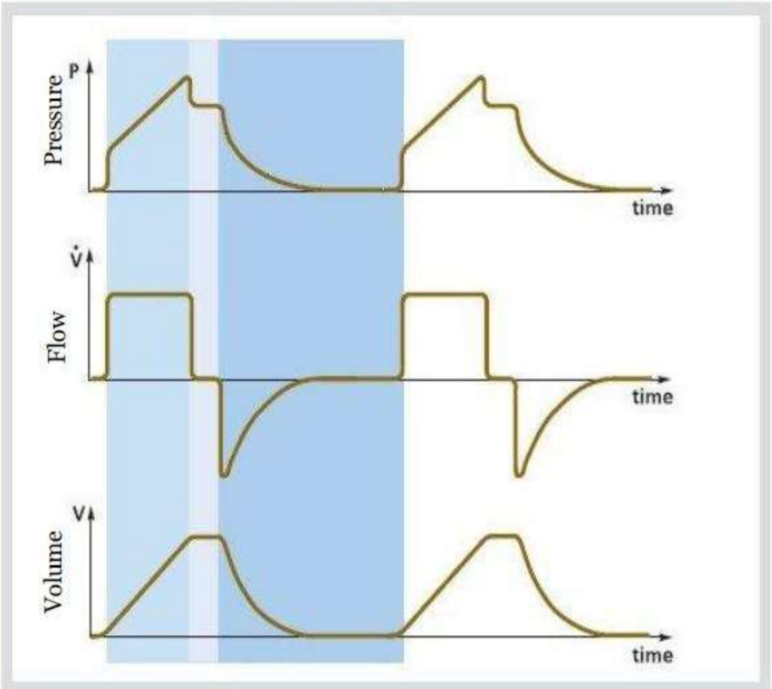
Scalars and loops in mechanical ventilation

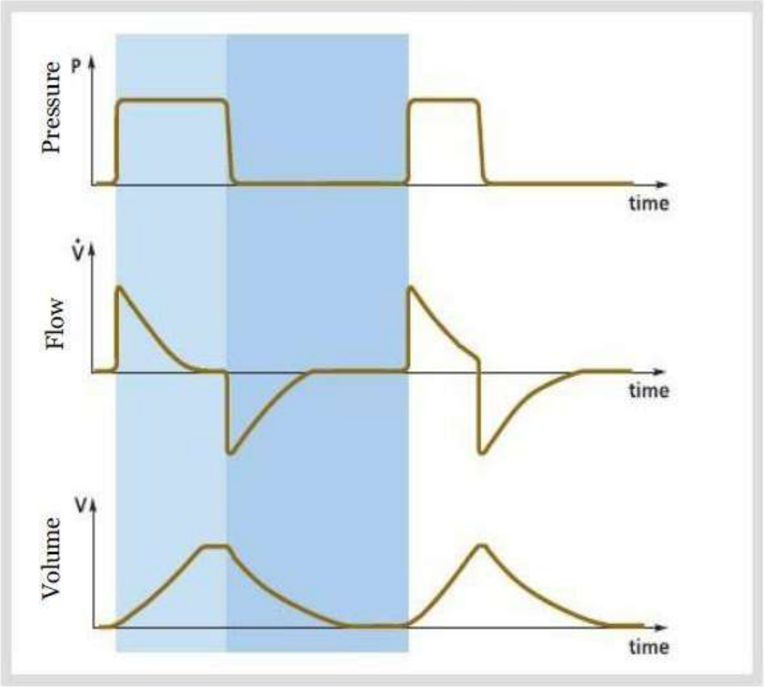
29/3/2019

Scalars

- Scalars waveform representations of pressure, flow or volume on the y axis vs time on the x axis
- Ventilators measure airway pressure and airway flow
- Volume is derived from the flow measurement
- *Pressure and flow* provide all the information necessary to explain the physical interaction between ventilator and patient
- Volume scalar – tidal volume delivered during inspiration and expiration

Scalars

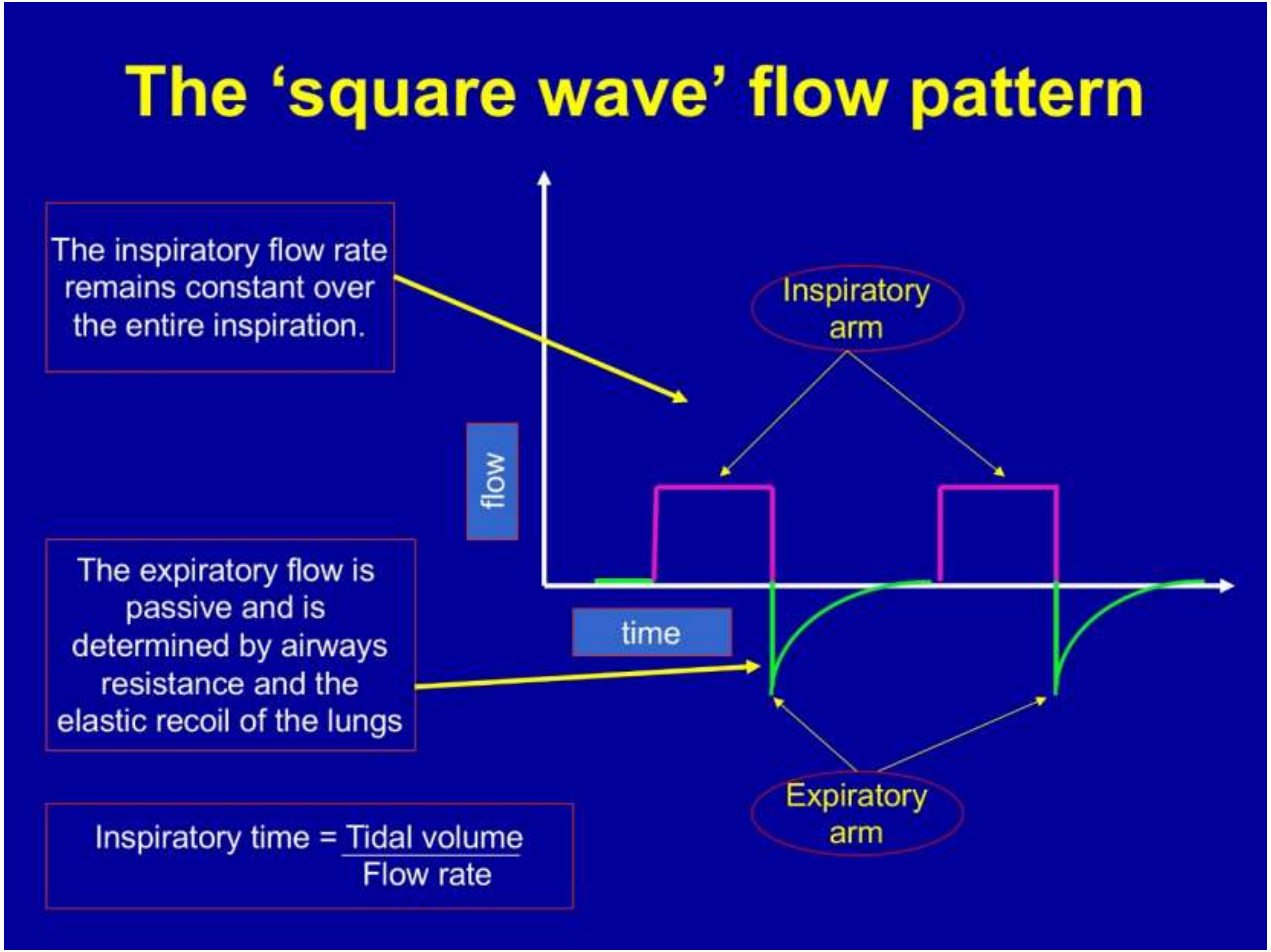

P
Pressure
time
V̇
Flow
time
V
Volume
time


P
Pressure
time
V̇
Flow
time
V
Volume
time

Flow time waveform

- Inspiratory arm
  - Active in nature
  - Character dependent on the ventilator flow settings and mode of ventilation
  - Volume A/C – ‘square wave’ ‘ramp pattern’
  - Pressure A/C – Decelerating ramp – subtle variation compliance and/or demand
- Expiratory arm
  - Passive
  - Character dependent on the elastic recoil and lung resistance
  - Patients active effort

Iyer *et al.* ATS review: Ventilator waveform interpretation and analysis



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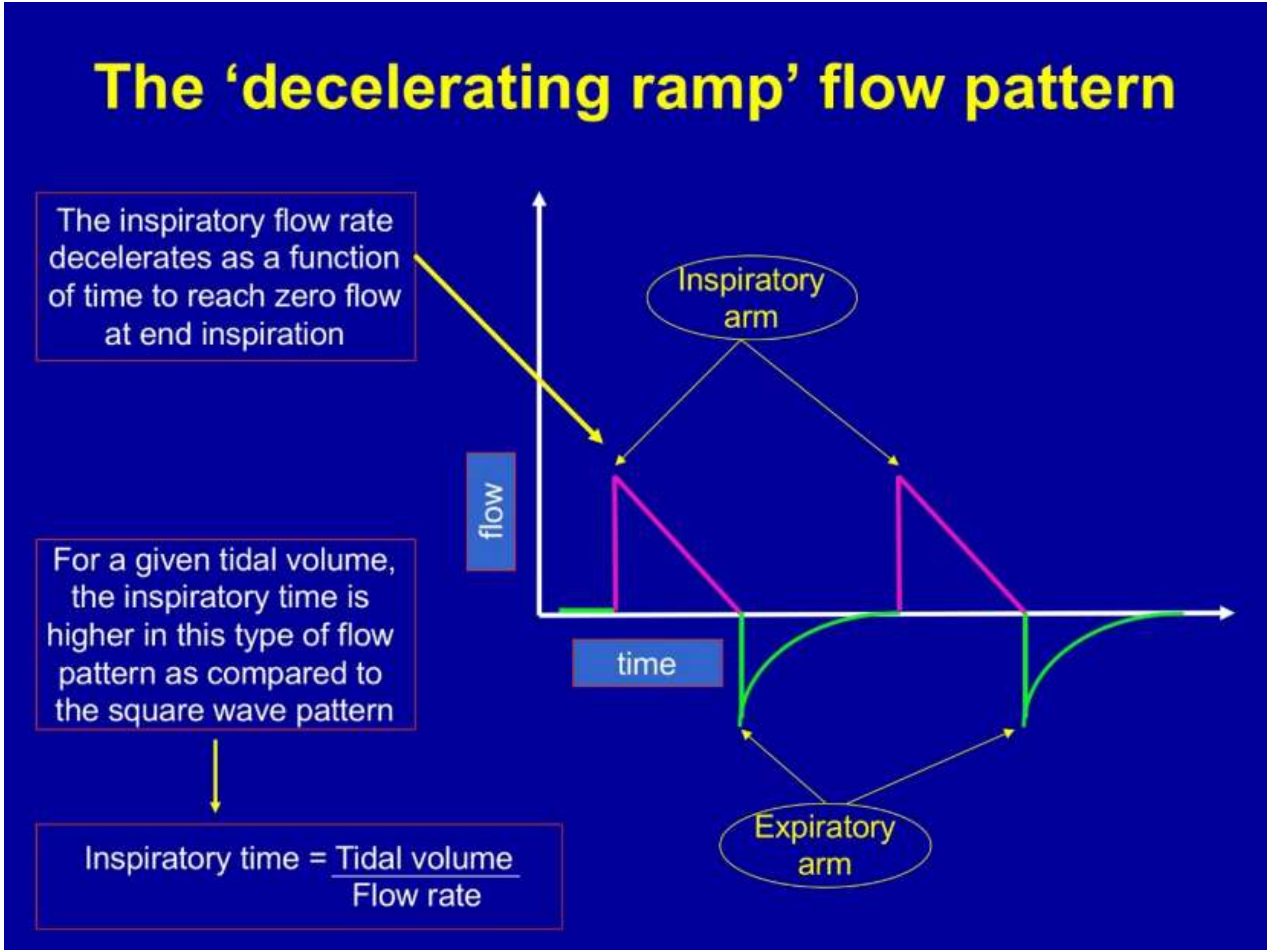


Iyer *et al.* ATS review: Ventilator waveform interpretation and analysis

Flow time waveform

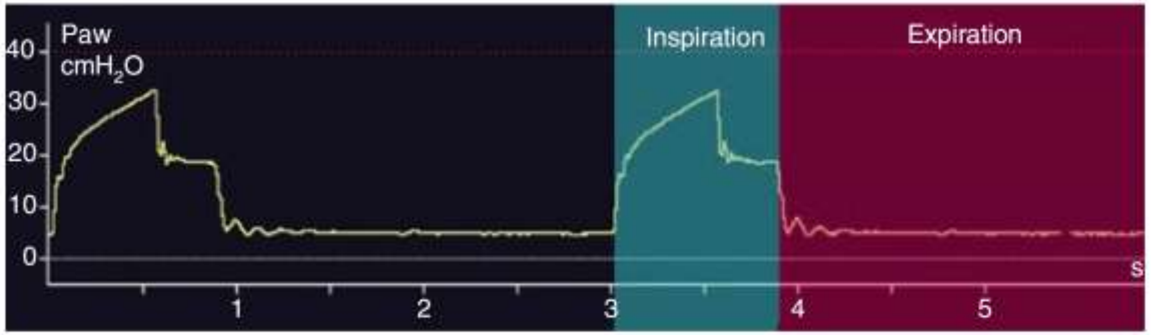
- Square wave
  - Inspiratory time shortest to achieve set V_t
  - Highest Ppeak
  - Low mean pressure (Hemodynamic stability –CO and venous return unaffected)
- Decelerating ramp
  - Inspiratory time is longer to achieve similar V_t
  - Lower Ppeak
  - Pmean high can affect CO and venous return
- Ascending ramp
  - Gradual rise in flow associated with discomfort and flow hunger

