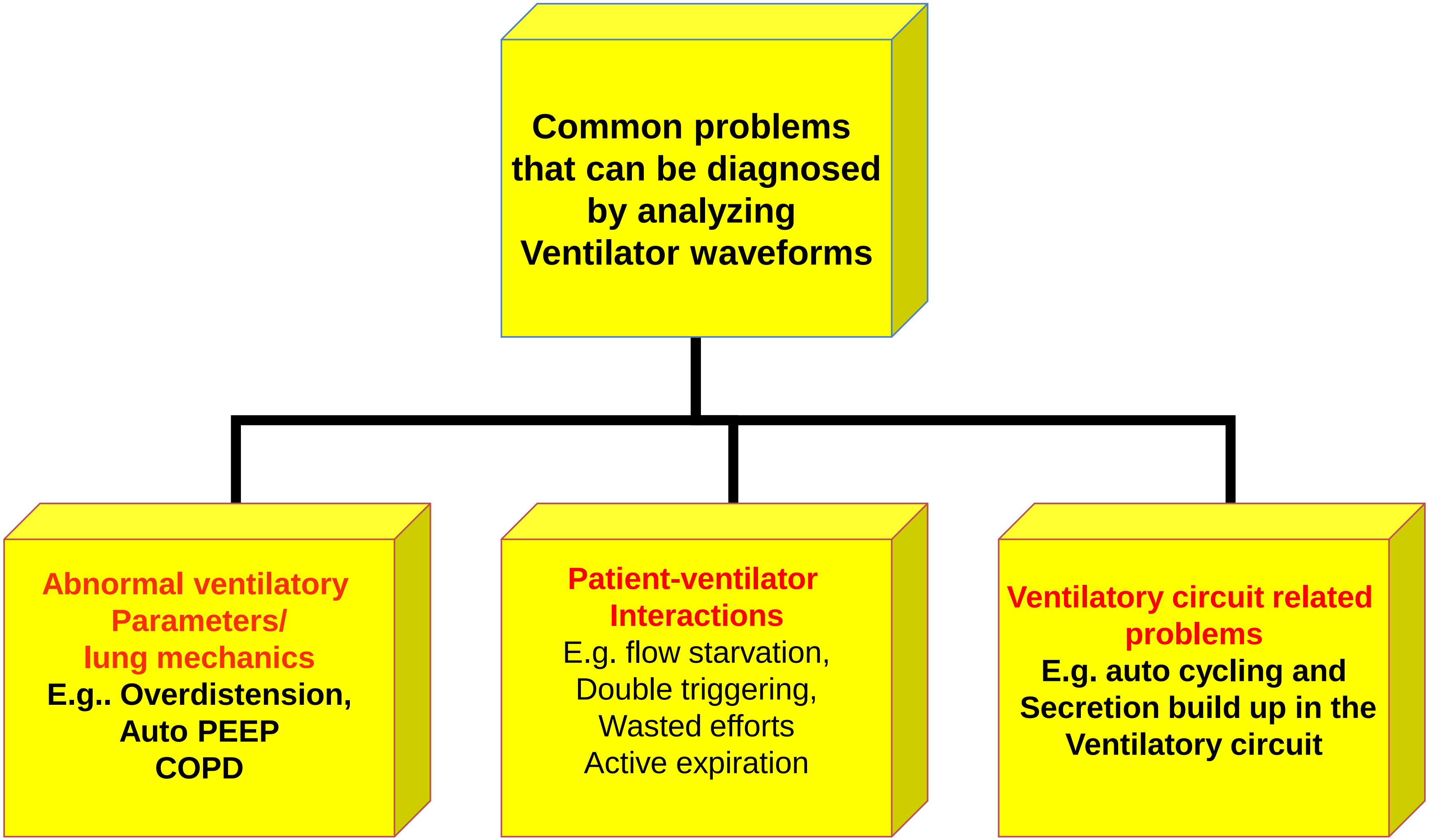
e.g. ARDS



The increase in the peak airway pressure is driven by the **decrease** in the lung compliance. Increased airways resistance is often also a part of this scenario.

This is an **abnormal** pressure-time waveform

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E.g. flow starvation, Double triggering, Wasted efforts Active expiration
Ventilatory circuit related problems
E.g. auto cycling and Secretion build up in the Ventilatory circuit

Recognizing Lung Overdistension

Flow-time waveform

- Flow-time waveform has both an inspiratory and an expiratory arm.

- The shape of the expiratory arm is determined by:
  - the elastic recoil of the lungs
  - the airways resistance
  - and any respiratory muscle effort made by the patient during expiration (due to patient-ventilator interaction/dys=synchrony)

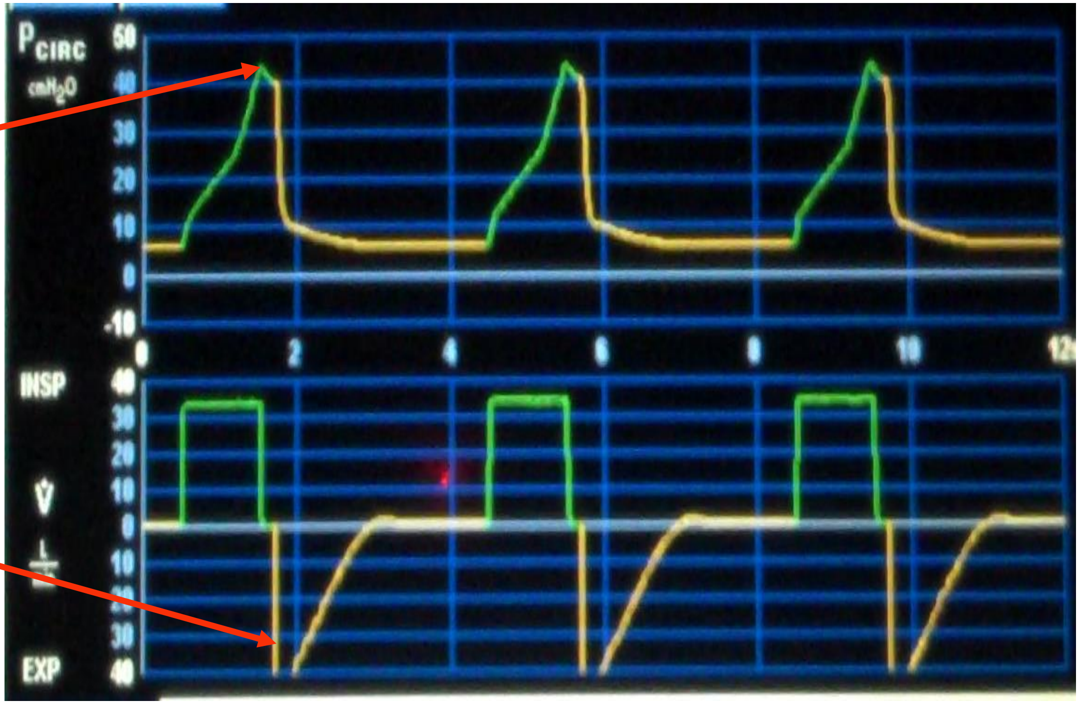
- It should always be looked at as part of any waveform analysis and can be diagnostic of various conditions like COPD, auto-PEEP, wasted efforts, overdistention etc.

Recognizing lung overdistension

Suspect this when:

There are high peak and plateau Pressures...

Accompanied by high expiratory flow rates



PEARL: Think of
low lung compliance (e.g. ARDS),
excessive tidal volumes,
right mainstem intubation etc

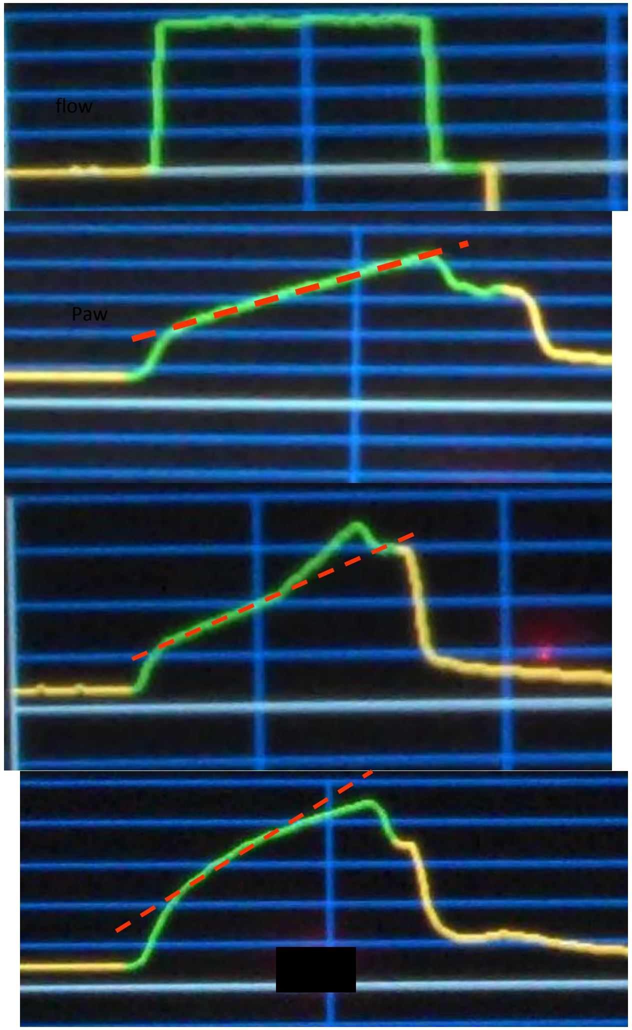
The Stress Index

- **In AC volume ventilation using a constant flow waveform observe the pressure time scalar.**

- **Normal, linear change in airway pressure Stress index =1**

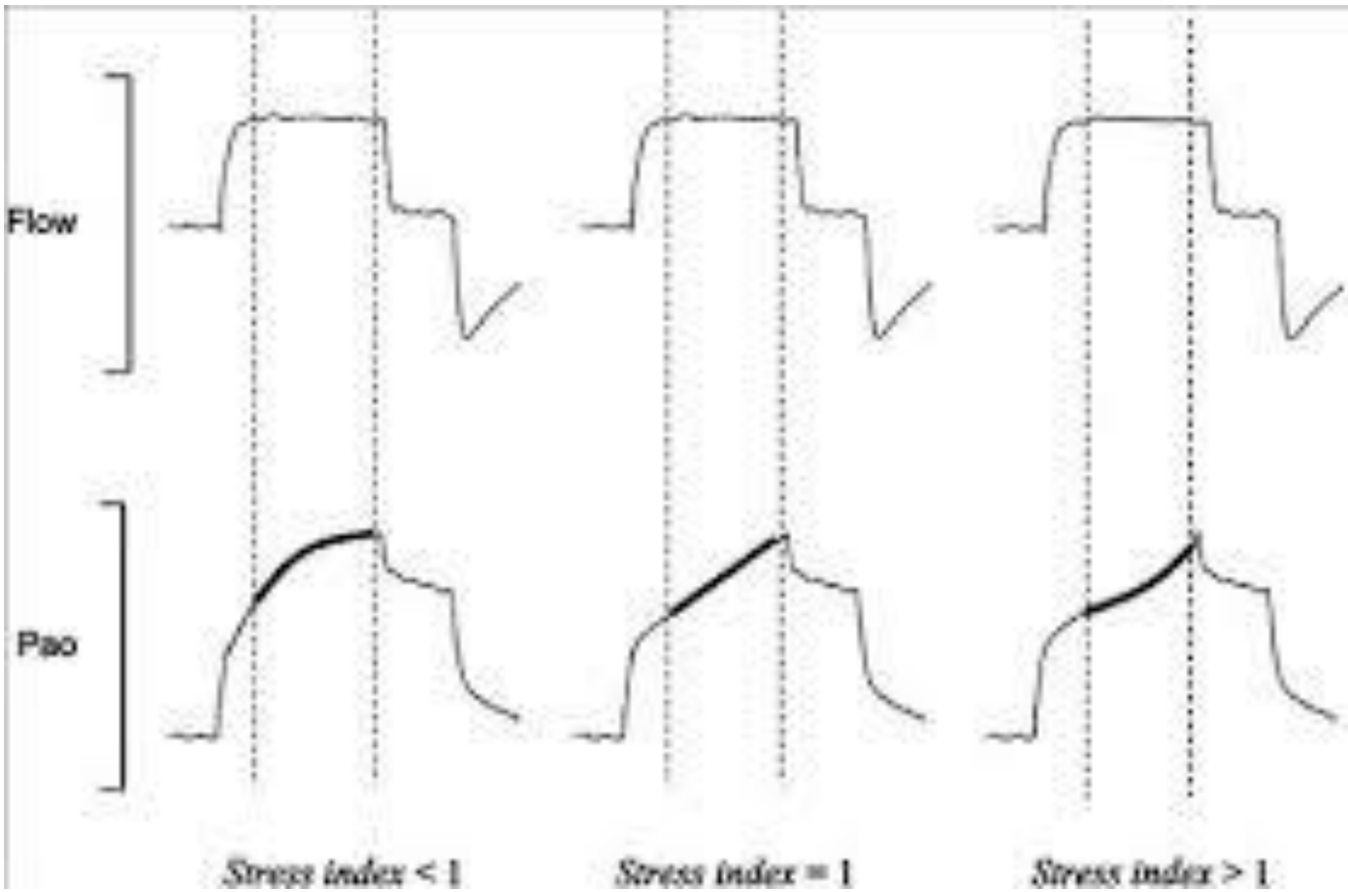
- **Upward concavity indicates decreased compliance and lung overdistension**
  Stress index > 1