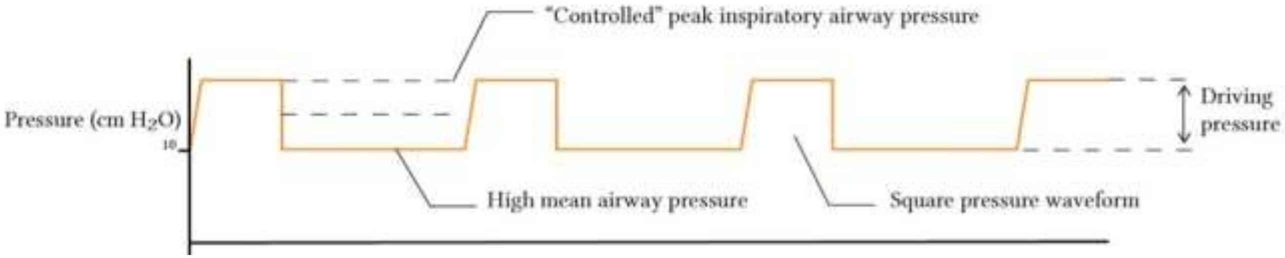
- No studies flow pattern alone but animal models show no significant difference between square and decelerating ramp in terms of oxygenation, CO2 elimination or hemodynamic parameters

Markström AM *et al.* Anesthesiology. 1996 Apr;84(4):882-9

Pressure curve

- The pressure curve is positive during mechanical ventilation
- Baseline pressure above zero appears when PEEP is applied and assisted inspiration is shown as an increase in pressure above PEEP during volume delivery





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Pressure time waveform

- Ventilator circuit
- Generation of pressures within the circuit
- The equation of motion
- Pressure time waveform

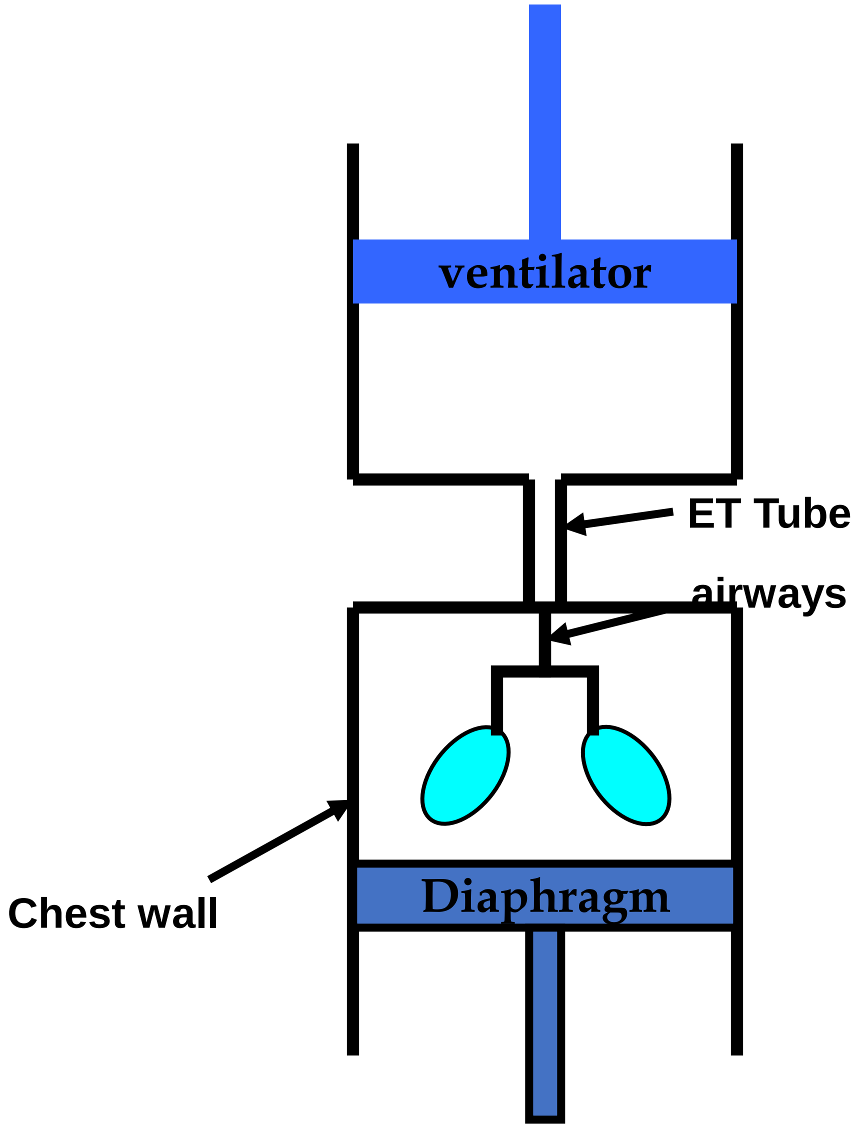
Iyer *et al.* ATS review: Ventilator waveform interpretation and analysis

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 patients airways.

The ventilator makes up the first part of the circuit. Its pump like action 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.



Generation of airway pressures

- Respiratory system mechanical system consisting of a resistive (airways) and elastic (lungs and chest wall) element in series
- Pressure contributed by airways - result of inherent resistance of the airways and the rate of airflow (so Flow x Resistance)
- Contribution of pressure by elastic element depends on compliance of lung+chest wall and volume being given (so Volume/Compliance)

$$\mathbf{P_{aw}} = \text{Flow x Resistance} + \frac{\text{Volume}}{\text{Compliance}}$$

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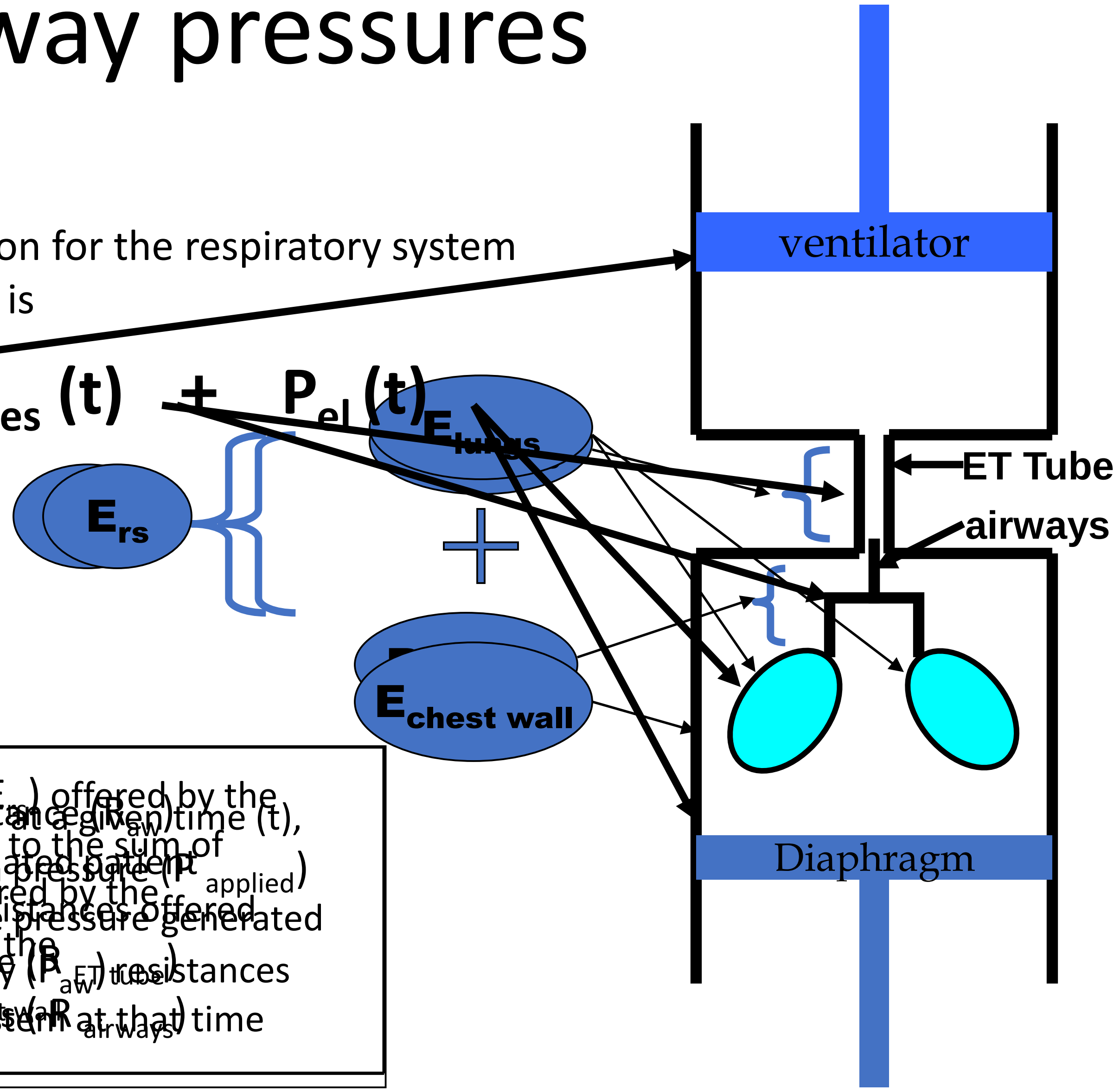
Generation of airway pressures

Thus the equation of motion for the respiratory system is

$$P\ applied\ (t) = P_{res}\ (t) + P_{el}\ (t)$$



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

Thus to move air into the lungs at a given time (t), the ventilator has to generate a pressure ($P_{applied}$) that is sufficient to overcome the pressure generated by the elastic ($P_{el\ (t)}$) and airway (P_{aw}) resistances offered by the respiratory system at that time

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 ($R_{airways}$)

Pressure time waveform

- Reflection of pressures generated within airways during each phase of the ventilator cycle

1. Pressure generated to overcome airway resistance

   No volume delivered

→

2. Subsequently pressure rises linearly to reach peak

   Corresponds to flow and volume delivery

→

3. After pressure peaks and flow declines pressure drops by amt = Pres and reaches Plat

→

4. Return to baseline after pause/peak to set PEEP during expiration

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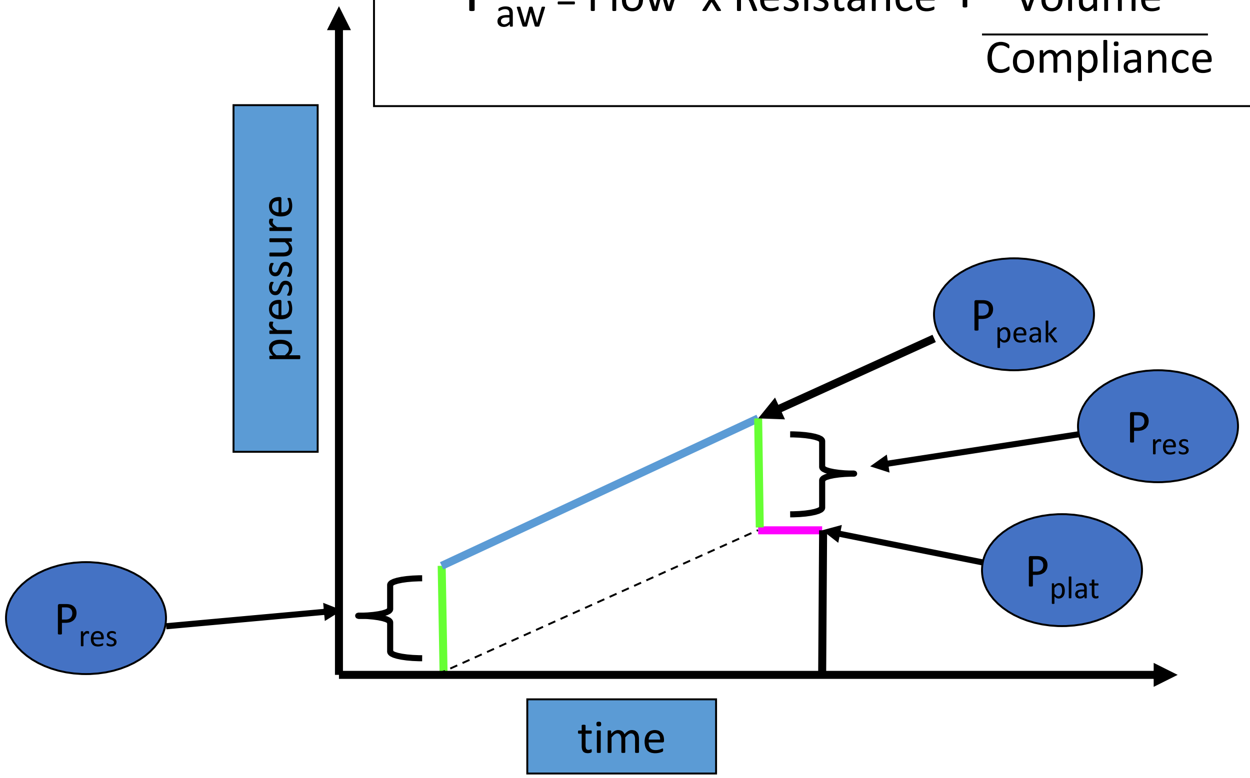
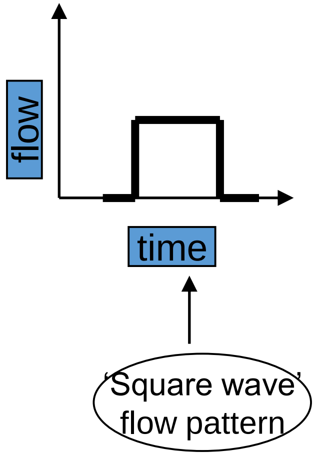
Pressure-time waveforms using a 'square wave' flow pattern

$$P_{aw} = \text{Flow} \times \text{Resistance} + \frac{\text{Volume}}{\text{Compliance}}$$

1

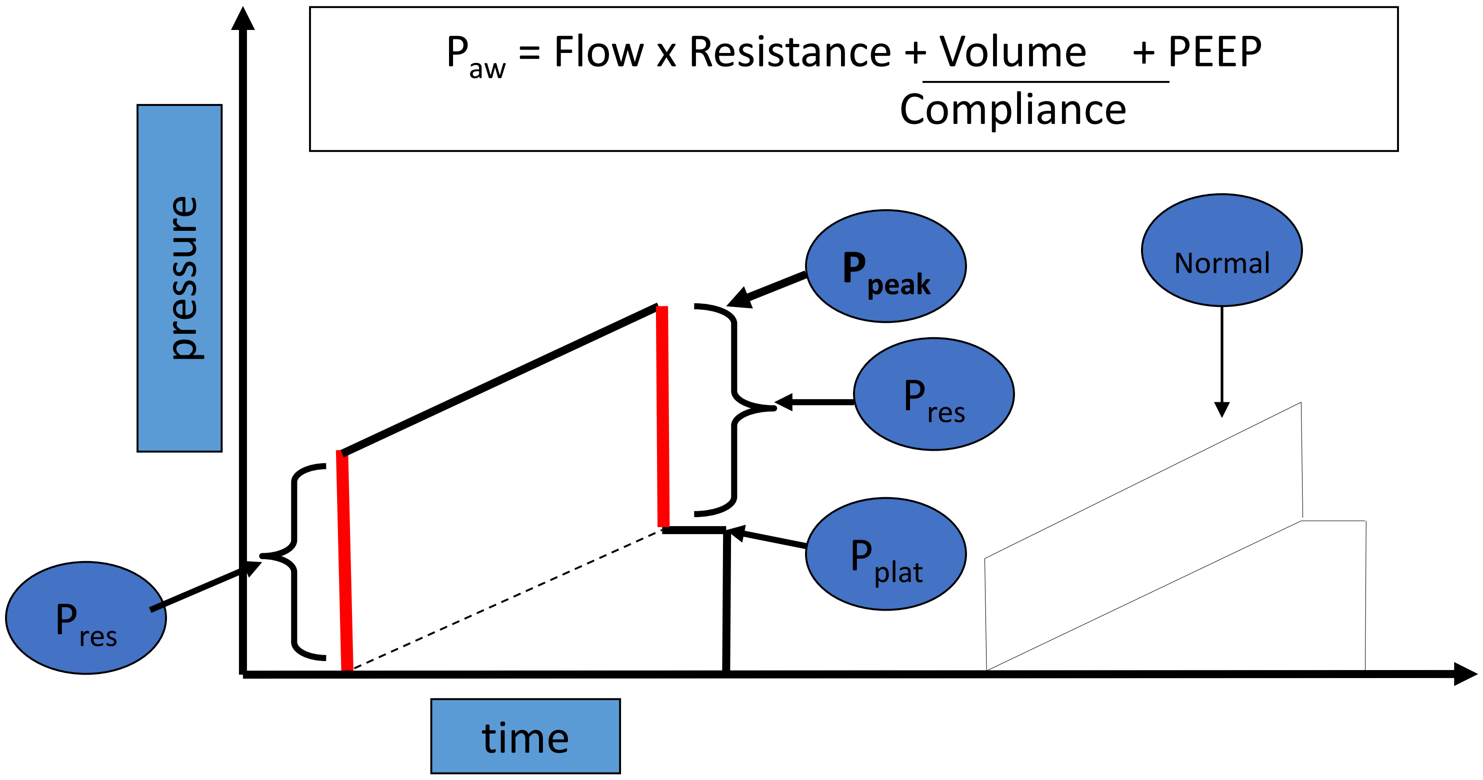


Normal values:
P_{peak} < 40 cm H_2O
P_{plat} < 30 cm H_2O
P_{res} < 10 cm H_2O



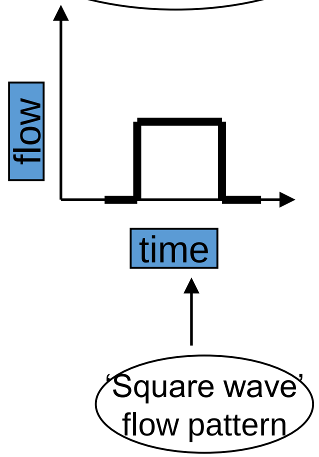
Normal pressure-time waveform
With normal peak pressures (P_{peak}) ;
plateau pressures (P_{plat})and
airway resistance pressures (P_{res})

Pressure-time waveform - obstruction



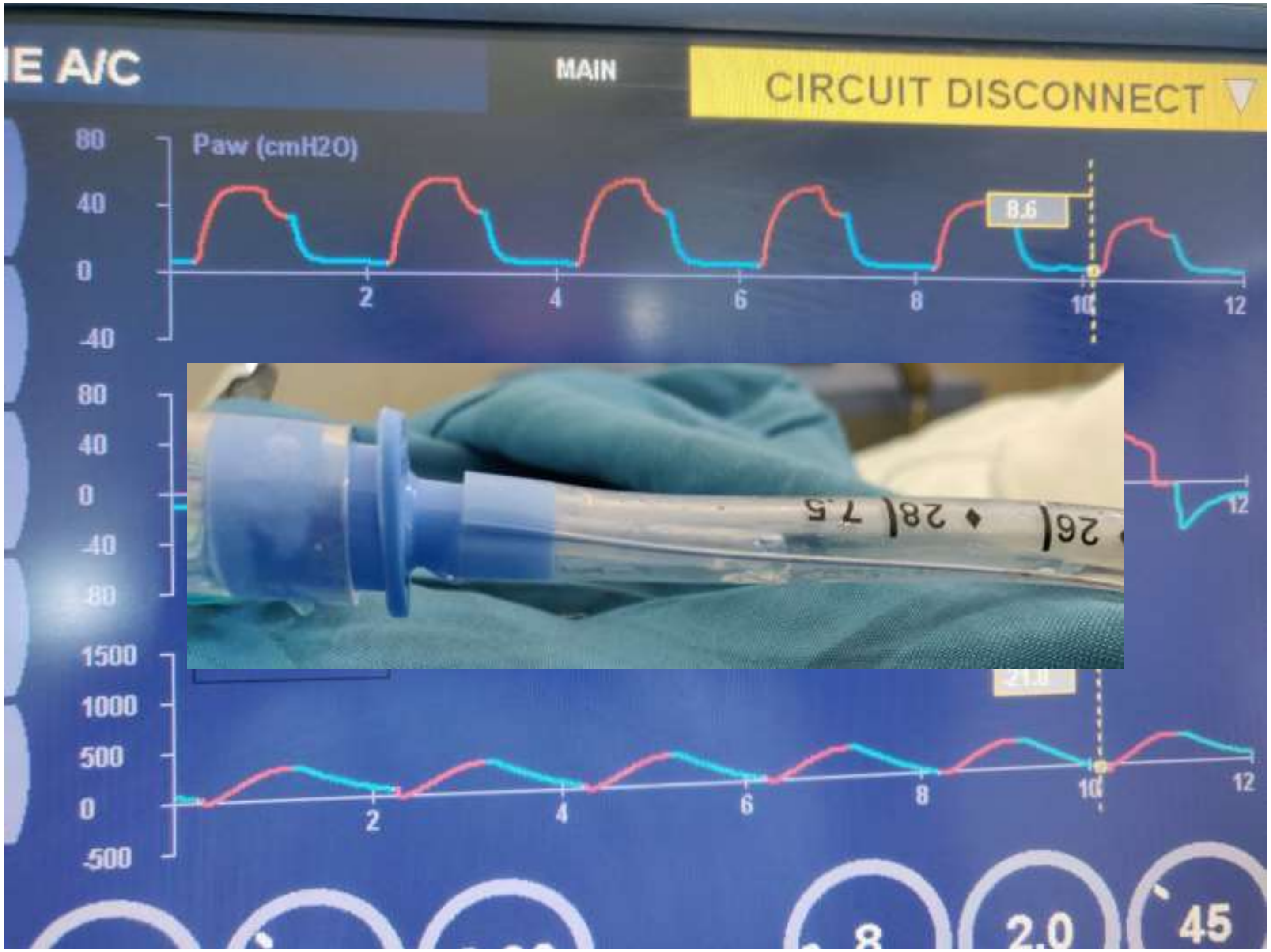
#2

e.g. ET tube blockage



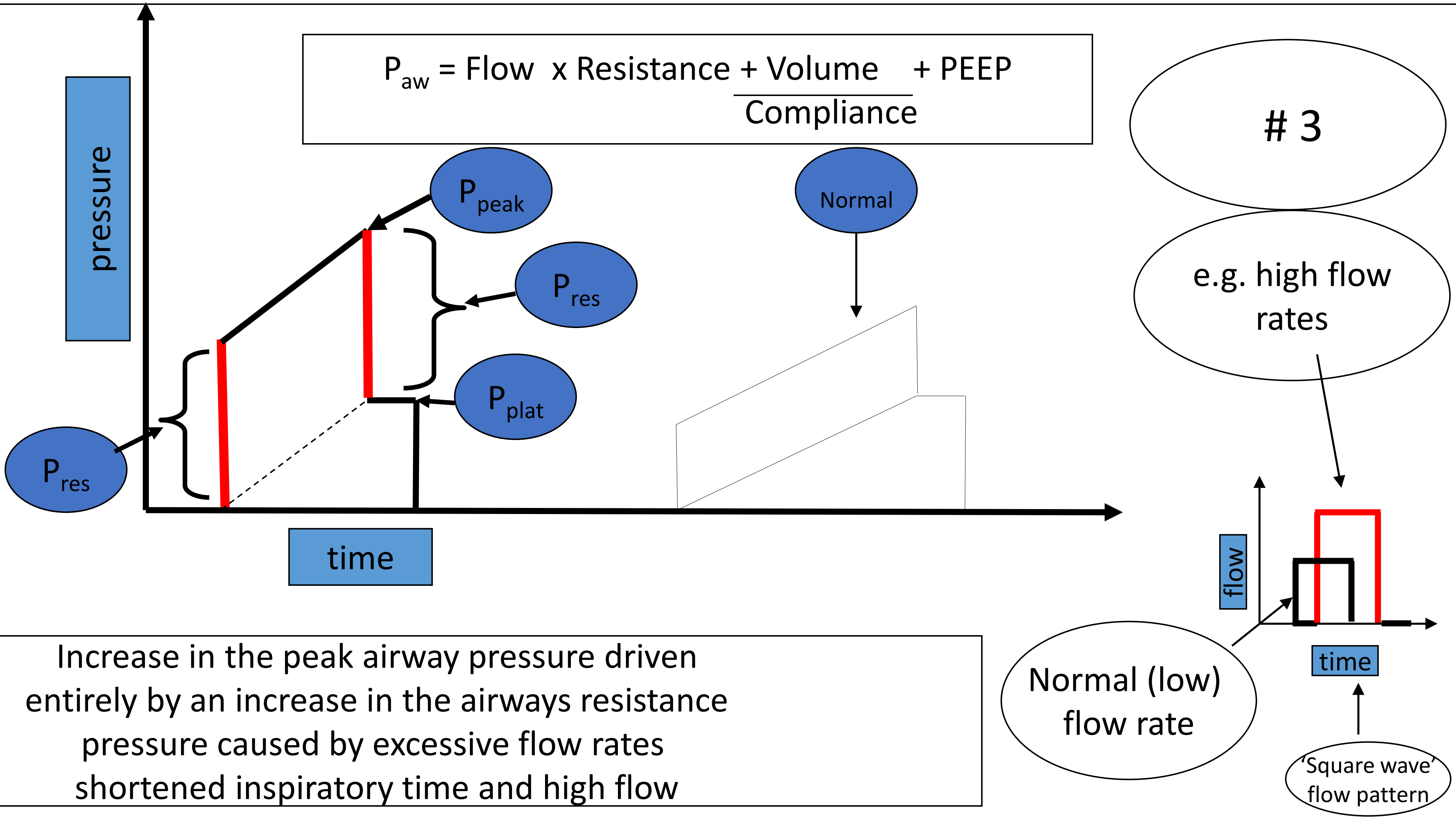
Increase in peak airway pressure driven by an increase in the airways resistance normal plateau pressure

ET Tube obstruction



Pressure time waveform –high flow

$$P_{aw} = \text{Flow} \times \text{Resistance} + \frac{\text{Volume}}{\text{Compliance}} + \text{PEEP}$$



Increase in the peak airway pressure driven entirely by an increase in the airways resistance pressure caused by excessive flow rates shortened inspiratory time and high flow