- **Downward concavity indicates increased compliance and potential alveolar recruitment**
  Stress index < 1

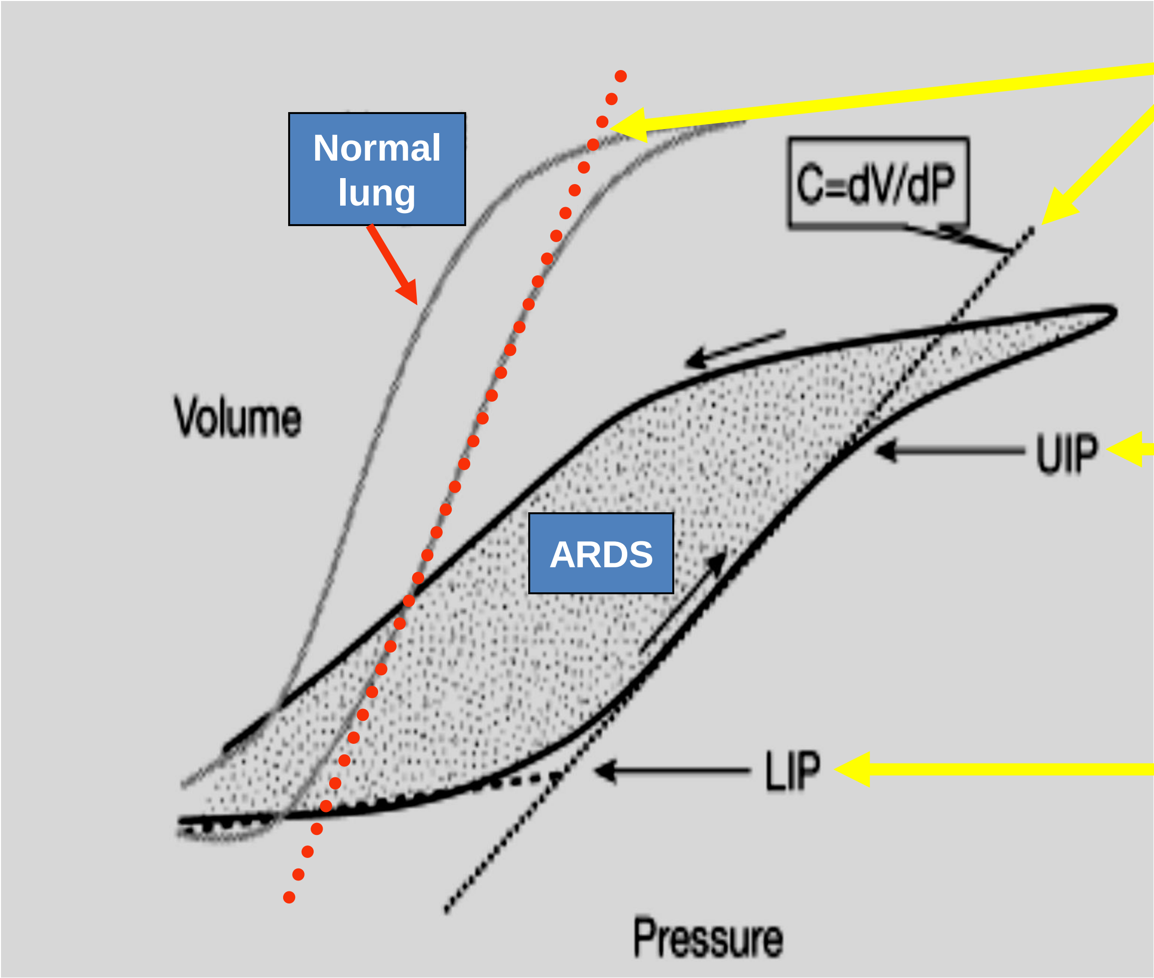


Note: Patient effort must be absent

The Stress Index



Pressure-volume loop



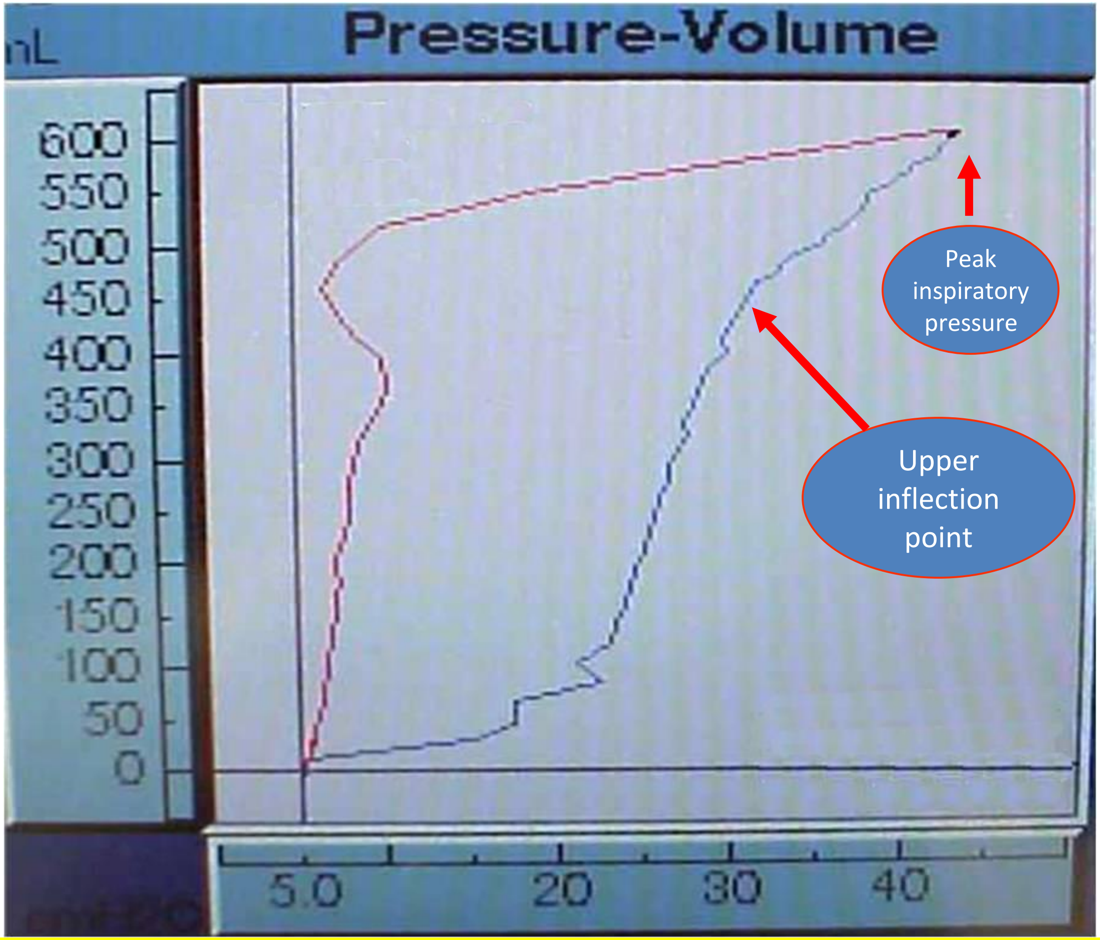
Compliance (C)
is markedly reduced in the injured lung on the right as compared to the normal lung on the left

Upper inflection point (UIP)
above this pressure, additional alveolar recruitment requires disproportionate increases in applied airway pressure

Lower inflection point (LIP)
Can be thought of as the minimum baseline pressure (PEEP) needed for optimal alveolar recruitment

I. de Chazal and R. D. Hubmayr *British Journal of Anaesthesia* 91 (1): 81–91 (2003)

Overdistension



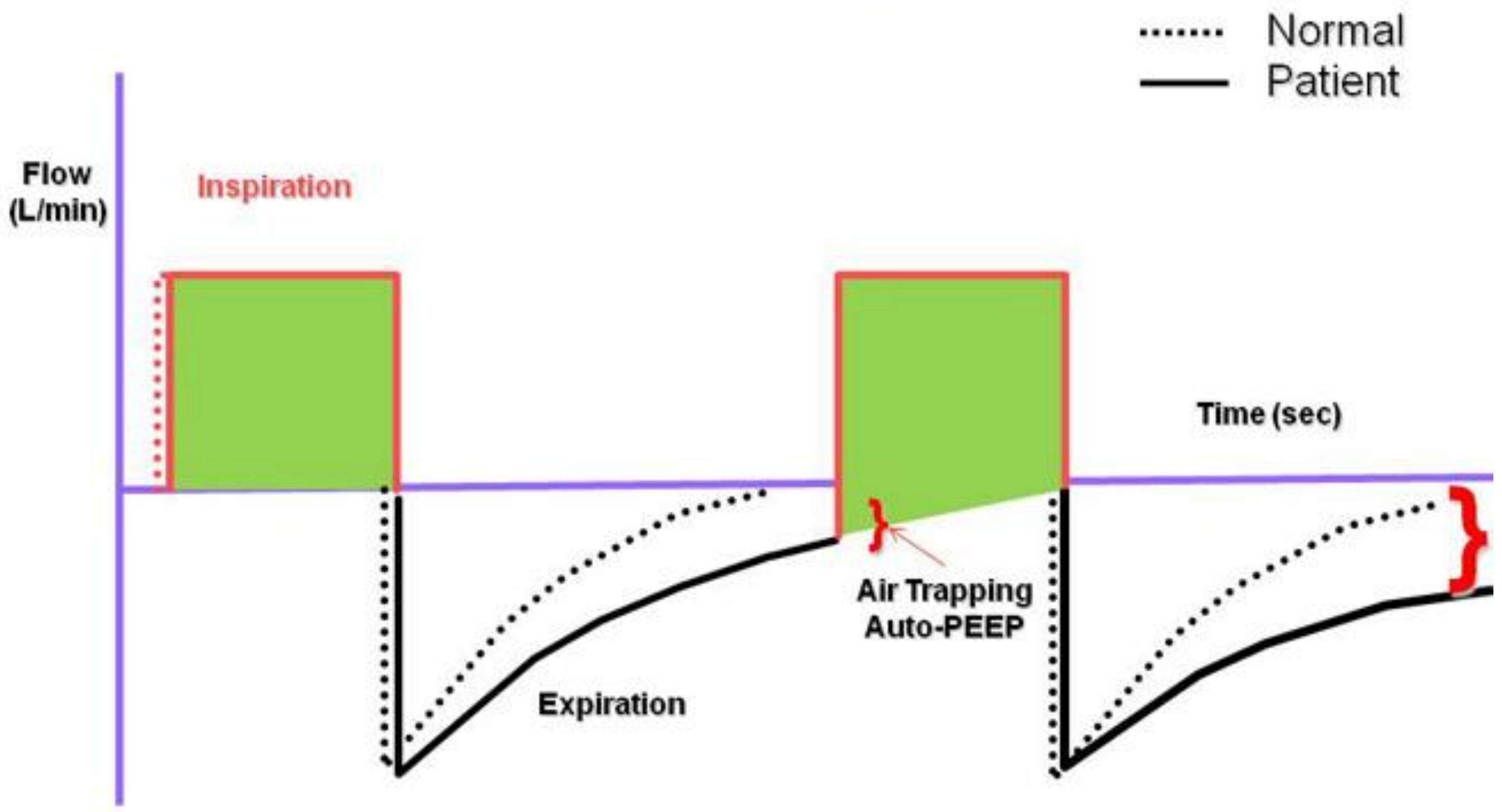
Note: During normal ventilation the LIP cannot be assessed due to the effect of the inspiratory flow which shifts the curve to the right

Recognizing Auto-PEEP

Dynamic Hyperinflation (Gas Trapping)

- Dynamic hyperexpansion, defined as premature termination of exhalation, often occurs when respiratory rate, inspiratory time, or both have been increased.
- By not permitting exhalation to finish, an increase in mean airway pressure results.
- Gas trapping may occur leading to an elevation in PCO_2.
- Careful attention must be paid to dynamic hyperexpansion in patients with obstructive lung disease whose long time constants and slow emptying can result in progressive air trapping, hypercarbia, and eventually decreased cardiac output.