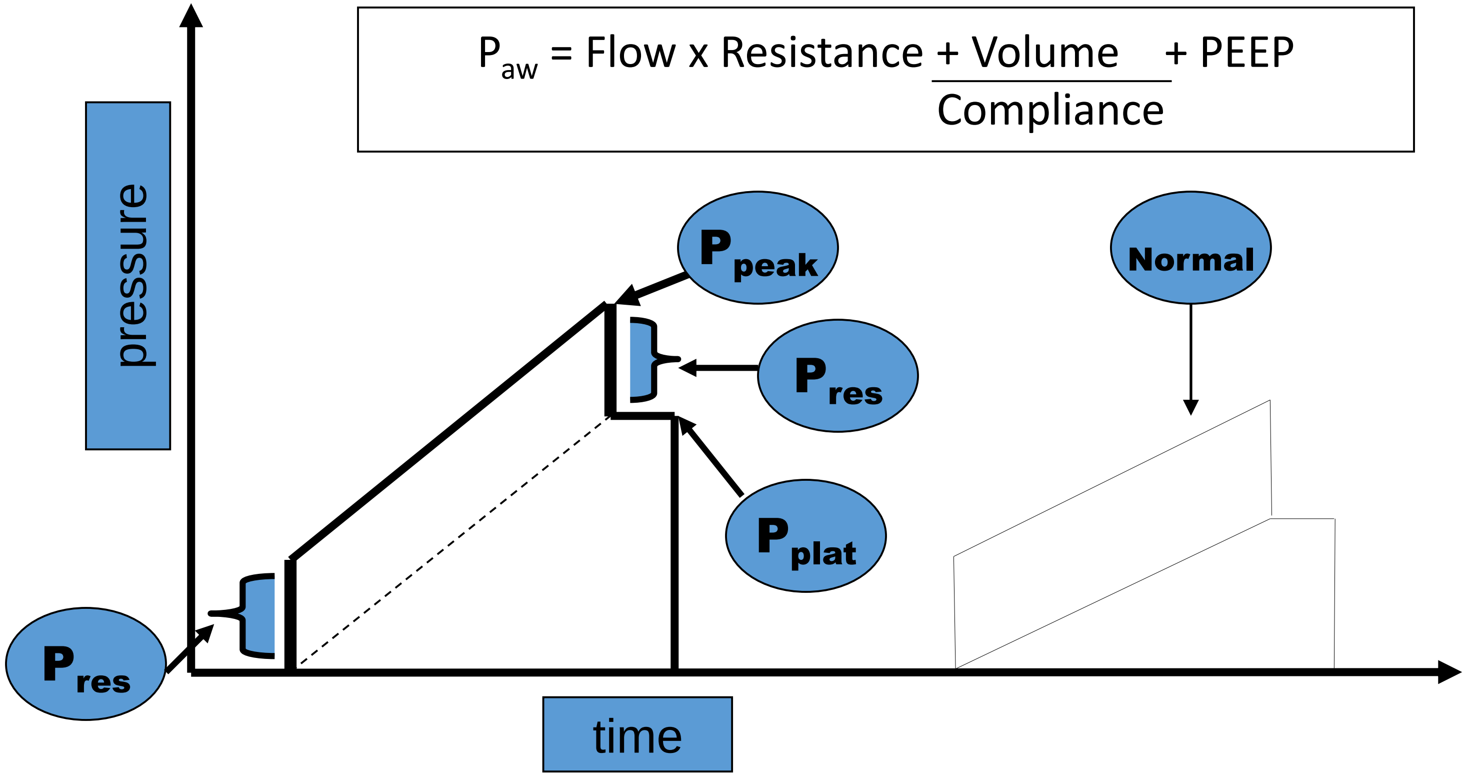
High airflow causing increase in airway resistance

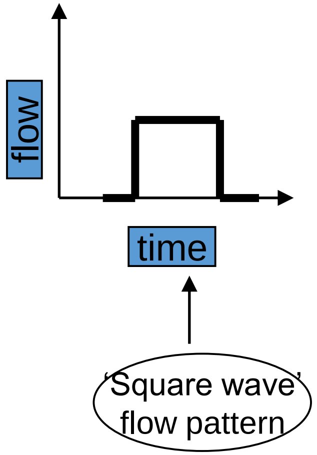
Pressure time waveform – reduced compliance

$$P_{aw} = \text{Flow x Resistance} + \frac{\text{Volume}}{\text{Compliance}} + \text{PEEP}$$

4

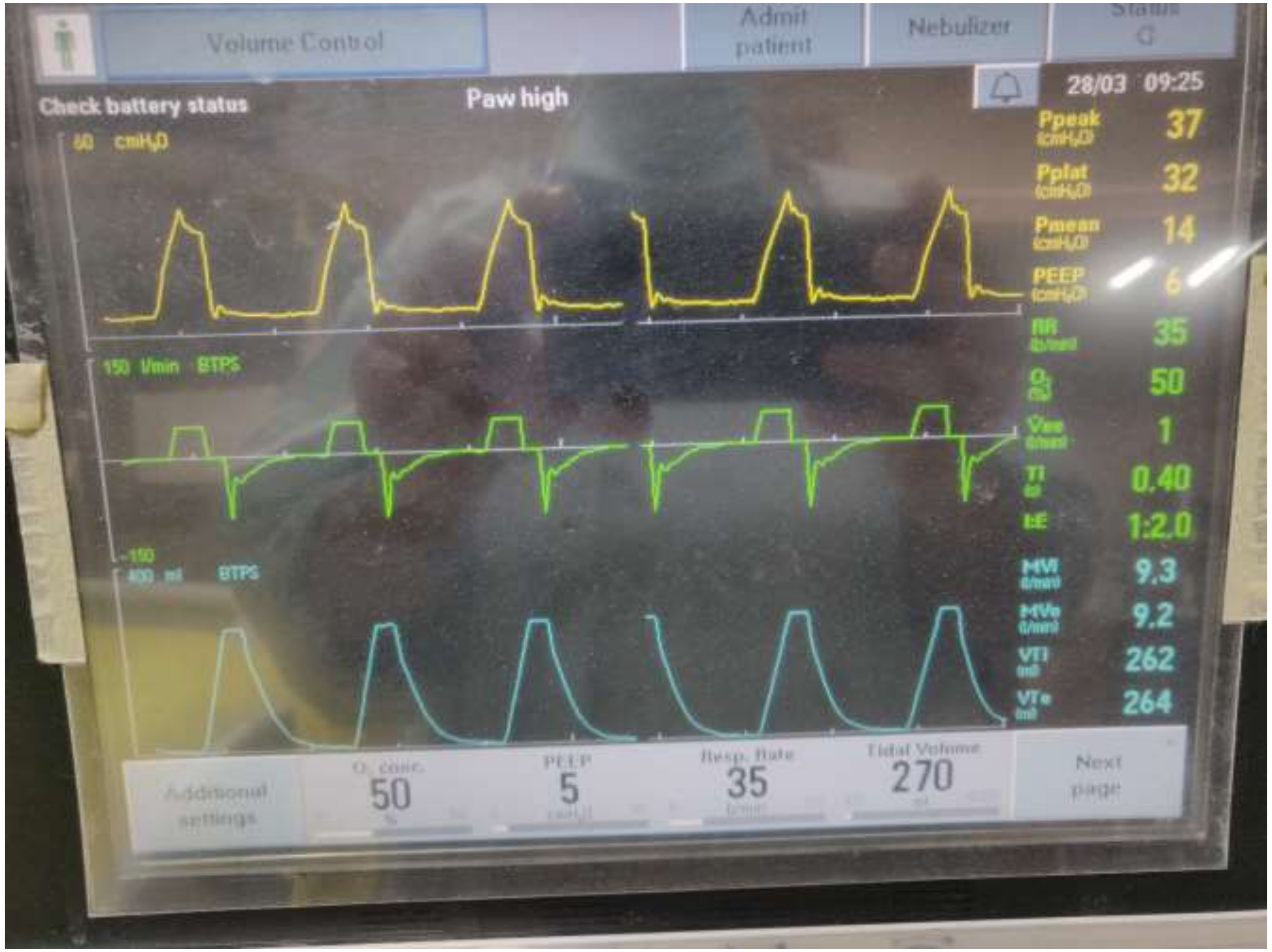
e.g. ARDS



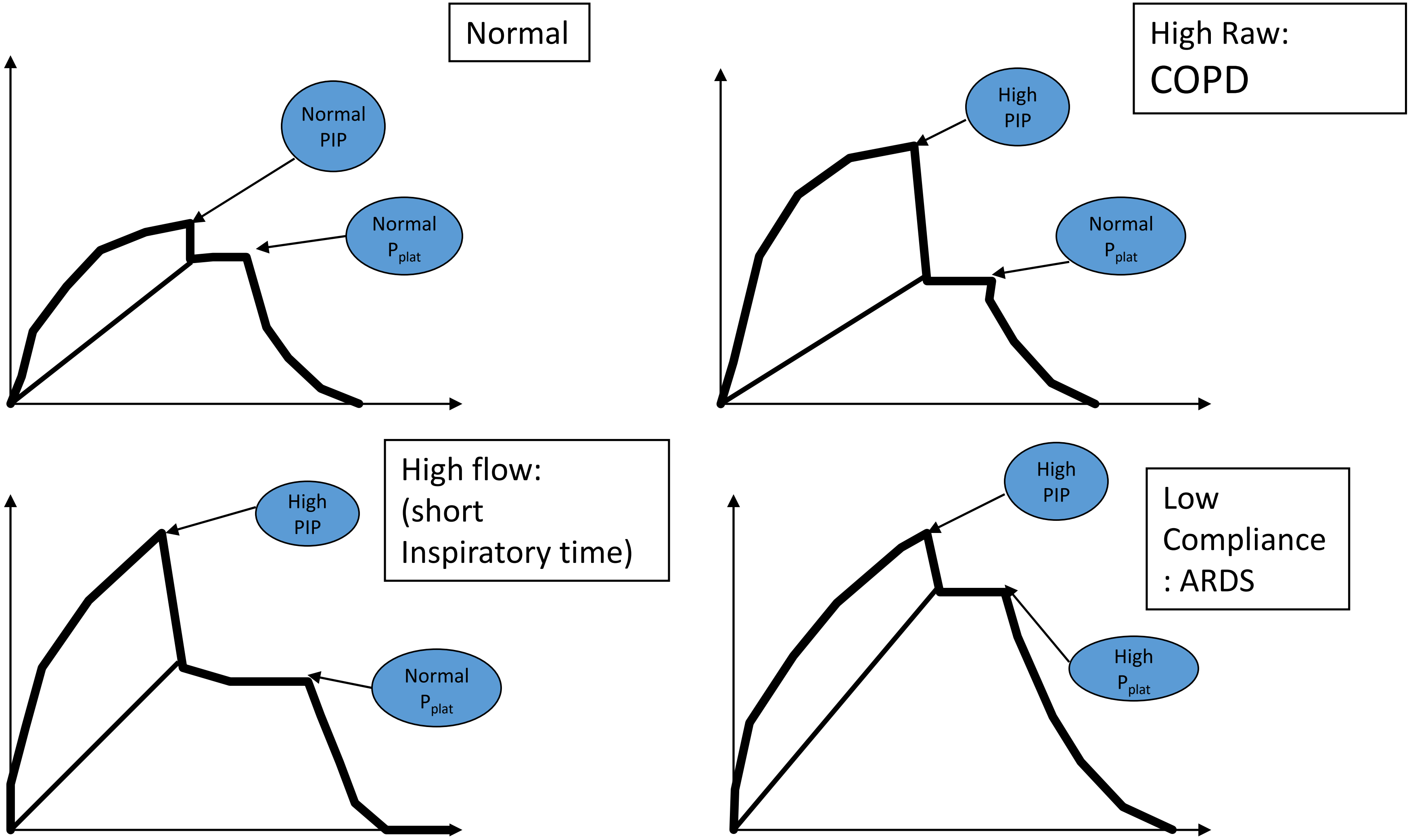


Increase in the peak airway pressure is driven entirely by the decrease in the lung compliance

Reduced compliance

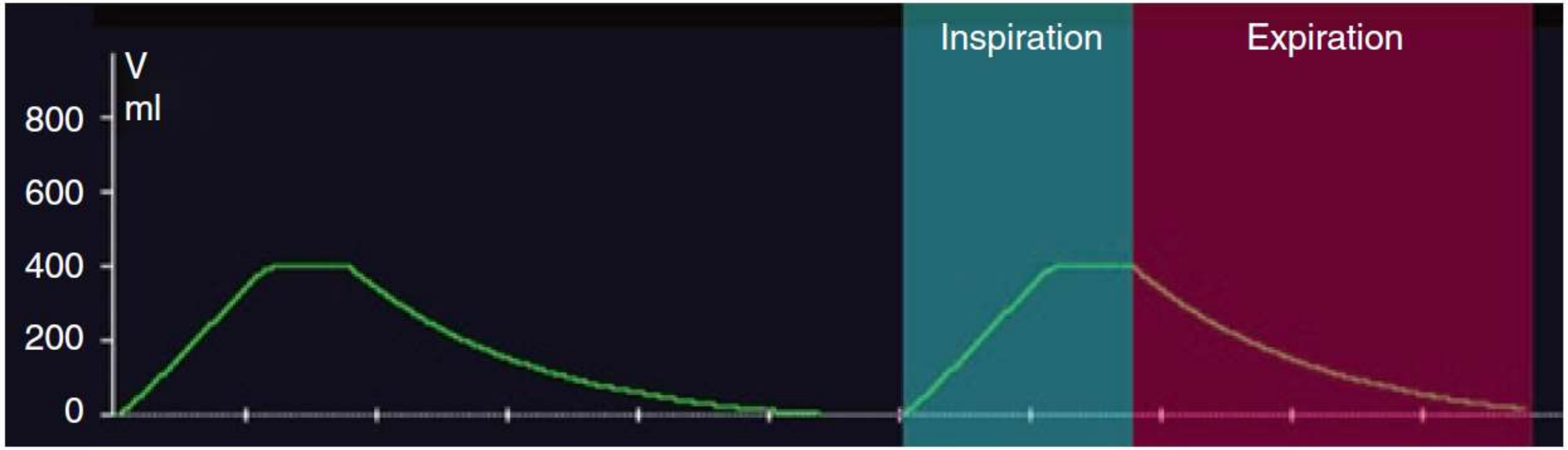


Pressure time waveform with decelerating ramp flow



Volume time waveform

- Volume is not measured directly
- Derived from the flow measurement - area under the flow-time curve
- Important info on airleak, active expiration and hyperinflation



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Independent and dependent variables

- Pressure control - preset inspiratory pressure and time with volume and flow delivery dependent on the patient’s respiratory mechanics
- Pressure is independent variable, while volume and flow are dependent variables
- Volume control - right-hand side of the equation is predetermined (preset tidal volume and flow) making pressure delivery dependent on the patient’s respiratory mechanics
- Volume and flow are considered independent variables in the equation of motion, and pressure is the dependent variable

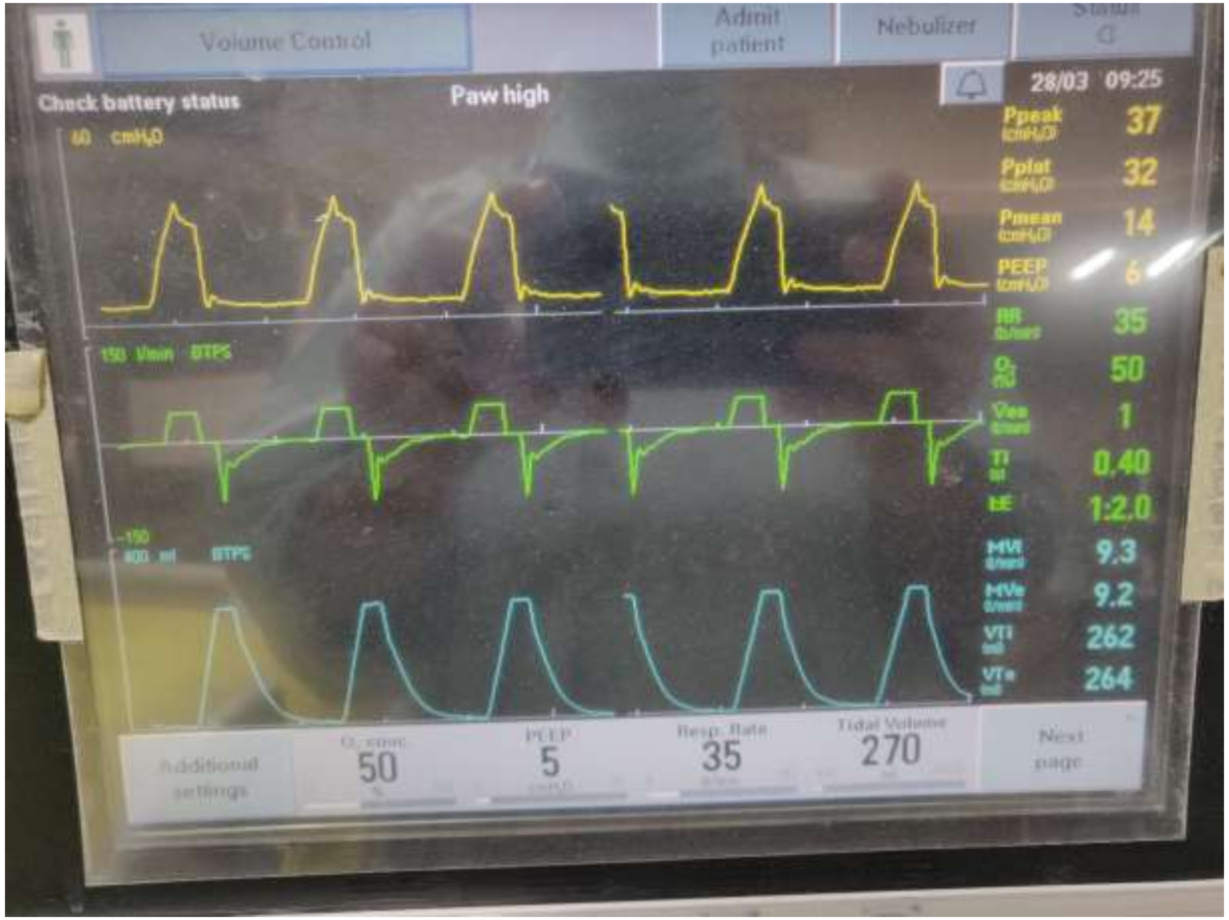
Mode of ventilation and waveforms

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) Flow-volume loop
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)	

Waveforms observed during Volume A/C

- Pressure time
  - Influenced by patients efforts compliance and resistance
- Flow time
  - Inspiratory flow pattern fixed
  - Expiratory flow – depends on compliance, elastic recoil pressure presence of active expiration and obstruction to flow
- Volume time
  - Leaks
  - Dynamic hyperinflation

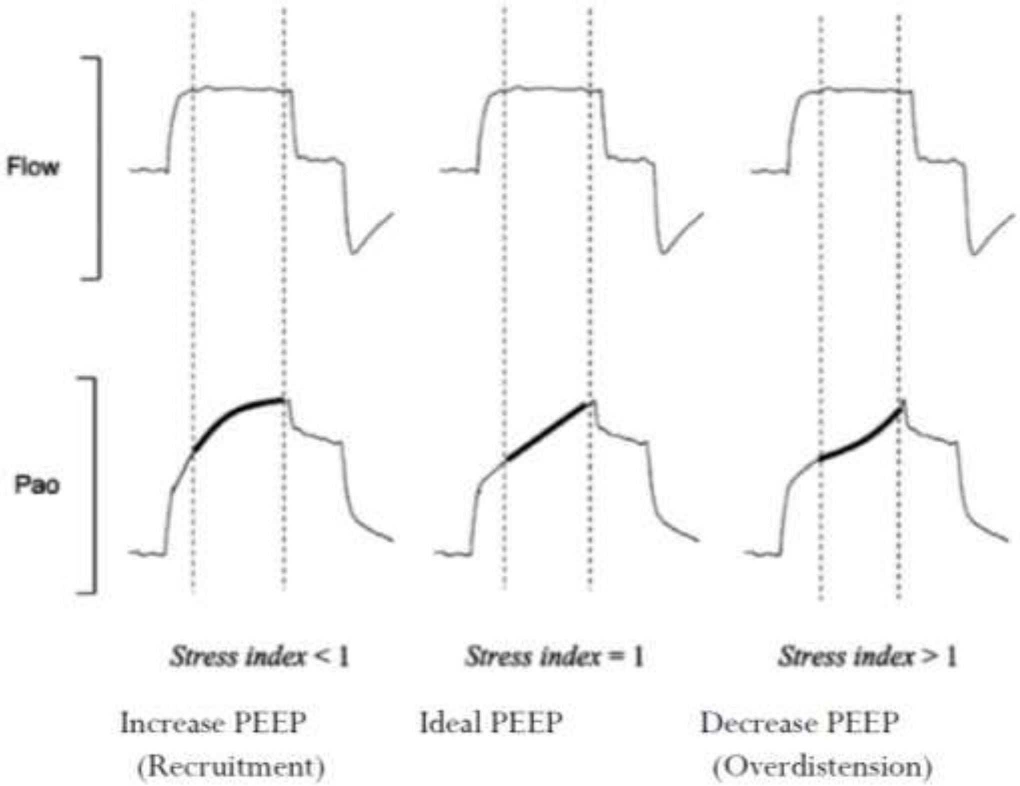
Low compliance increase in elastic recoil with increased PEF



Stress index – Pressure time waveform

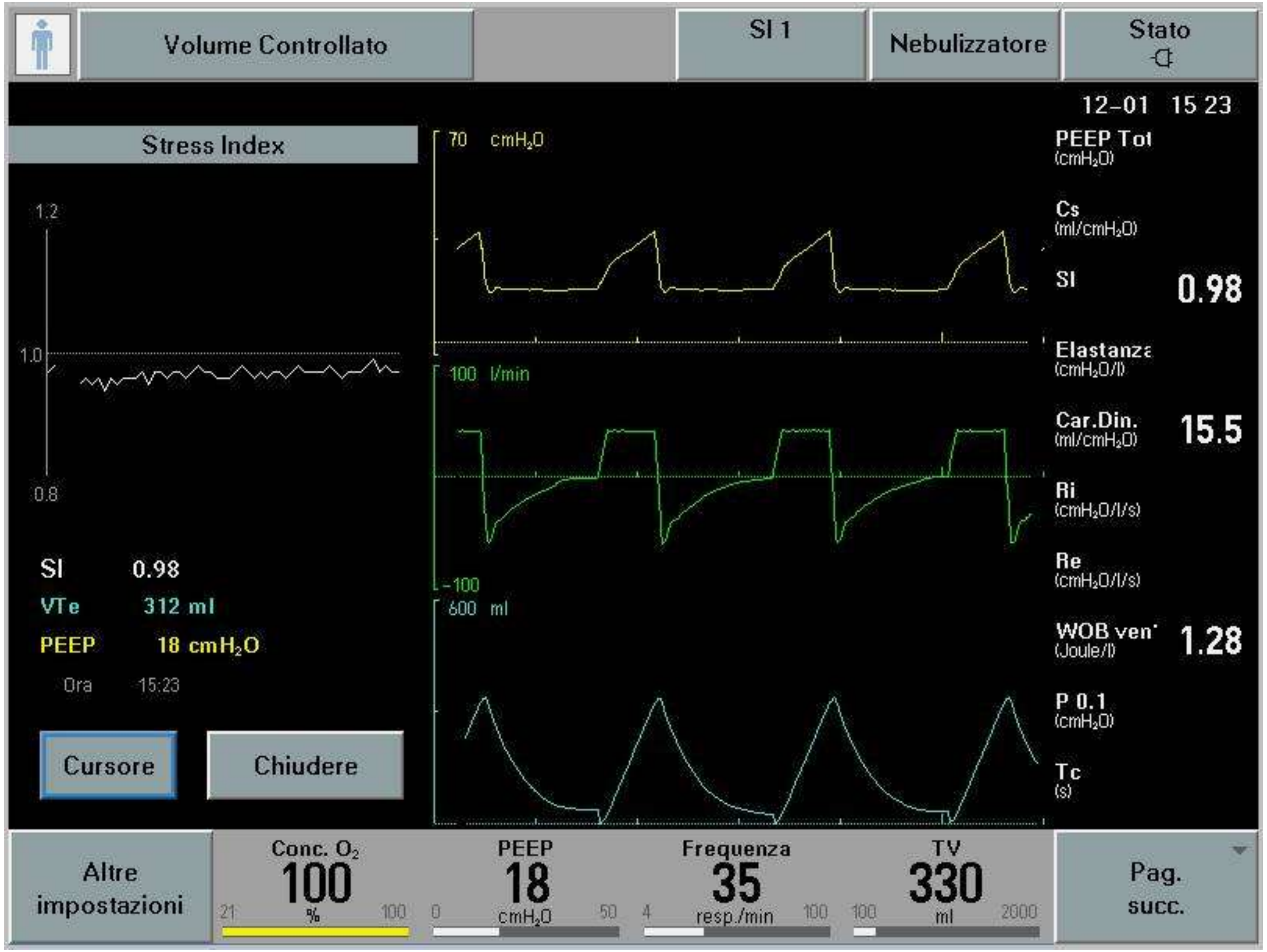
- At constant flow, the slope of the airway pressure-time curve is proportional to elastance (inversely proportional to resistance)
- In passively breathing patients and at constant flow – shape of the pressure time curve provide overview about compliance/recruitable/overdistension
- When rate of pressure increase with time is small indicating a recruitable lung (Curve convex upwards)
- When rate of pressure change is higher indicating overdistention

Stress index Pressure time waveform



Stress index – Pressure time waveform

- The stress index is a dimensionless coefficient, can quantitatively describe the shape of the pressure time curve
- Paw = k × tb
- Paw is the airway pressure, t is the time, k is a constant of proportionality (to make time equal pressure), and b is a parameter that describes the degree of concavity of the pressure-time curve
- >1 overdistension <1 recruitable lung
- It requires dedicated data acquisition instruments and analytic software (ie separate module)
- Servo-i, Maquet, Solna, Sweden has a pre-installed software module



Volume Controllato
SI 1
Nebulizzatore
Stato
12-01 15 23
Stress Index
1.2
1.0
0.8
SI 0.98
VTe 312 ml
PEEP 18 cmH2O
Ora 15:23
Cursore
Chiudere
70 cmH2O
100 l/min
-100
600 ml
PEEP Tot (cmH2O)
Cs (ml/cmH2O)
SI 0.98
Elastanza (cmH2O/l)
Car.Din. (ml/cmH2O) 15.5
Ri (cmH2O/l/s)
Re (cmH2O/l/s)
WOB ven' (Joule/l) 1.28
P 0.1 (cmH2O)
Tc (s)
Altre impostazioni
Conc. O2 100 % 21 100
PEEP 18 cmH2O 0 50
Frequenza 35 resp./min 4 100
TV 330 ml 100 2000
Pag. succ.