Air Trapping

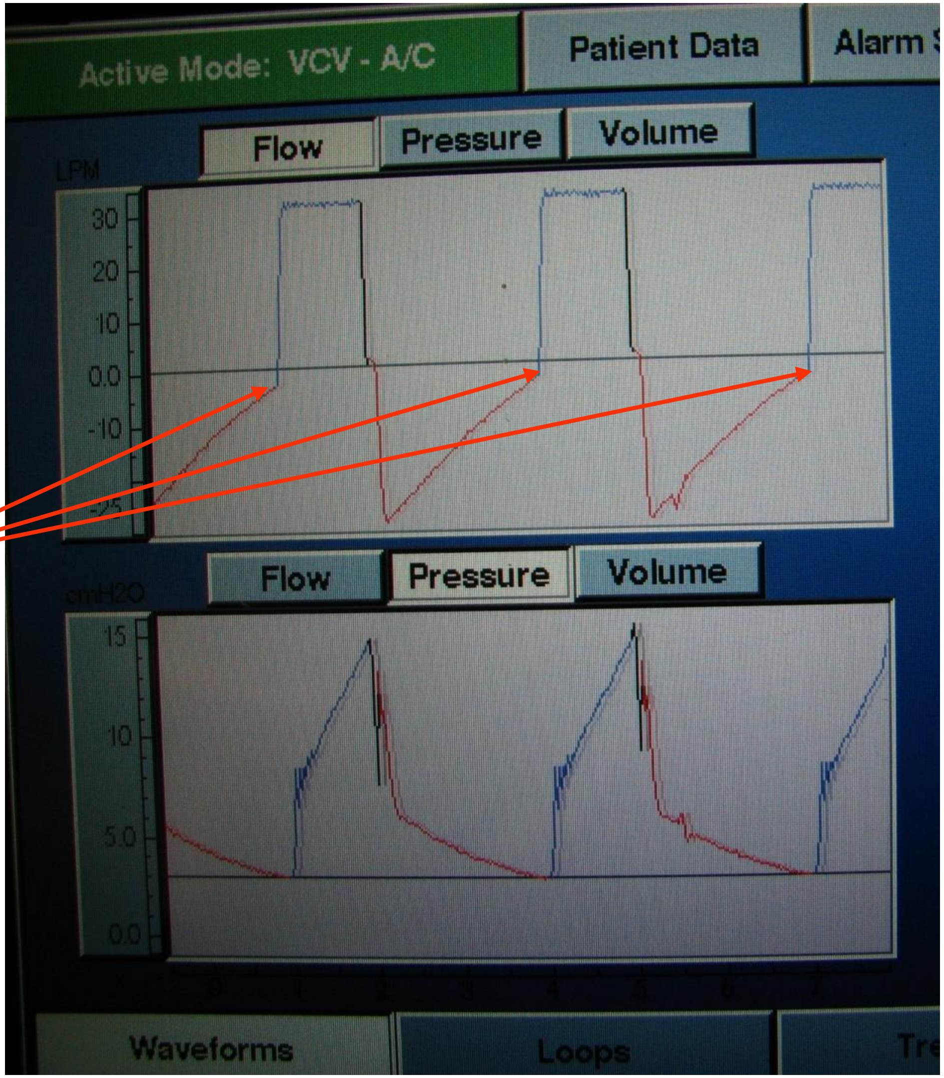


Expiratory flow continues and fails to return to the baseline prior to the new inspiratory cycle

Detecting Auto-PEEP

Recognize Auto-PEEP when

Expiratory flow continues and fails to return to the baseline prior to the new inspiratory cycle



The development of auto- PEEP over several breaths in a simulation

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

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

Understanding how flow rates affect I/E ratios and the development of auto PEEP

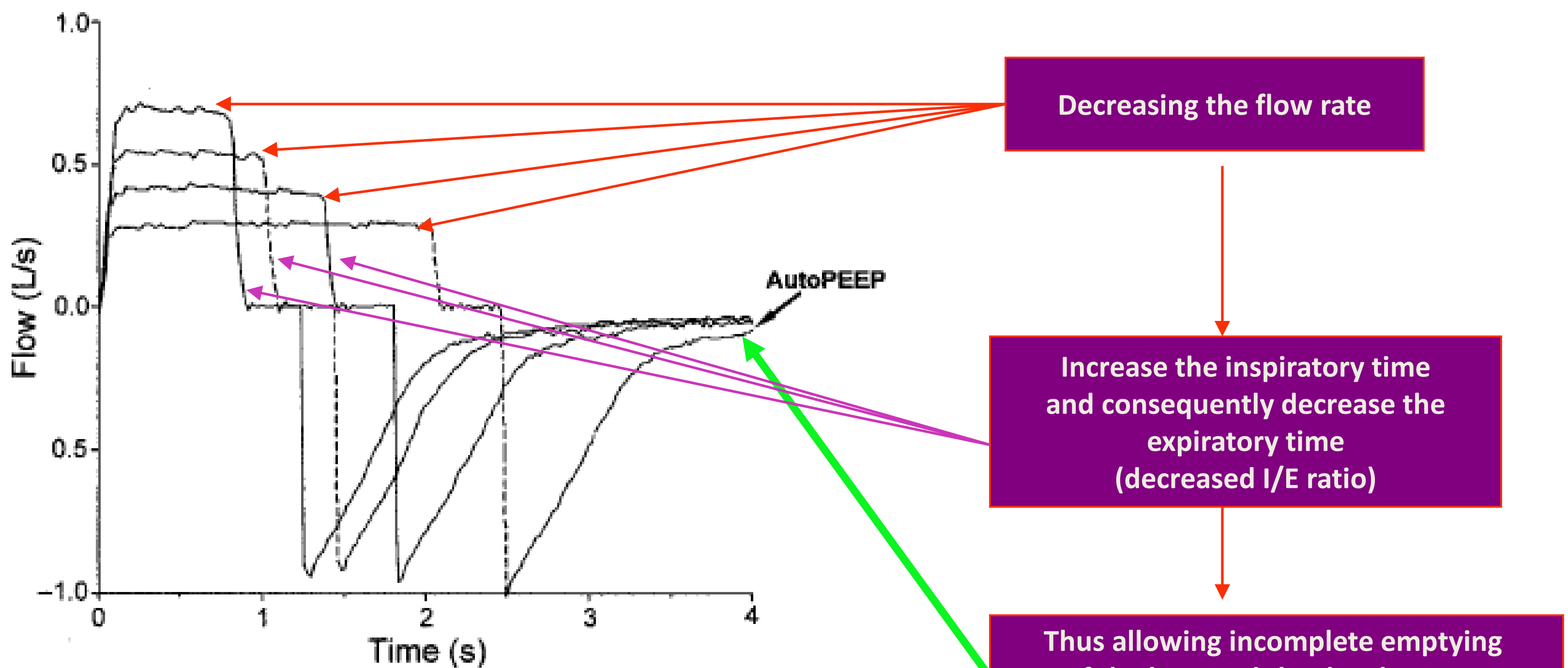
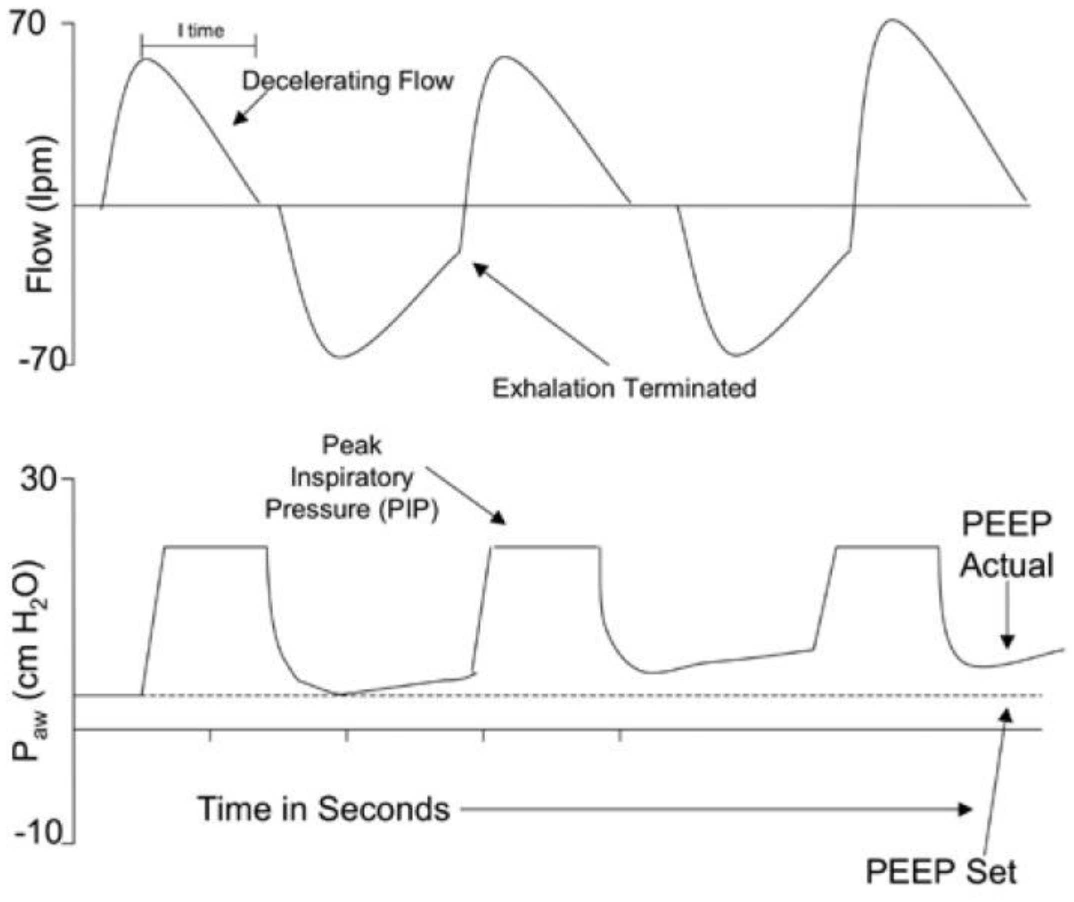


Fig. 1. Flow waveform showing air trapping by decreasing flow at equal tidal volume. Progressive reduction in expiratory time generates auto-PEEP when the expiratory time is not long enough to exhale all of the preceding tidal volume.

Lluis Blanch MD, PhD et al: Respiratory Care Jan 2005 Vol 50 No 1



70
I time
Decelerating Flow
Flow (lpm)
-70
Exhalation Terminated
Peak
Inspiratory
Pressure (PIP)
30
PEEP
Actual
P_{aw} (cm H_2O)
Time in Seconds
-10
PEEP Set

Understanding how inspiratory time affect I/E ratios and the development of auto-PEEP

- In a similar fashion, an increase in inspiratory time can also cause a decrease in the I: E ratio and favor the development of auto-PEEP by not allowing enough time for complete lung emptying between breaths.

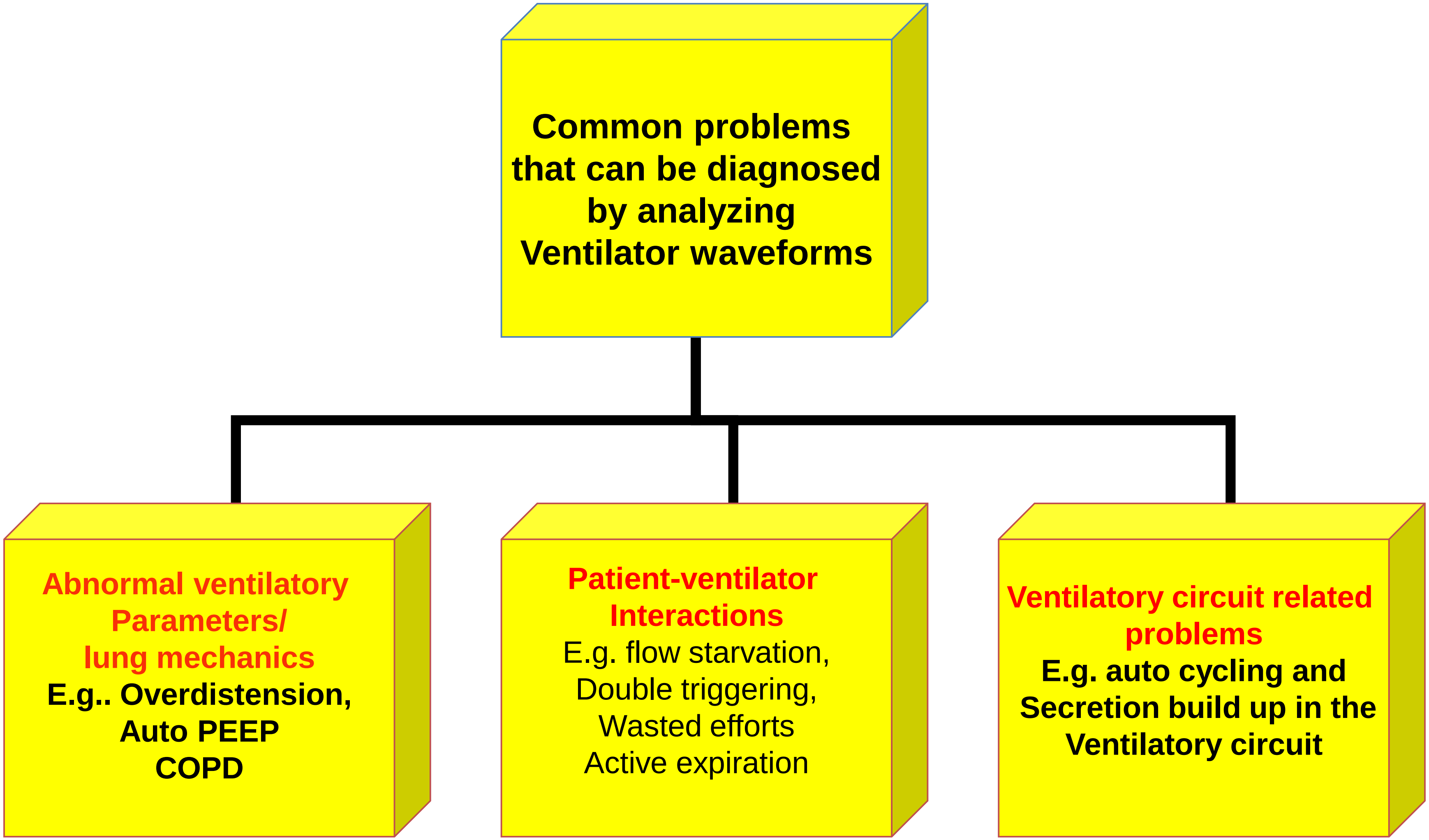
Recognizing Expiratory Flow Limitation
(e.g. COPD, asthma)

Recognizing prolonged expiration (air trapping)

Recognize
airway obstruction
when

Expiratory flow quickly tapers off and then enters a prolonged low-flow state without returning to baseline (auto- PEEP)

This is classic for the flow limitation and decreased lung elastance characteristic of COPD or status asthmaticus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PATIENT-VENTILATOR INTERACTIONS

Wasted efforts
Double triggering
Flow starvation
Active expiration

Ventilator Dyssynchrony: Inaccurate Sensing of Patient's Effort

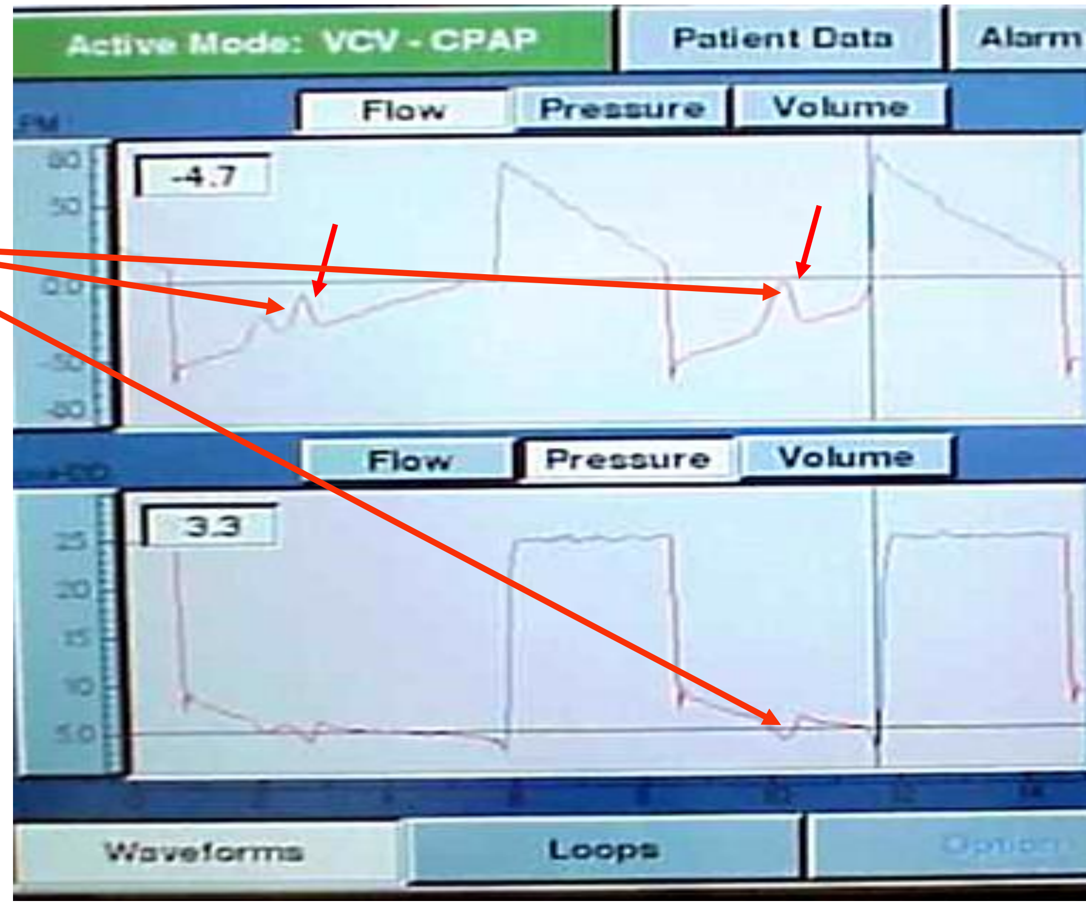
- Many modern ventilators sense patient effort
  - by detecting decreases in airway pressure or
  - flow between the inspiratory and expiratory limbs of the circuit.
- Inadequate sensing of patient effort leads to tachypnea, increased work of breathing, ventilator dyssynchrony, and patient discomfort.
- Flow triggering is often used in children, as it is very sensitive to patients with minimal respiratory effort and small endotracheal tubes.
- Dyssynchrony also occurs when an air leak leads to loss of PEEP, resulting in excessive ventilator triggering (auto cycling).
- The unstable pressure baseline that occurs due to leak may be misinterpreted as patient effort by the ventilator.

Recognizing ineffective/wasted patient effort

Patient inspiratory effort fails to trigger vent resulting in a wasted effort

Results in fatigue, tachycardia, increased metabolic needs, fever etc

Causes: High AutoPEEP, respiratory muscle weakness, inappropriate sensitivity settings



Recognizing double triggering

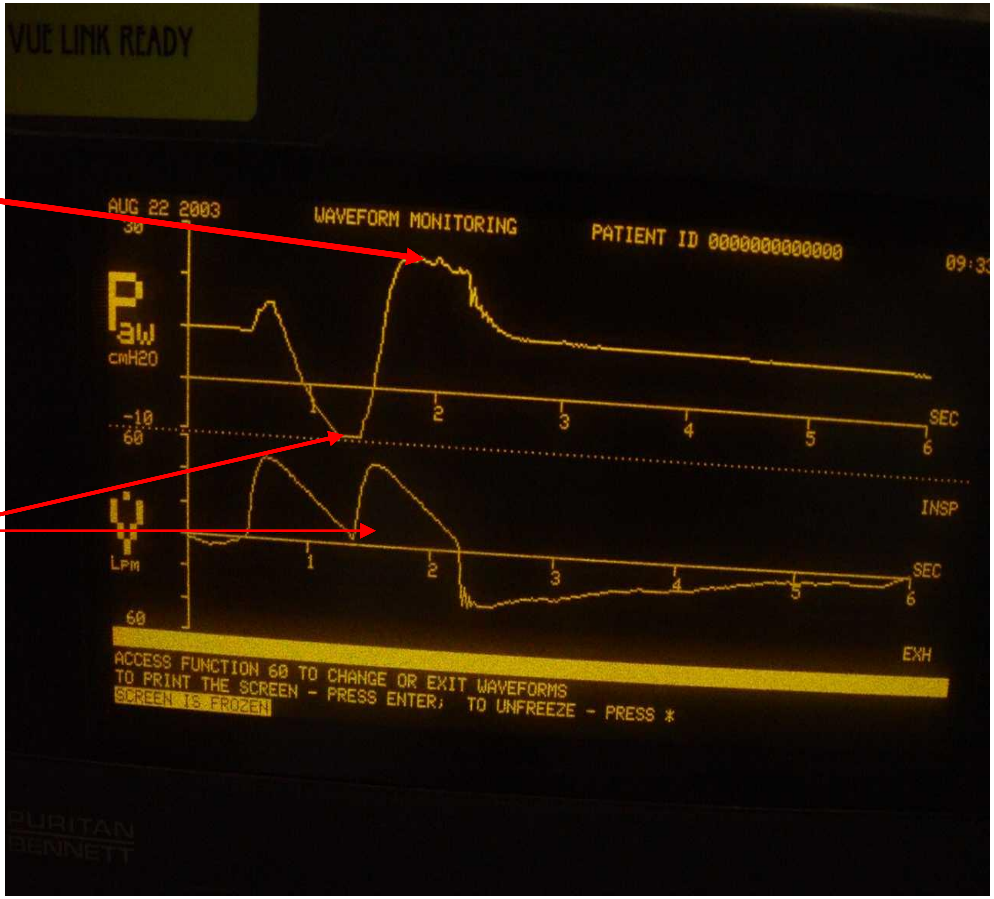
High peak airway pressures and double the inspiratory volume

Continued patient inspiratory effort through the end of a delivered breath causes the ventilator to trigger again and deliver a 2nd breath immediately after the first breath.

This results in high lung volumes and pressures.