Stress index can be accurately determined by visual inspection

- 36 subjects and collected 220 SI assessments by visual inspection and software calculated values
- Agreement between visual SI classification by the first and the second observer and the reference standard substantial (weighted kappa {95% CI} being 0.86 {0.80 – 0.92} and 0.88 {0.82– 0.94})
- Inter-observer reliability was high (weighted kappa {95% CI} 0.96 {0.92– 0.99})
- Accuracy (95% CI) for visual SI classification was 93% (88 –96%)

Mie Sun et al Respiratory Care June 2018, respcare.06151

Stress index can be accurately determined by visual inspection

RESPIRATORY CARE Paper in Press. Published on June 26, 2018 as DOI: 10.4187/respcare.06151

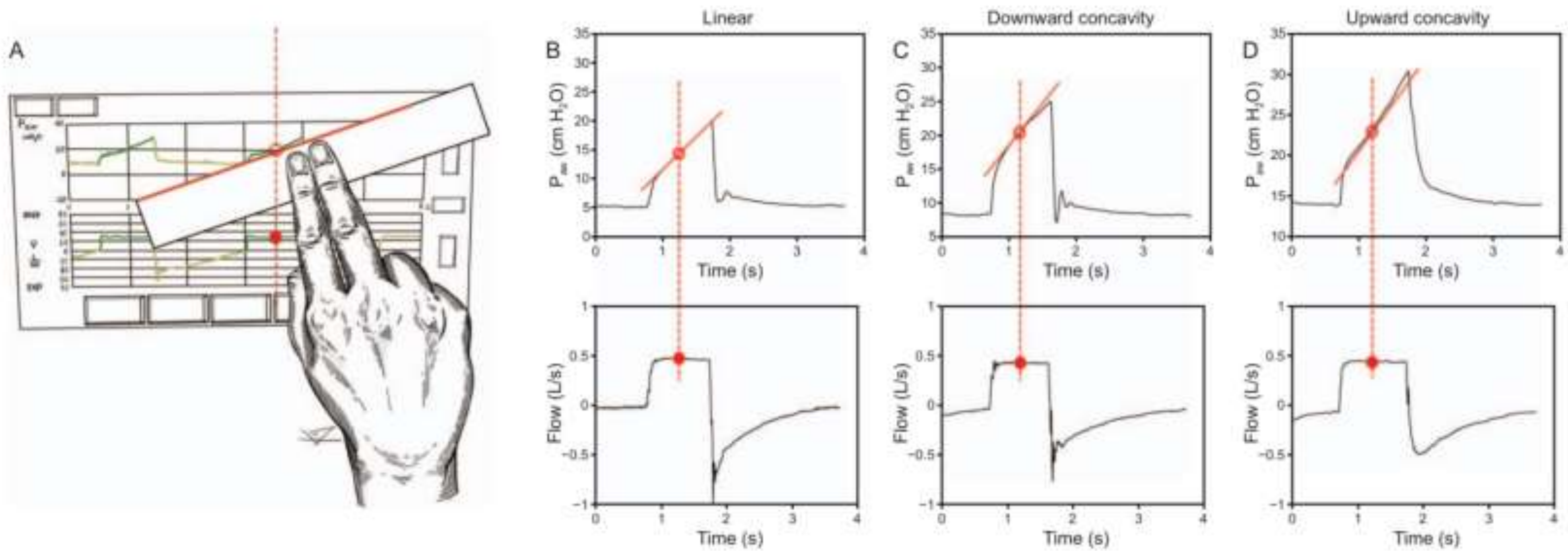


Fig. 1. Schematic of the method for visually inspecting the airway pressure-time (P_{aw}-t) waveform and stress index (SI) classification. First, the mid-point on the constant inspiratory flow (red dot) is identified; second, the corresponding point (red dashed line and red circle) on the P_{aw}-t waveform is confirmed; third, a ruler is put on the ventilator screen to mark the tangent line (red solid line) passing through the middle point (A). The relationship of this tangent line and the P_{aw}-t waveform is visually inspected and classified into 3 categories. The P_{aw}-t waveform almost coincident with the tangent line is judged as a linear shape (B), indicating an SI value between 0.9 and 1.1. The off-line software measured SI to be 0.98 in this case. When the 2 sides of the P_{aw}-time waveform both deviate downward from the tangent line, this is categorized as a downward concavity (C), indicating an SI < 0.9. The off-line software measured SI to be 0.80 in this case. When the 2 sides of the P_{aw}-time waveform both deviate upward from the tangent line, this is categorized as an upward concavity (D), indicating an SI > 1.1. The off-line software measured SI to be 1.20 in this case.

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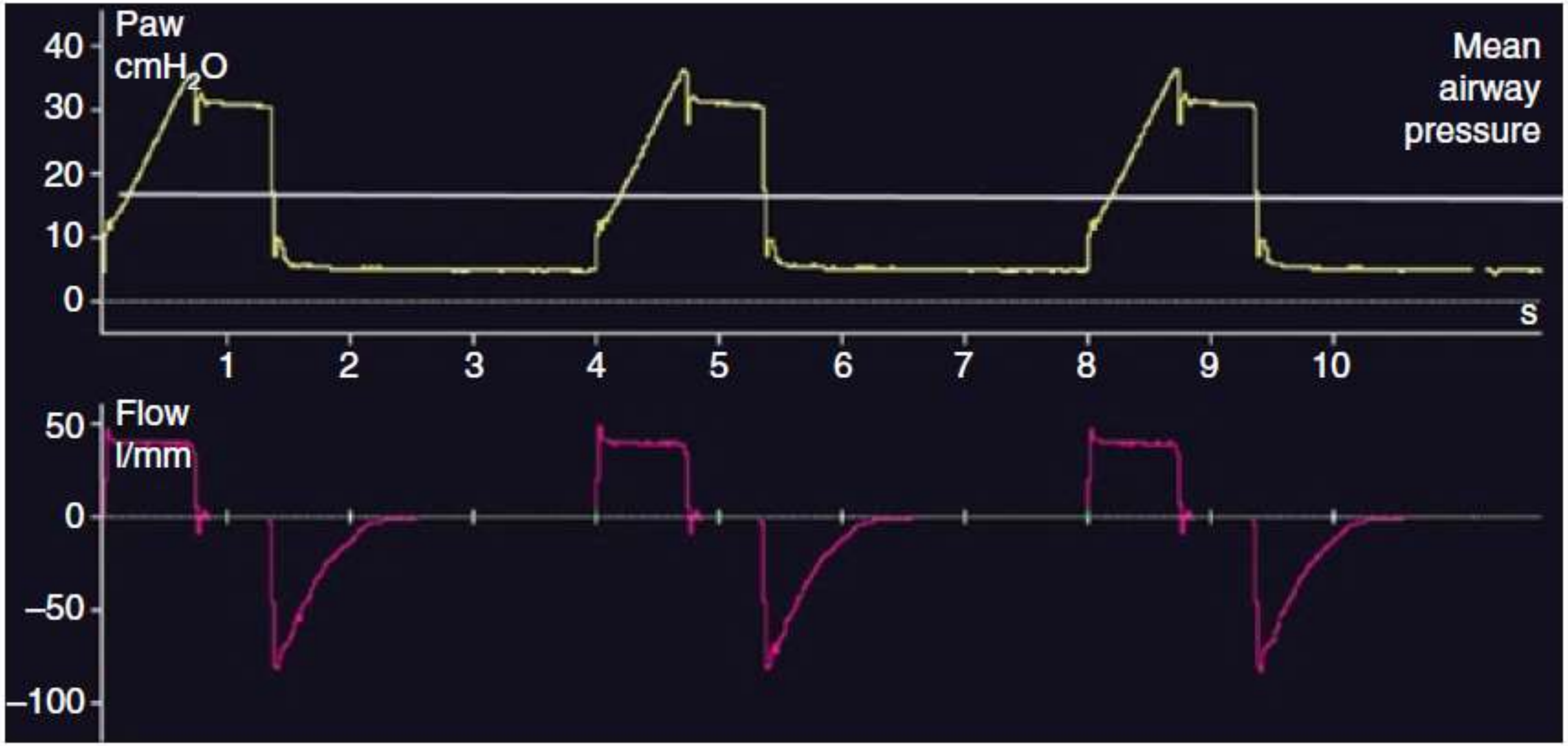
Mean airway pressure

- Average pressure over a ventilatory cycle (one inspiration and one expiration)
- Area below the pressure-time curve divided by the ventilatory period (inspiratory time plus expiratory time)
- Numerically, calculated as the average of many pressure samples taken over the ventilatory period
- PaO2 is proportional to mean airway pressure
- Cardiac output may be inversely proportional
- Increase airway pressure or increases the I:E ratio (increasing inspiratory time or decreasing expiratory time) increases mean airway pressure

Mean airway pressure



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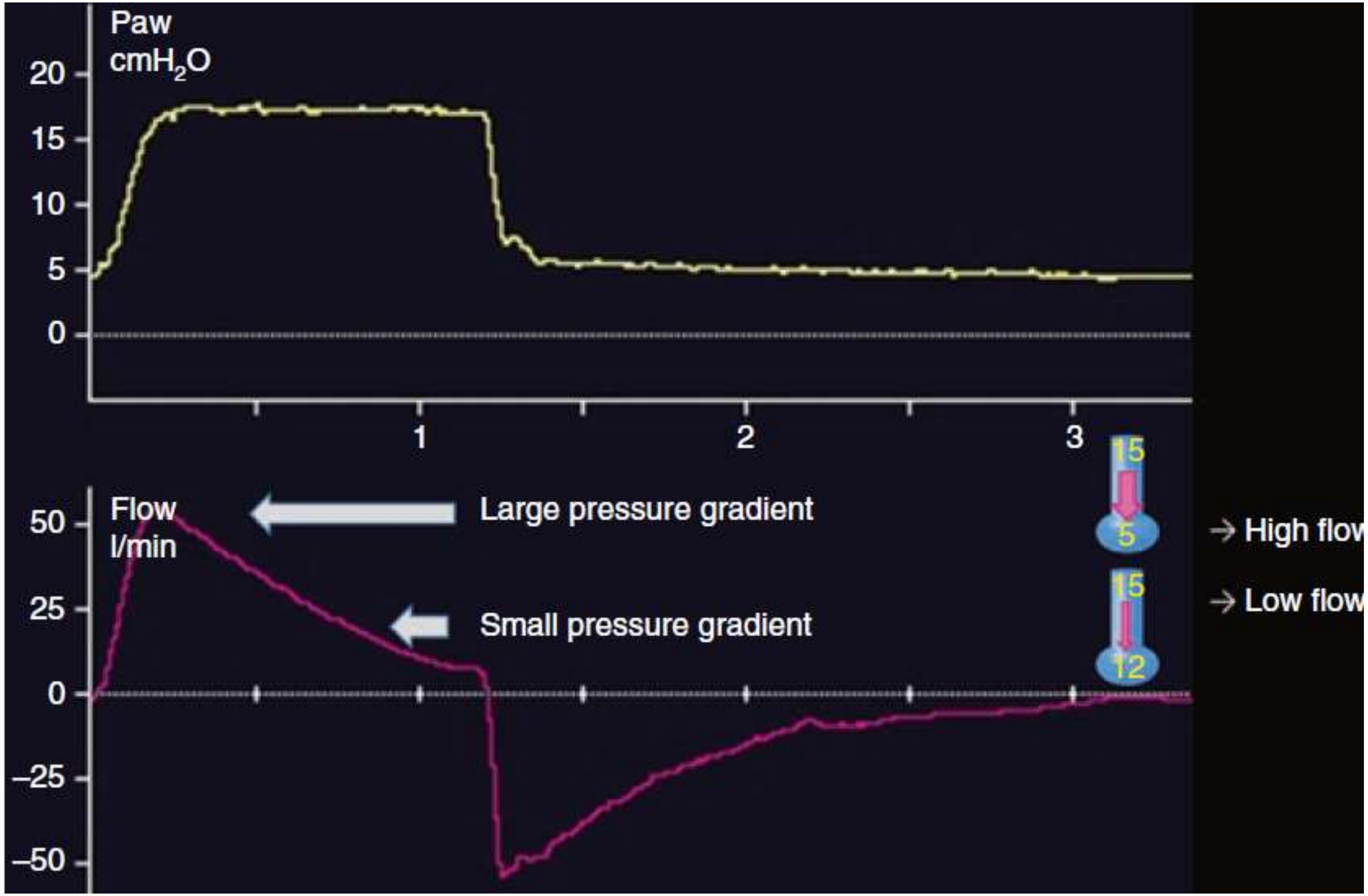
Waveforms observed in pressure A/C

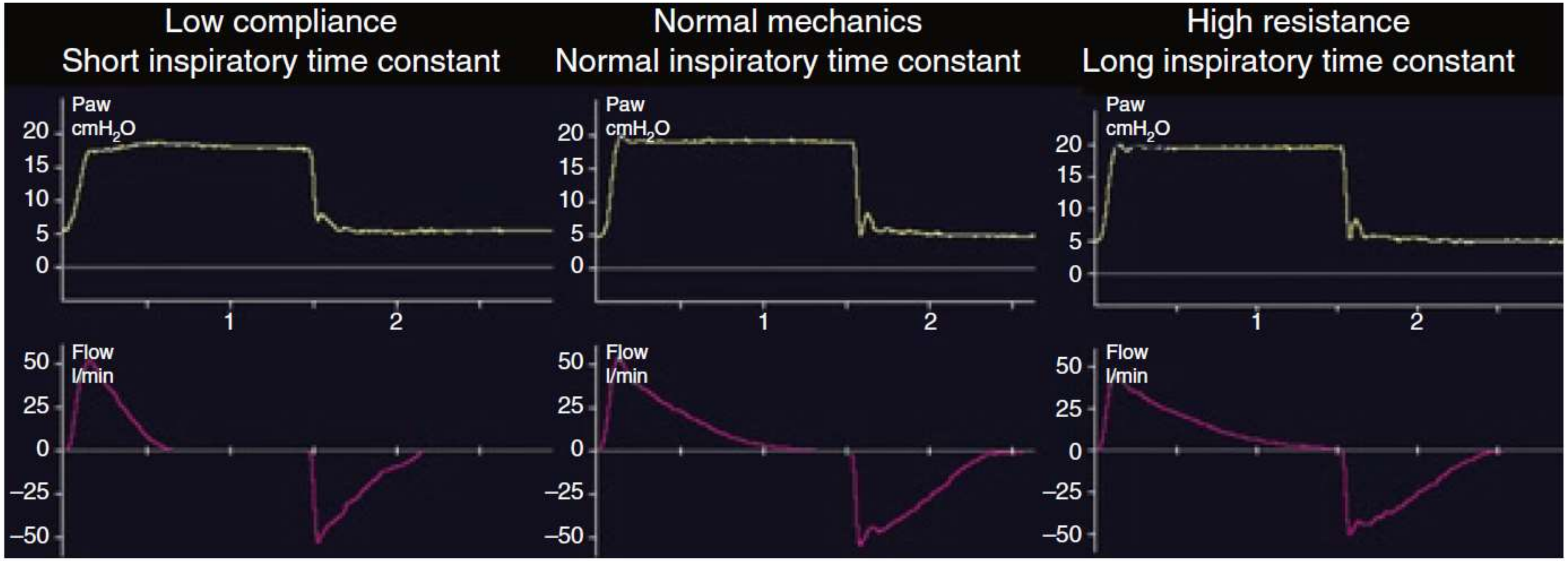
- Pressure time wave form - preset
  - Time/flow/pressure triggered
  - Pressure targeted
  - Time cycled
- Volume time wave form
  - Volume delivered depends on compliance, resistance and insp muscle usage
- Flow curve
  - Decelerating pattern
  - Rapid increase in flow initially followed by an exponential drop
  - Insp flow generated by the pressure gradient between the proximal airway and the alveoli