Causes: patient flow or volume demand exceeds ventilator settings

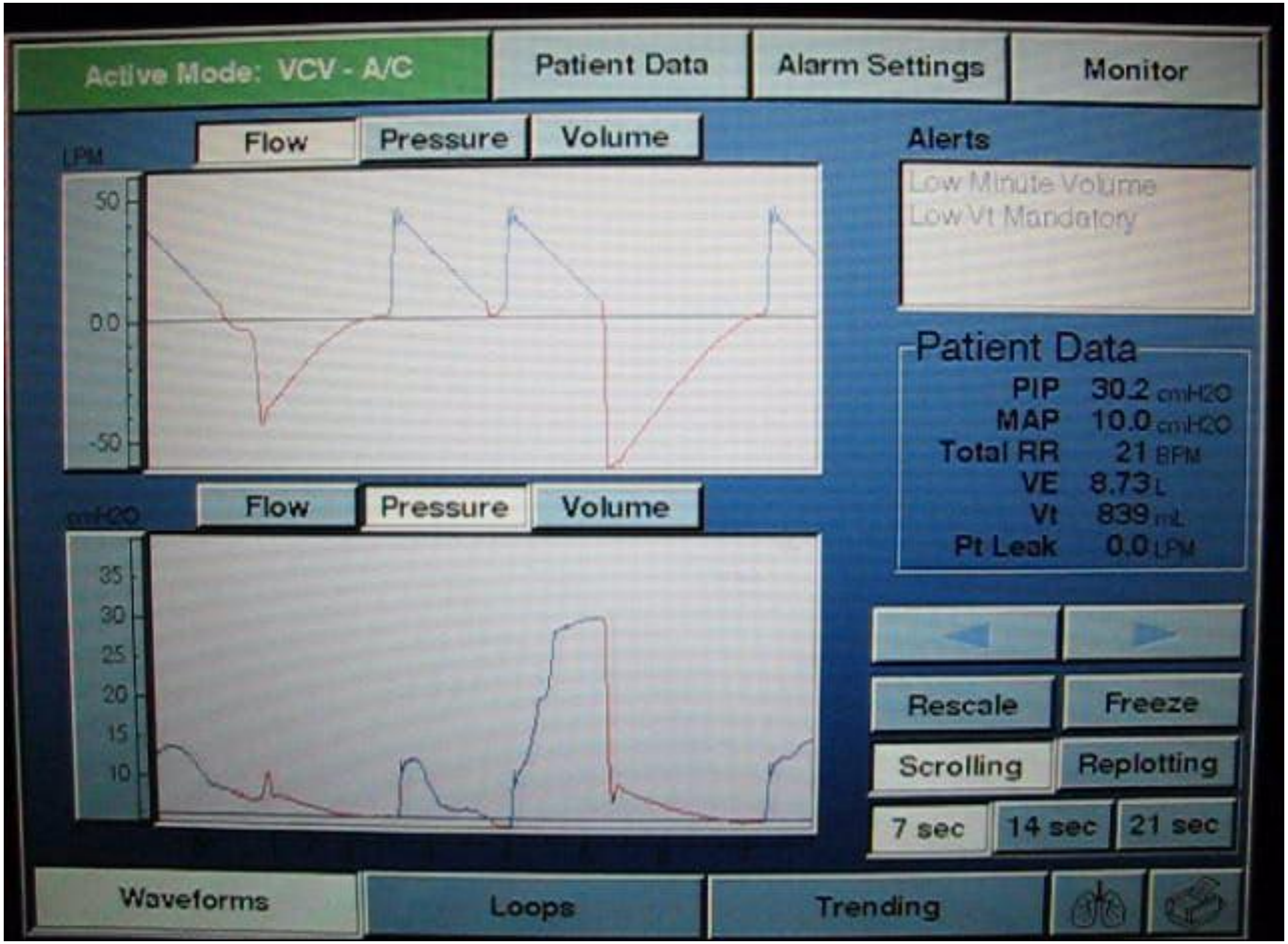
Consider: Increasing tidal volume, switching modes i.e. pressure support, increasing sedation or neuromuscular paralysis as appropriate



Ventilator Dyssynchrony: Inadequate Ventilatory Support

- Inadequate ventilatory support occurs when patient effort is not satiated by the inspiratory flow of the mechanical breath.
- As a result, patients attempt to initiate breaths during a mechanical breath.
- This phenomenon is seen as a reduction of airway pressure, seen as a decrease in airway pressure tracing during inspiration (flow dyssynchrony).
- In volume-limited ventilation a reduction of the inspiratory pressure as a result of dyssynchronous patient effort can translate into a higher PIP.
- Titration of flow rate, decreasing inspiratory time, or changing the mode of ventilation can help meet a patient’s inspiratory demand.

Another example of double triggering



Recognizing flow starvation

Look at the pressure-time waveform

If you see this kind of scooping or distortion instead of a smooth rise in the pressure curve….

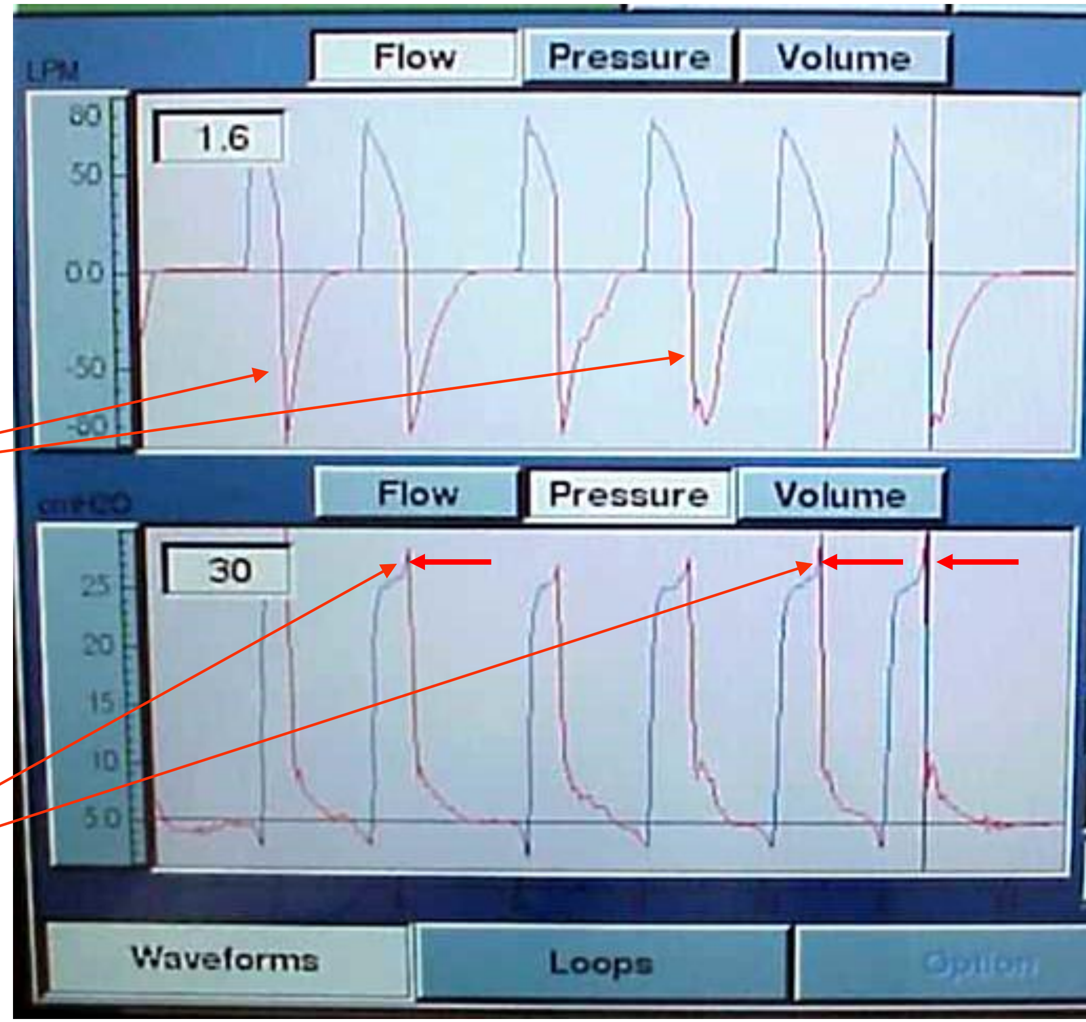
Diagnose flow starvation in the setting of patient discomfort, fatigue, dyspnea, etc on the vent

Recognizing active expiration

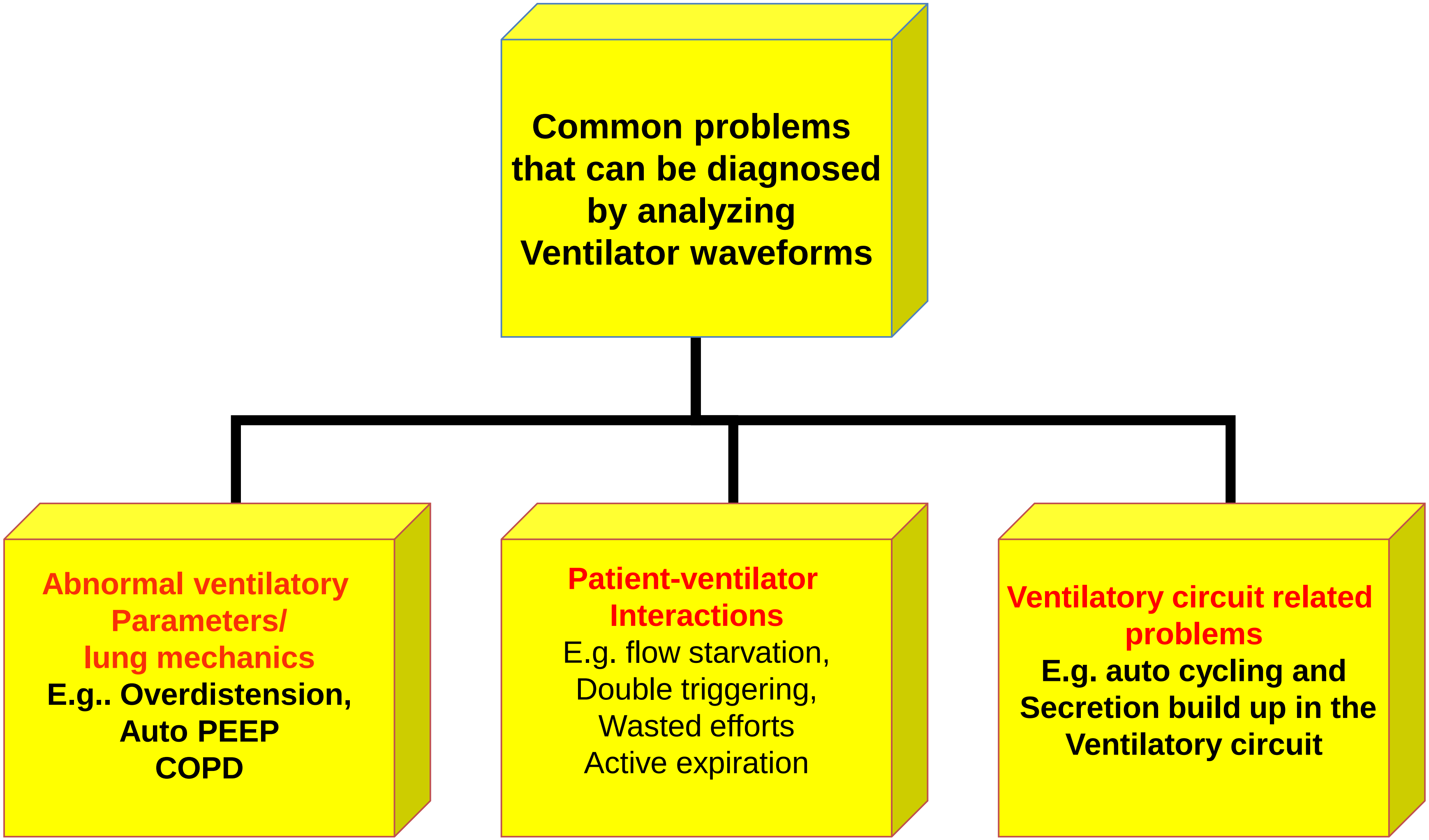
Look at the flow-time & pressure-time waveform

Notice the high and variable expiratory flow rates due to varying expiratory muscle effort

The patient's active expiratory efforts during the inspiratory phase causes a pressure spike.



PEARL: This is a high drive state where increased sedation/paralysis and mode change may be appropriate for lung protection.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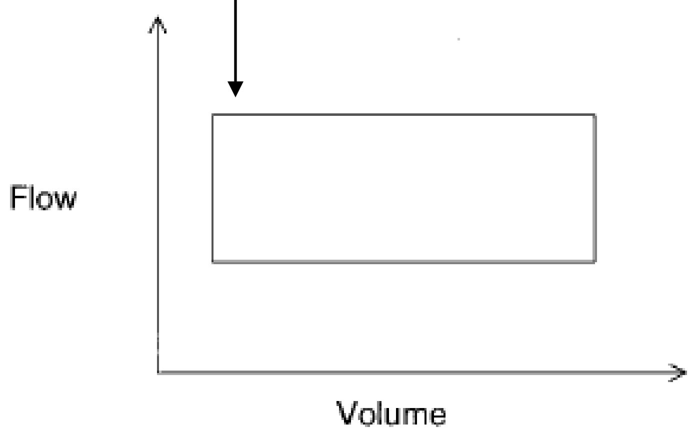
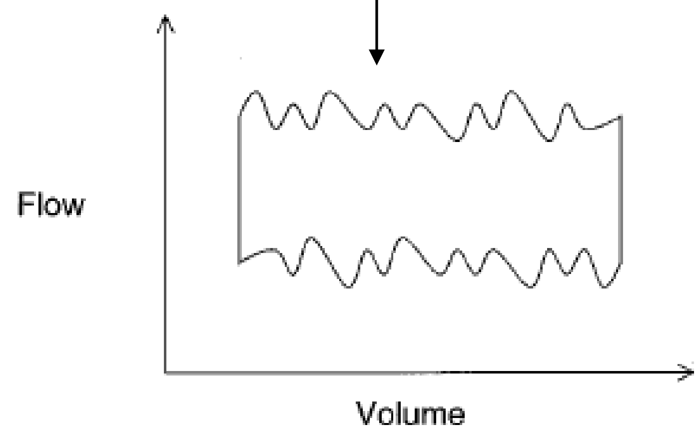
Recognizing
Airway Secretions
&
Ventilator Auto-Cycling

Recognizing airway or tubing secretions

Normal flow-volume loop



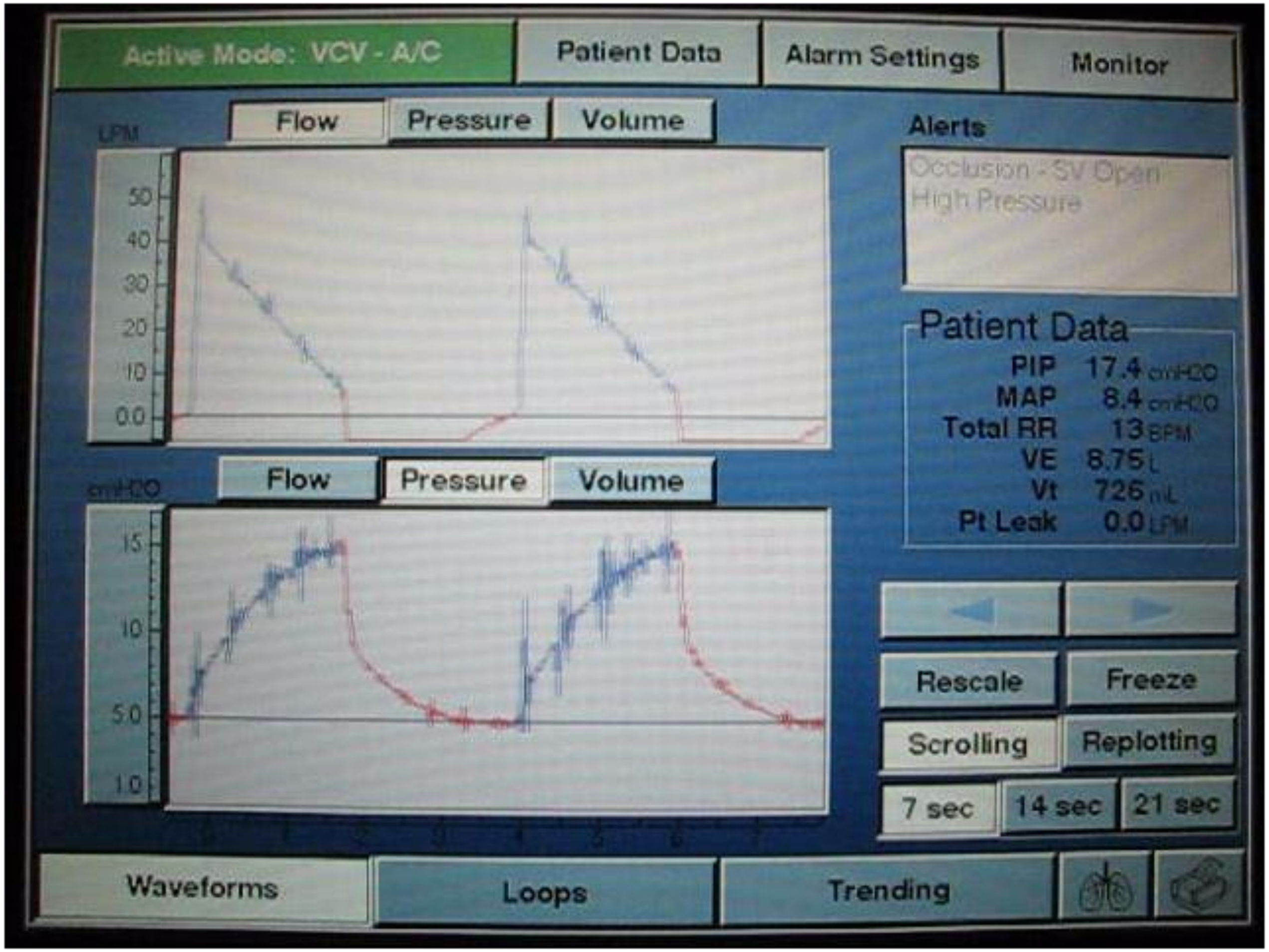
Flow volume loop showing a 'saw tooth' pattern typical of retained secretions



Bedside Detection of Retained Tracheobronchial Secretions in Patients Receiving Mechanical Ventilation : Is It Time for Tracheal Suctioning?
Jean Guglielminotti, Marc Alzieu, Eric Maury, Bertrand Guidet and Georges Offenstadt

CHEST 2000; 118:1095–1099

Characteristic scalars due to secretion build up in the tubing circuit



Recognizing ventilator auto-cycling

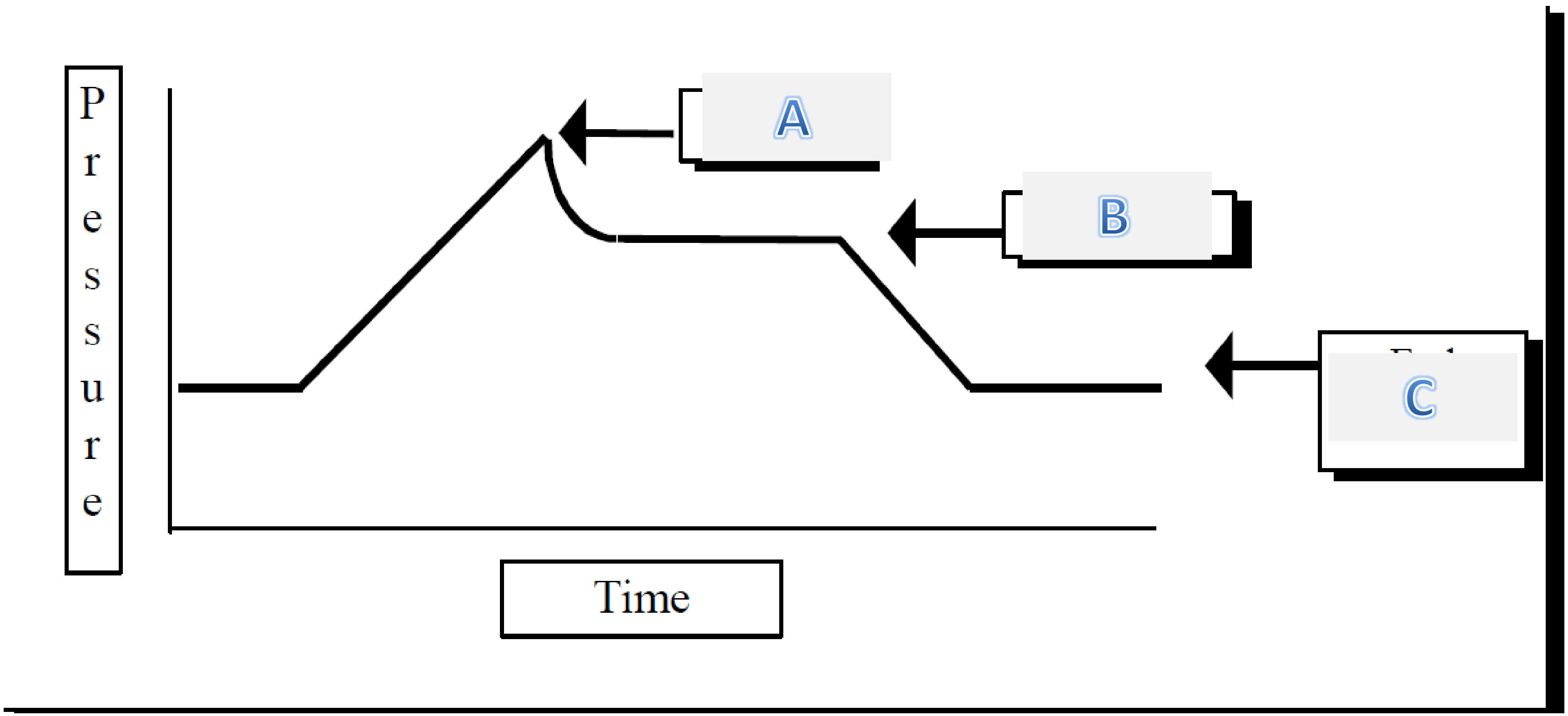
- Think about auto-cycling when
  - the respiratory rate increases suddenly without any patient input and
  - if the exhaled tidal volume and minute ventilation suddenly decrease.
- Typically occurs because of a leak anywhere in the system starting from the ventilator right up to the patients lungs
  - e.g. leaks in the circuit, ET tube cuff leak, lungs (pneumothorax)
- May also result from condensate in the circuit
- The exhaled tidal volume will be lower than the set parameters and this may set off a ventilator alarm for low exhaled tidal volume, low minute ventilation, circuit disconnect or rapid respiratory rate.

Take home points

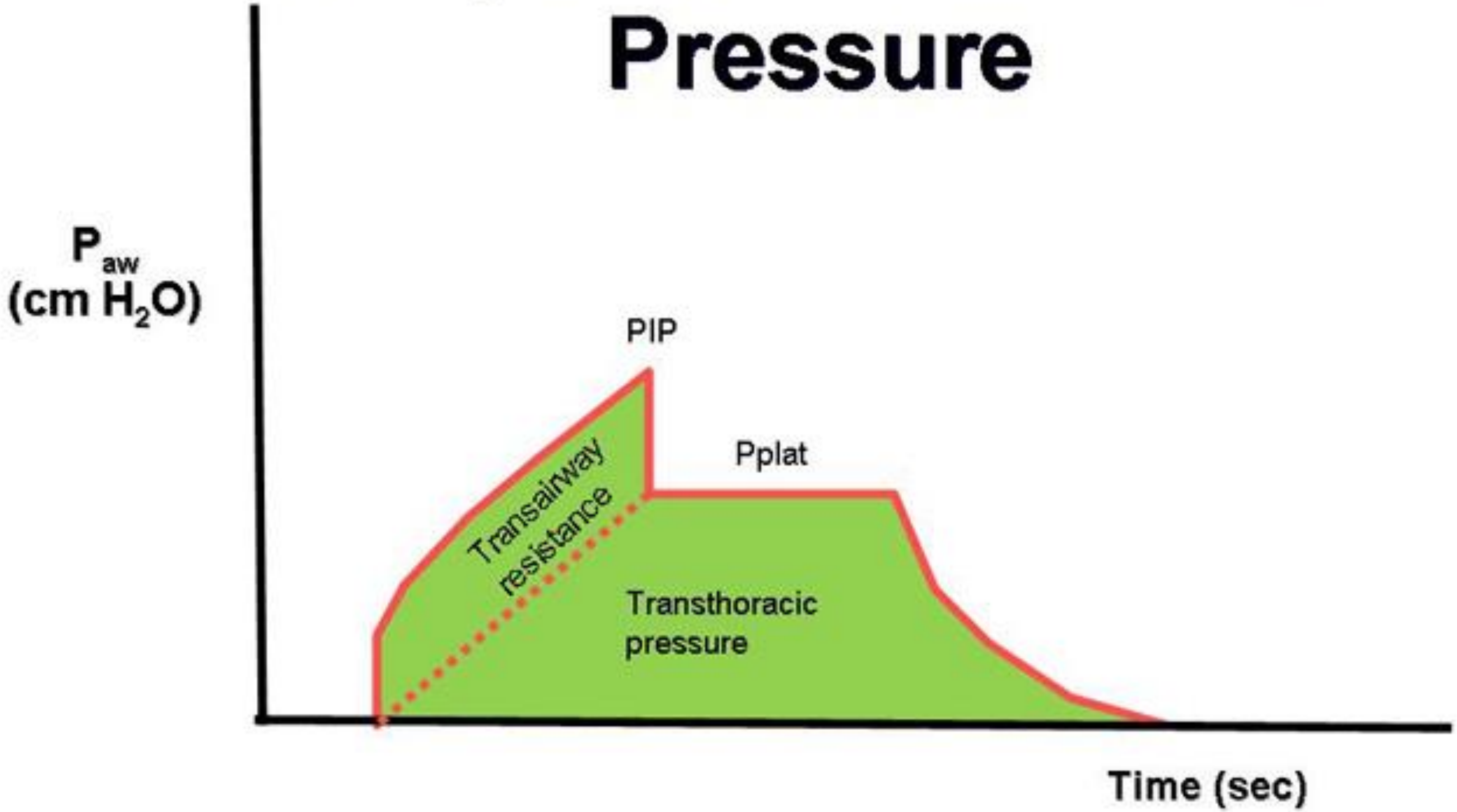
- Ventilator waveform analysis is an integral component in the management of a mechanically ventilated patient.
- Develop a habit of looking at the right waveform for the given mode of patient ventilation.
- Always look at the inspiratory and expiratory components of the flow-time waveform.
- Don’t hesitate to change the scale or speed of the waveform to aid in your interpretation.