Waveform observed in pressure A/C



Shape of the flow curve in pressure A/C

- Variation with varied respiratory system mechanics



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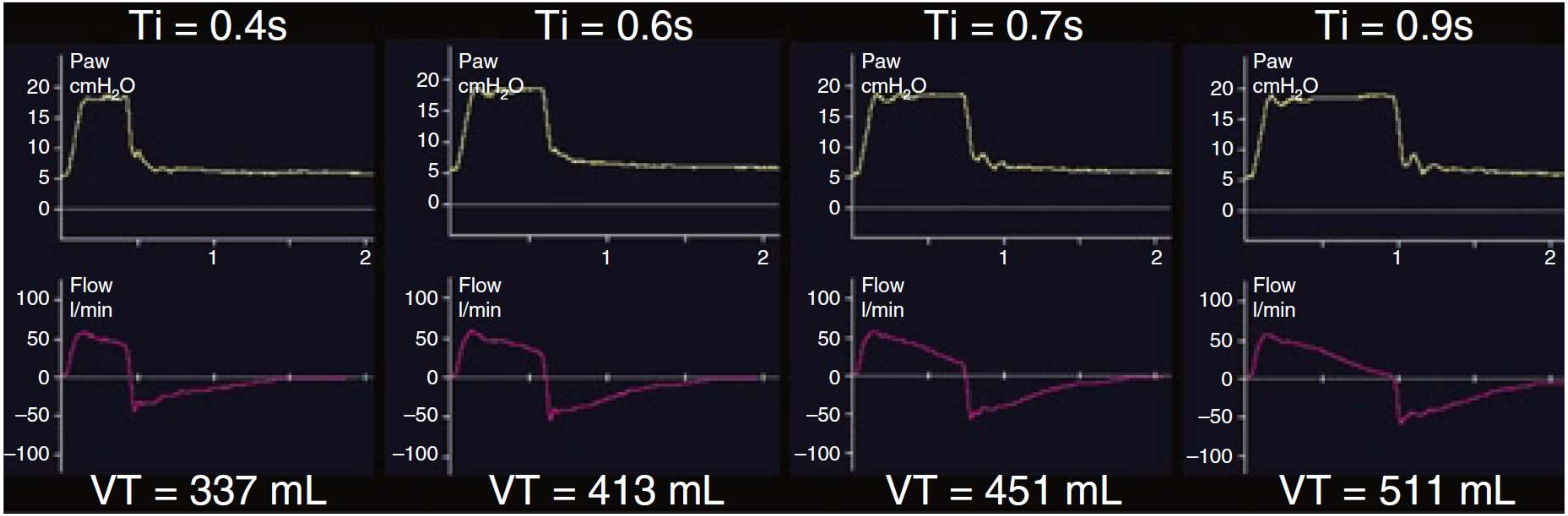
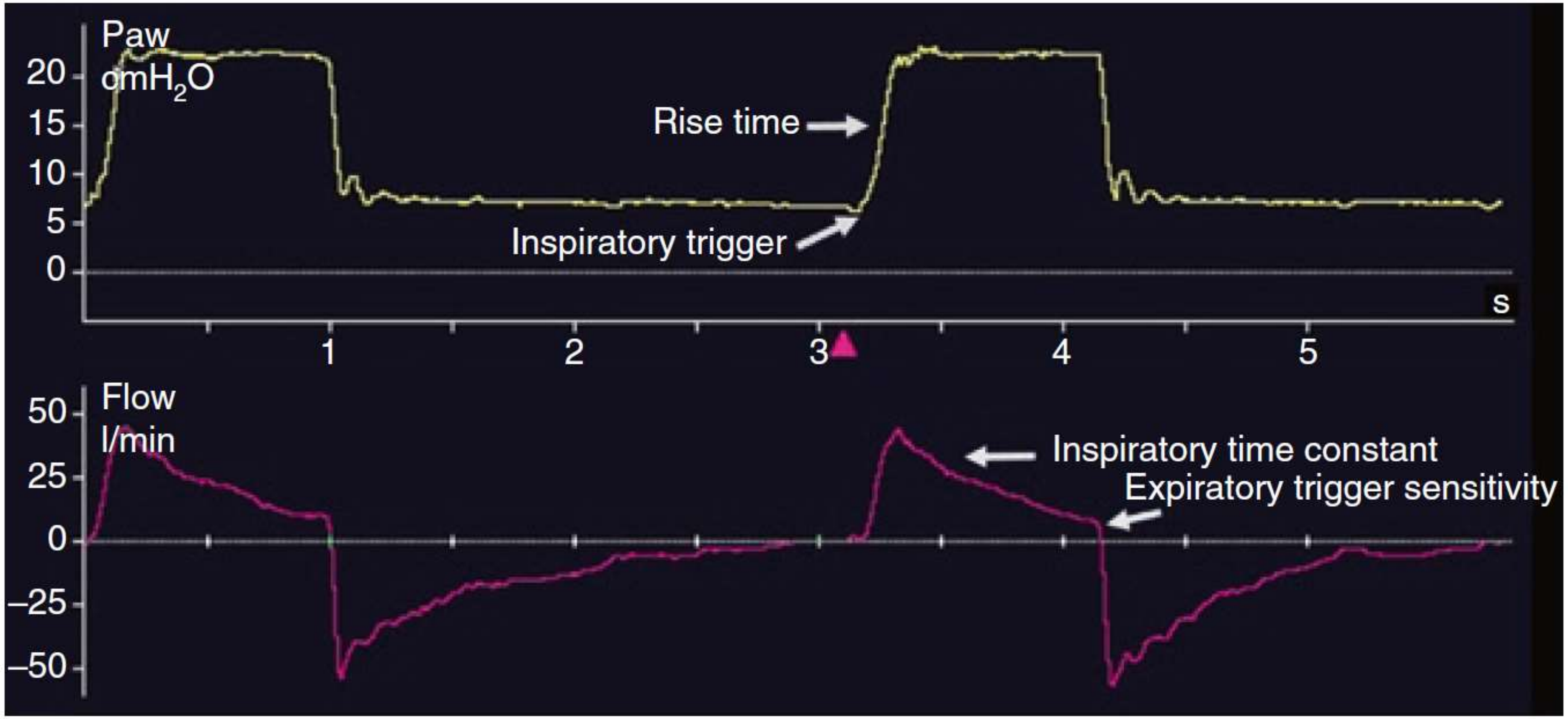
Shape of flow curve in pressure A/C

- Variation with inspiratory time



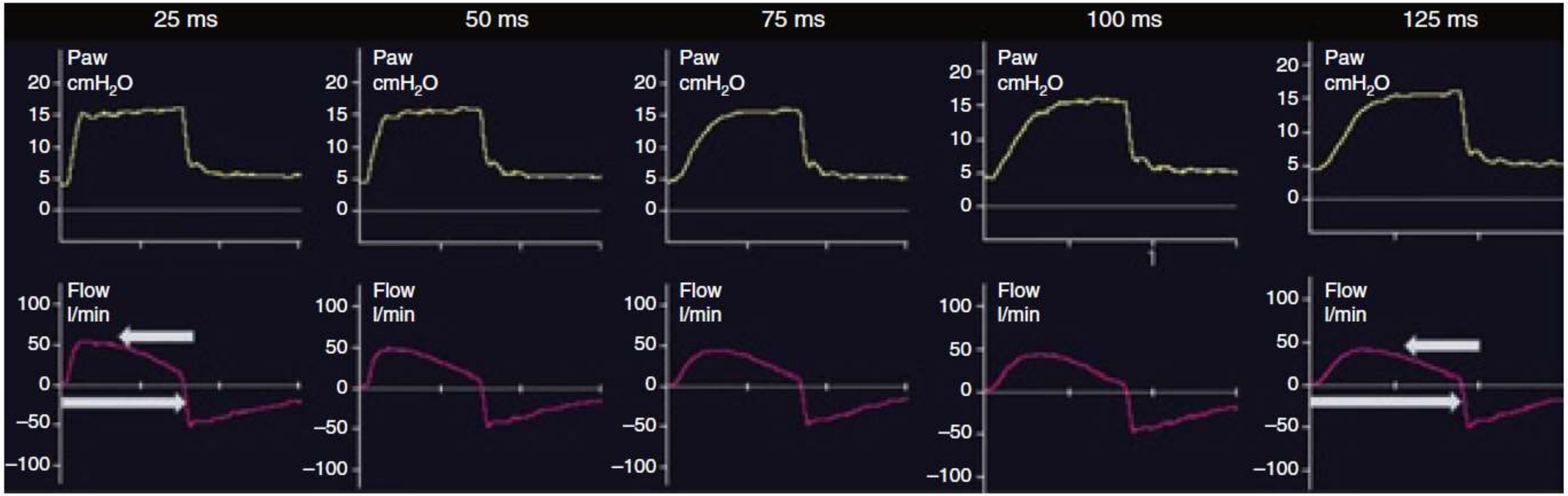
Waveforms observed in pressure support

- Flo
- Pre
- Flo nt
  (co



Waveforms observed in pressure support

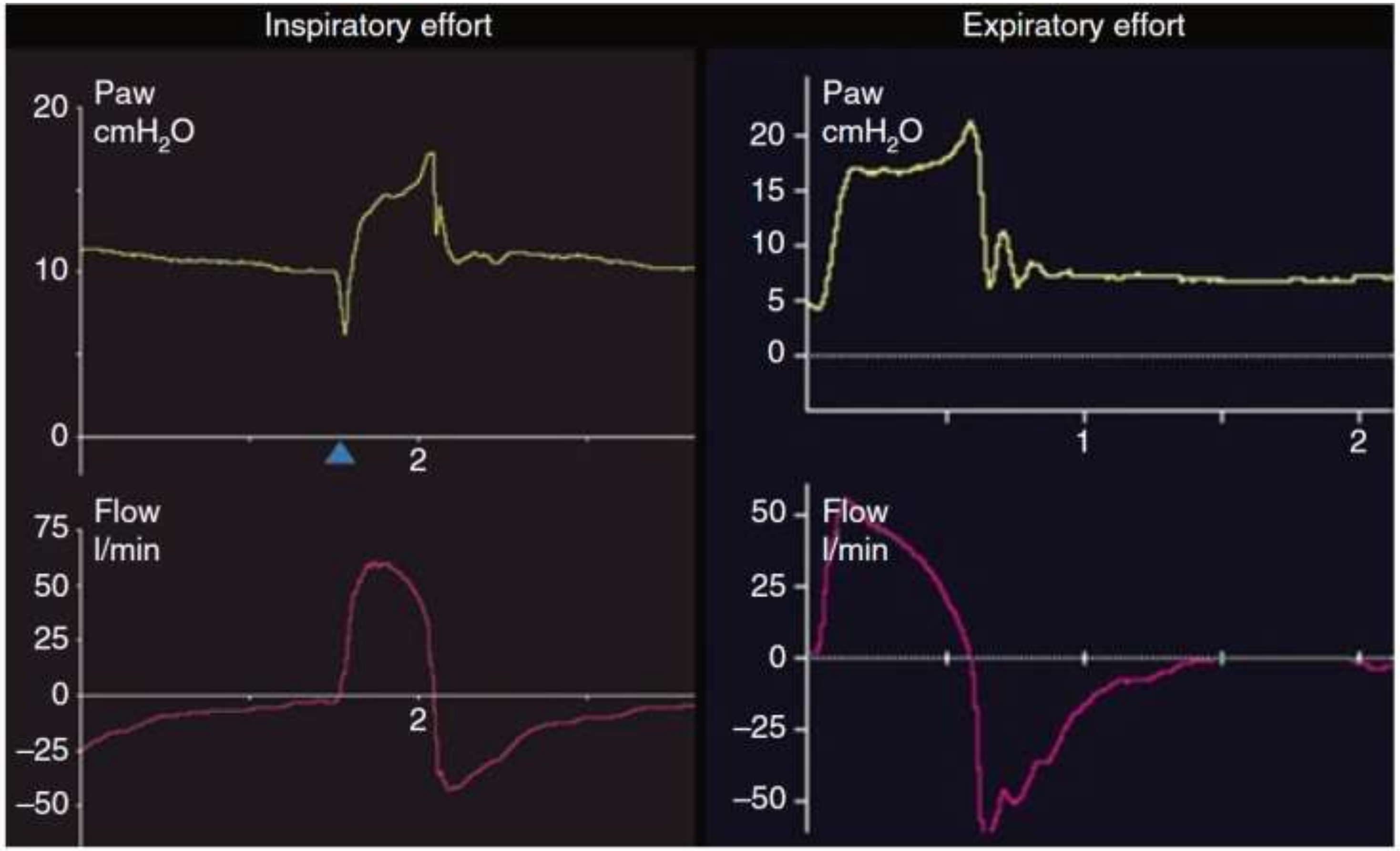
- Pressure rise time
  - Pressure rise time is the time to increase pressure from PEEP to set pressure



Waveforms observed in pressure support

- Shape of inspiratory flow
- Deviation of inspiratory flow from the exponential declining pattern indicates a respiratory muscle effort (inspiratory or expiratory)
- Rounded or constant inspiratory flow - a significant inspiratory effort during insufflation indicates insufficient pressure support
- Change in slope of inspiratory flow toward the baseline suggests expiratory muscle contraction during insufflation - caused by excessive pressure support or prolonged mechanical insufflation (delayed cycling)

Waveforms observed in pressure support



- Decrease Inspiratory Pressure support
- Increase Expiratory Trigger Sensitivity

Waveforms c … ıre support

- Ear

ond vertical line). The airway pressure tracing then drops transiently below the baseline end-expiratory pressure level because patient effort is still substantial after ventilator insufflation has ceased. The two cycles with this form of asynchrony are associated with increased effort (*dotted horizontal line*) and prolonged T_I. The duration of T_I on the second cycle (T_2) is longer than T_I on the first cycle (T_1) as reflected with the greater distance between the *arrowheads*. A large T_I favors this form of asynchrony.