Thank You

Where is the plateau pressure?



Components of Inflation Pressure



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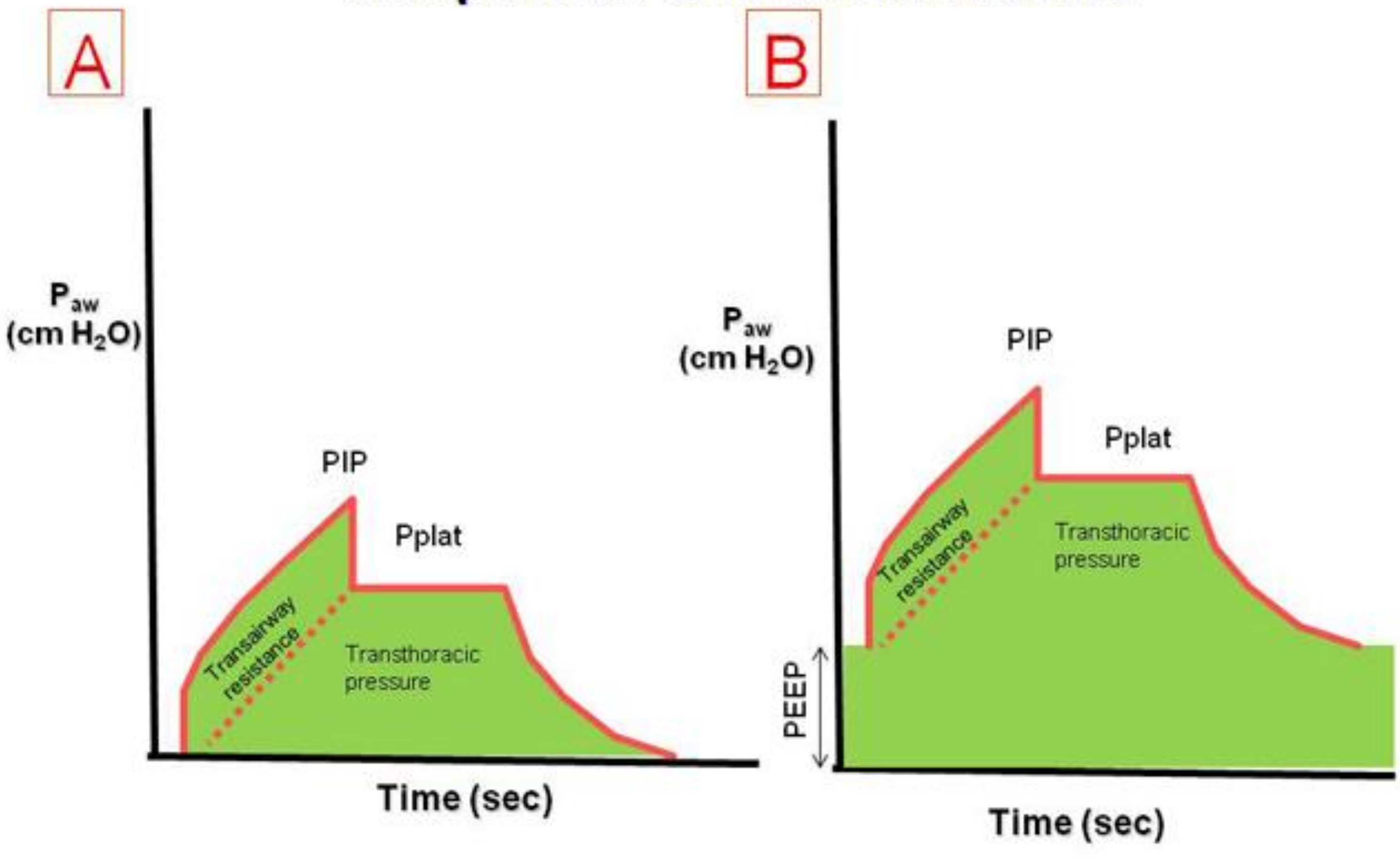
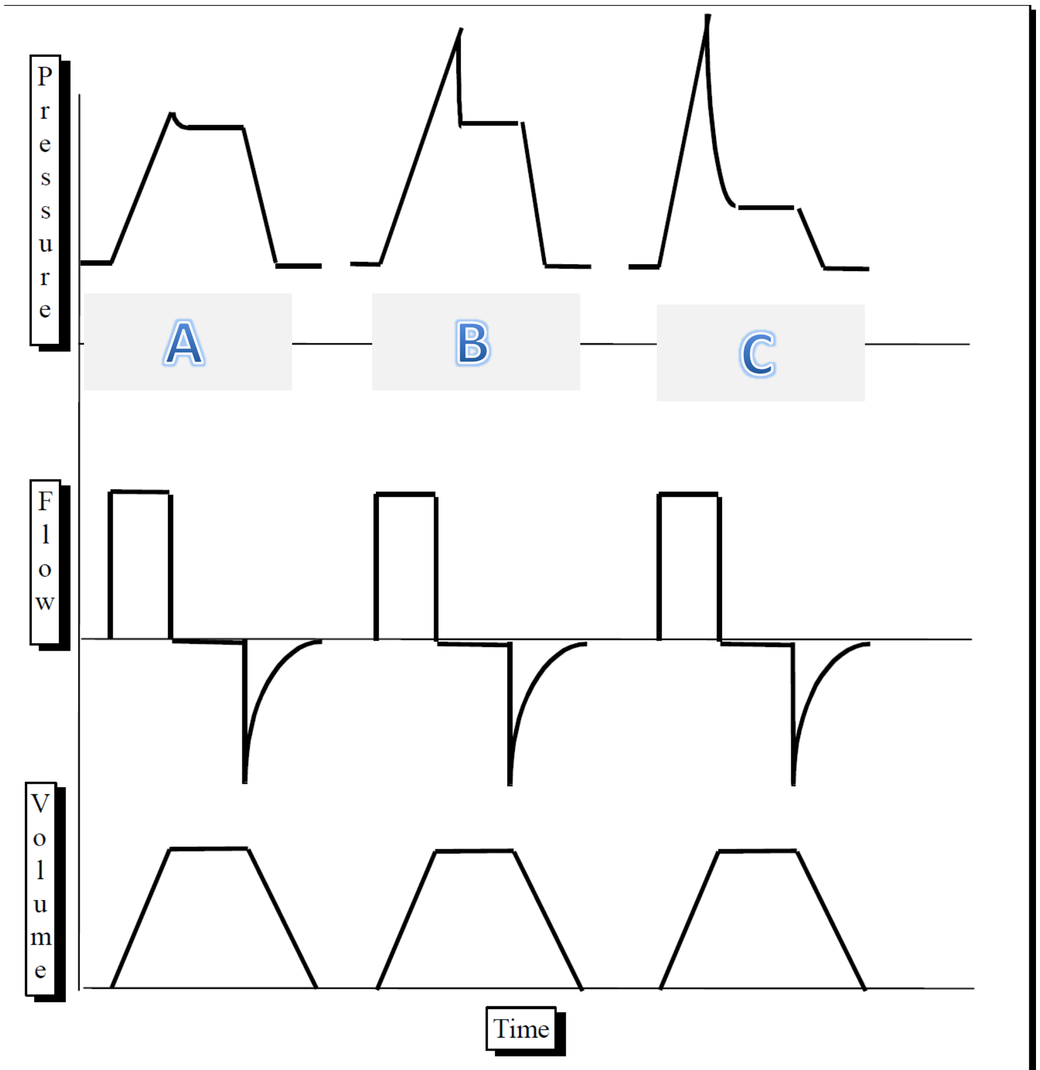
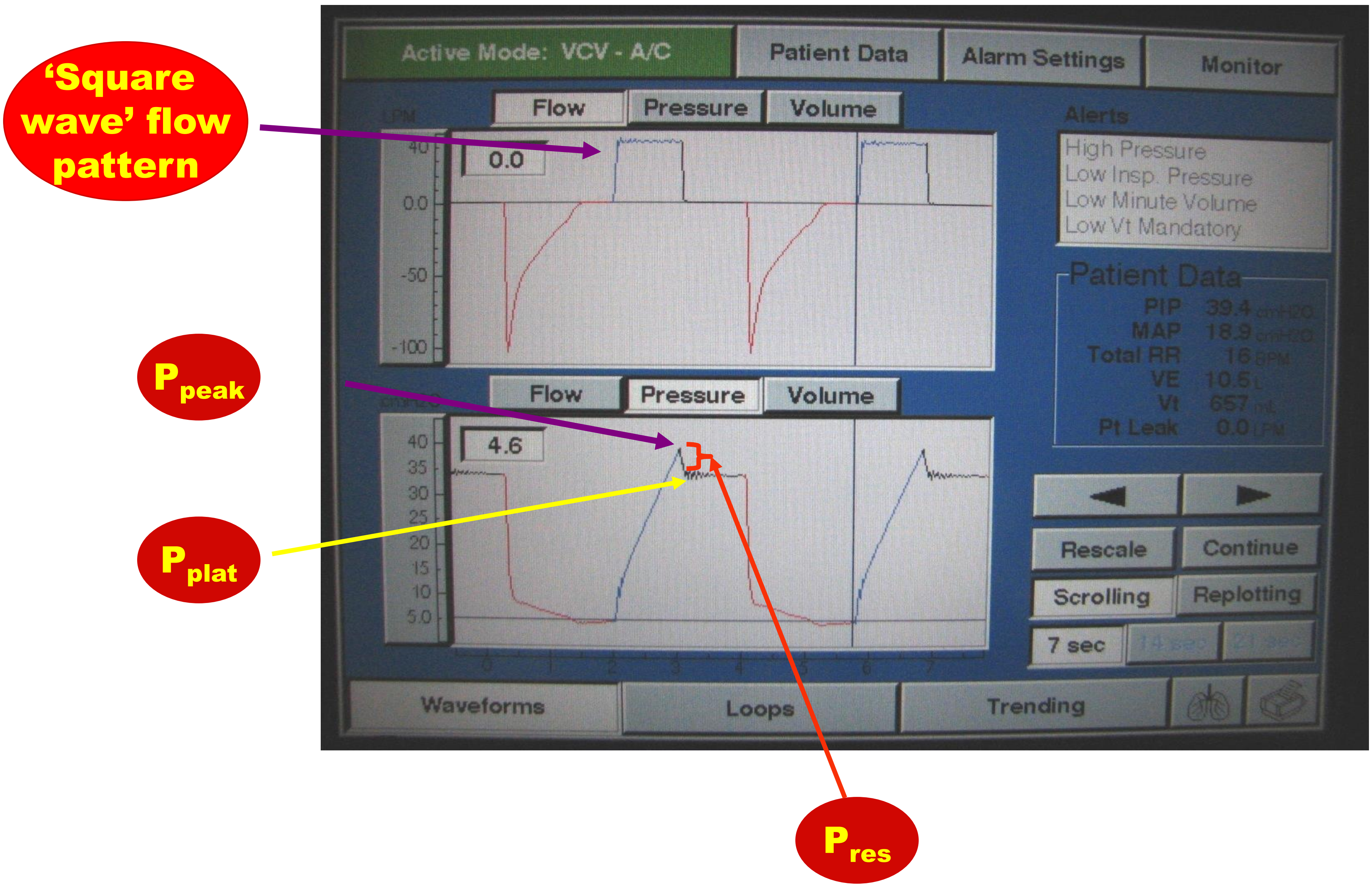




2. Which of the following waveforms indicate an increased resistance and a decreased compliance?

Waveform showing decreased lung compliance

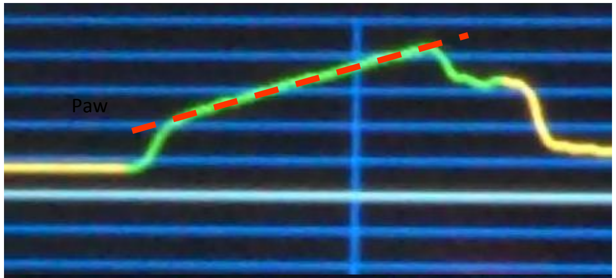


3. What is the best Stress Index?

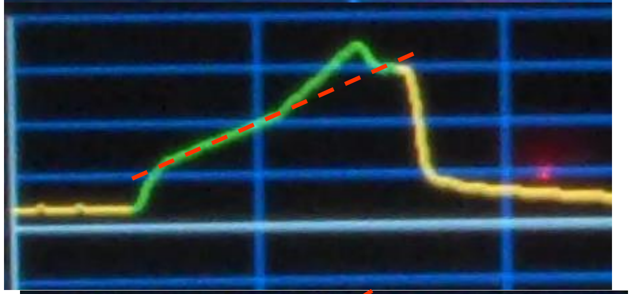
This is on AC volume ventilation using a constant flow waveform. The graph is a pressure time scalar.

Note: Patient effort must be absent

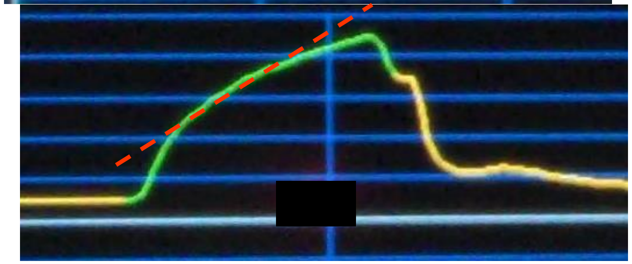
A



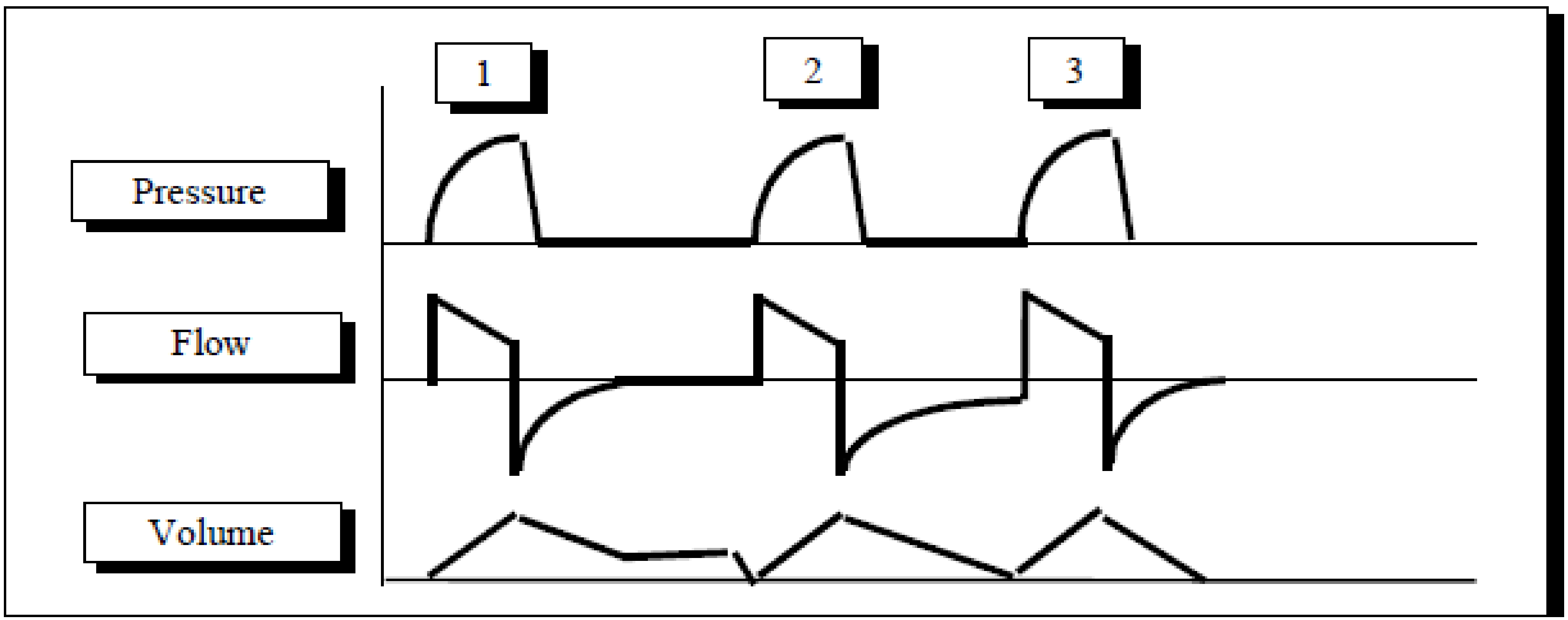
B



C



4. Which waveform shows autopeep?



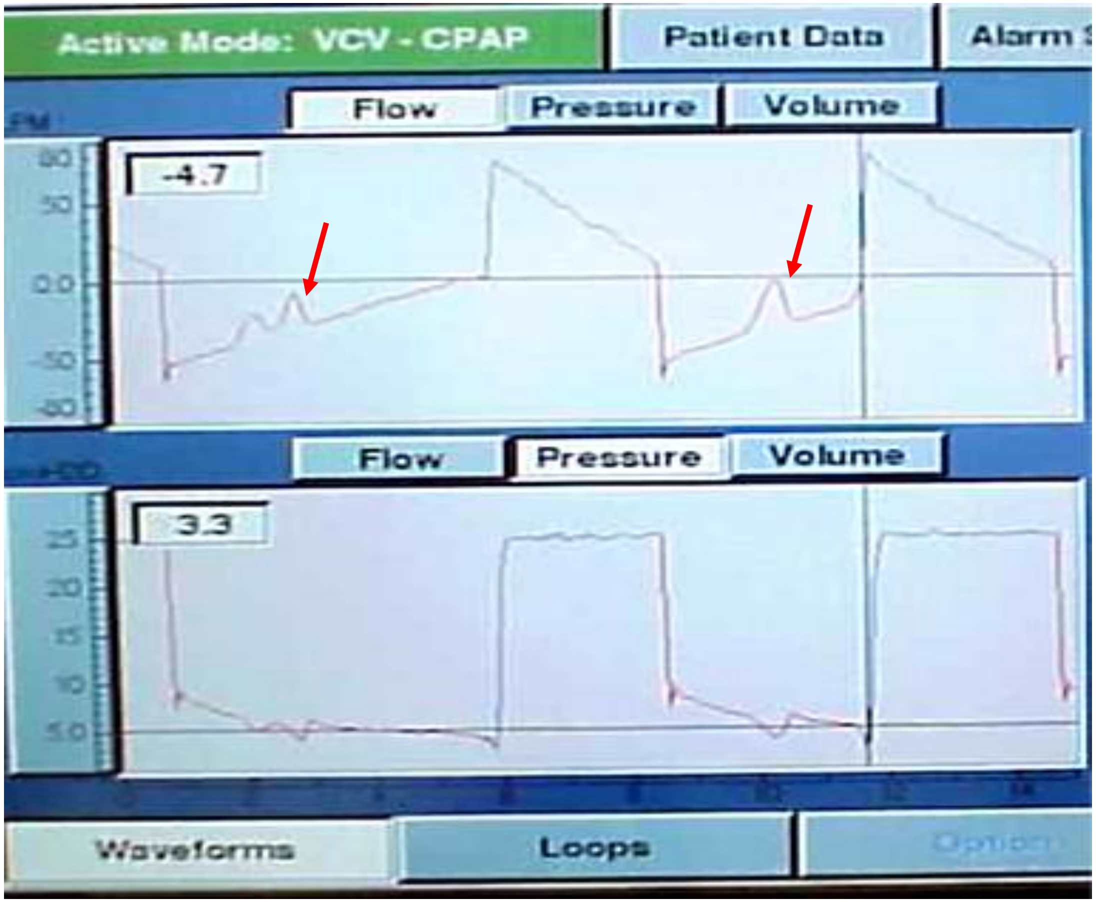
5. What is shown by the Red Arrow

A. Auto Peep

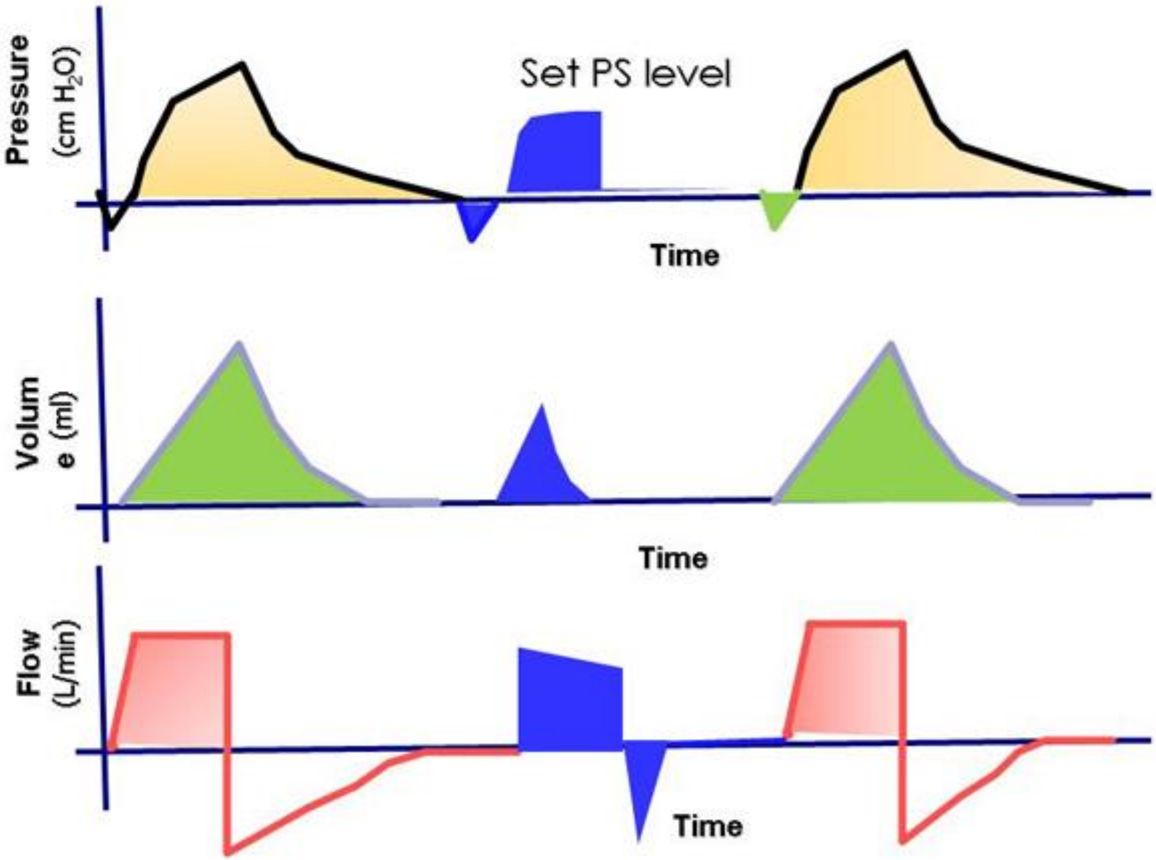
B. Retained Secretions

C. Ineffective Patient Effort

D. Double Triggering



SIMV+ PS
(Volume-Targeted Ventilation)



SIMV
(Volume-Targeted Ventilation)