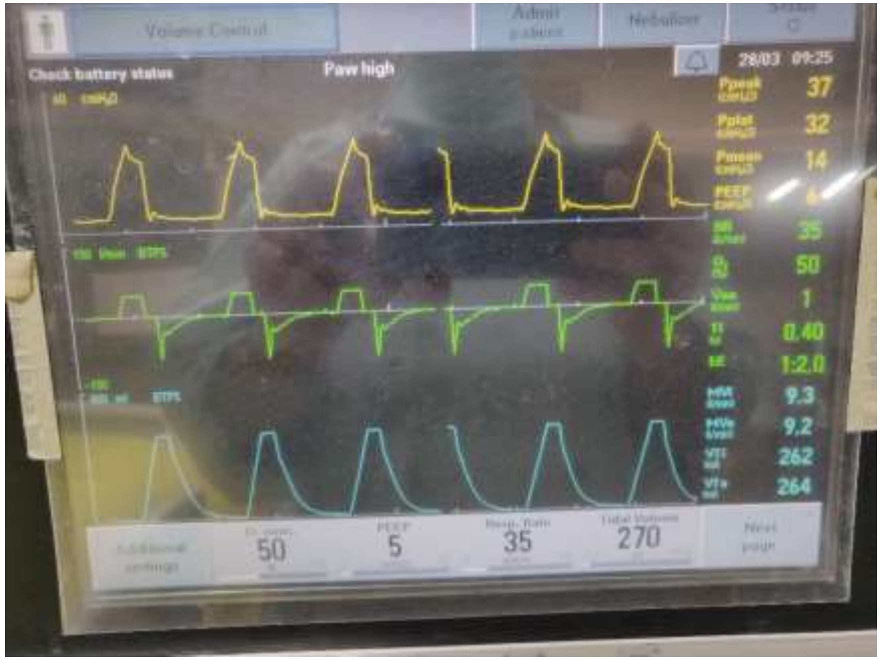
Early cycling

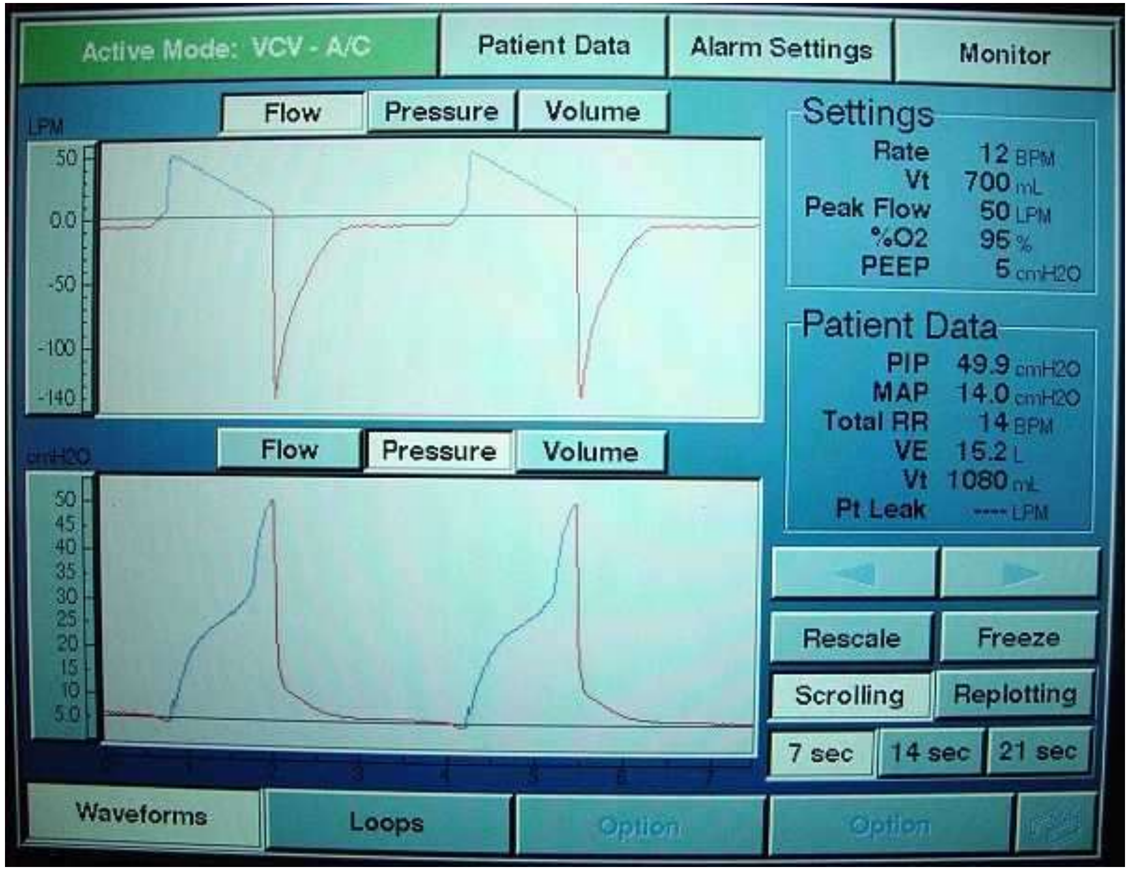
Common problems that can be diagnosed by analysis of scalars

- Abnormal lung mechanics
  - Auto PEEP
  - Overdistension
- Asynchrony
  - Trigger
  - Cycle
  - Flow
- Circuit related
  - Leaks
  - Secretions

Overdistension

- Stress index upward concavity of the pressure time scalar
- Increased Ppeak and Pplat
- High peak expiratory flow





Auto PEEP

- Expiration is int … the next inspiration some un-expire …
- Exerts a pressu …
- As a result, the … iration is higher than zero (atmo …
- This incomplet … inflation, and the positive alveola … EEP

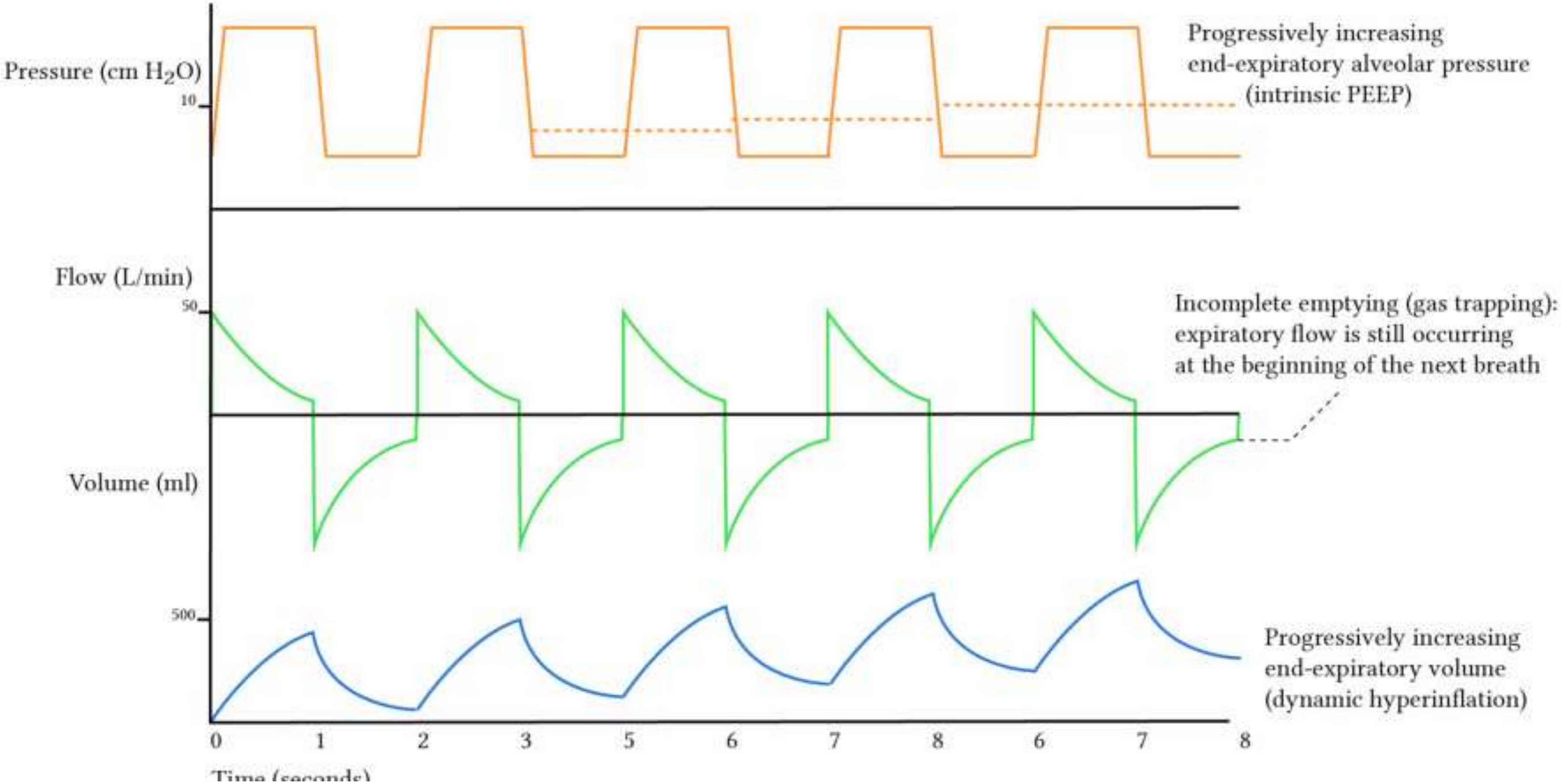
Physiologic mechanisms of auto-positive end-expiratory pressure

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

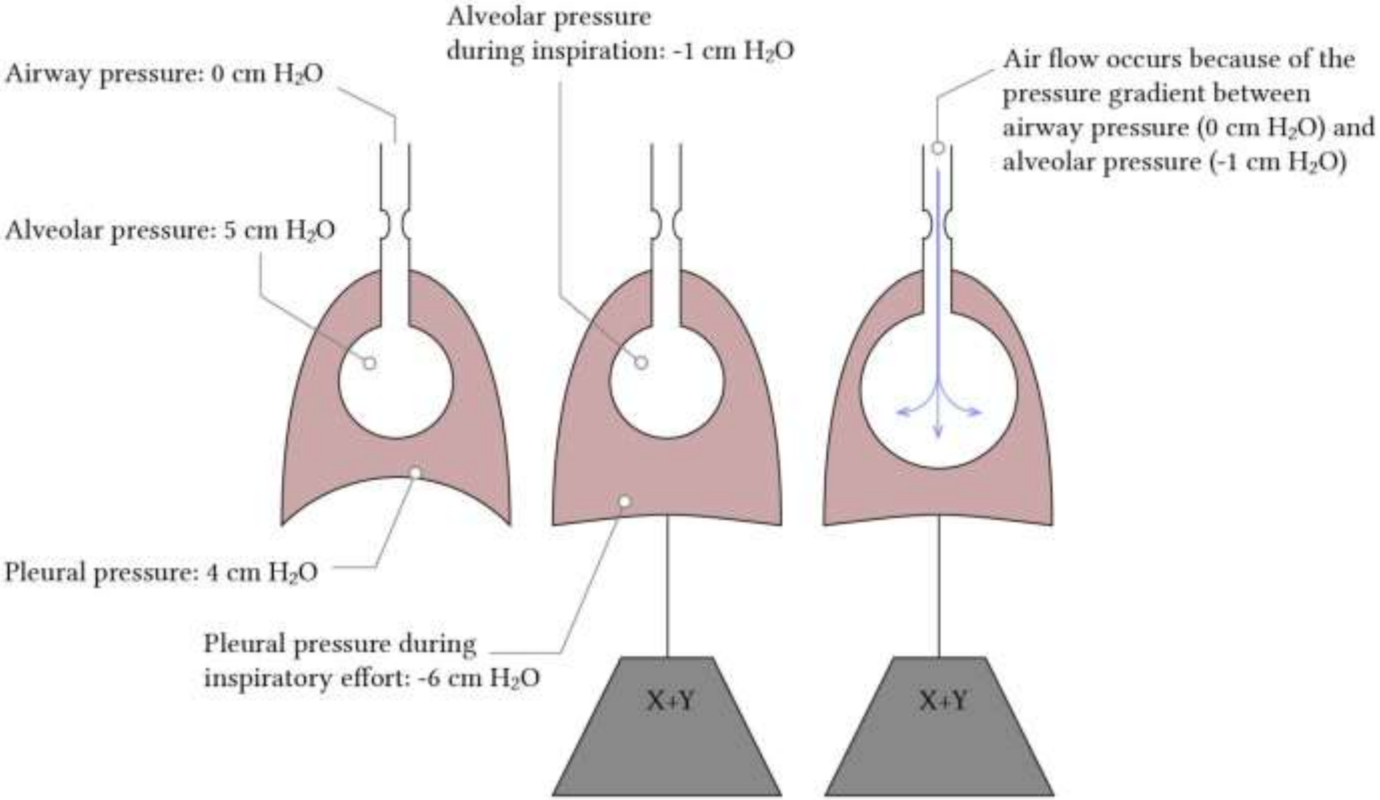
Auto PEEP



Pressure (cm H2O)
10
Progressively increasing
end-expiratory alveolar pressure
(intrinsic PEEP)
Flow (L/min)
50
Incomplete emptying (gas trapping):
expiratory flow is still occurring
at the beginning of the next breath
Volume (ml)
500
Progressively increasing
end-expiratory volume
(dynamic hyperinflation)
0
1
2
3
5
6
7
8
6
7
8

Auto PEEP

airway obstruction and intrinsic PEEP.



X = normal amount of inspiratory effort

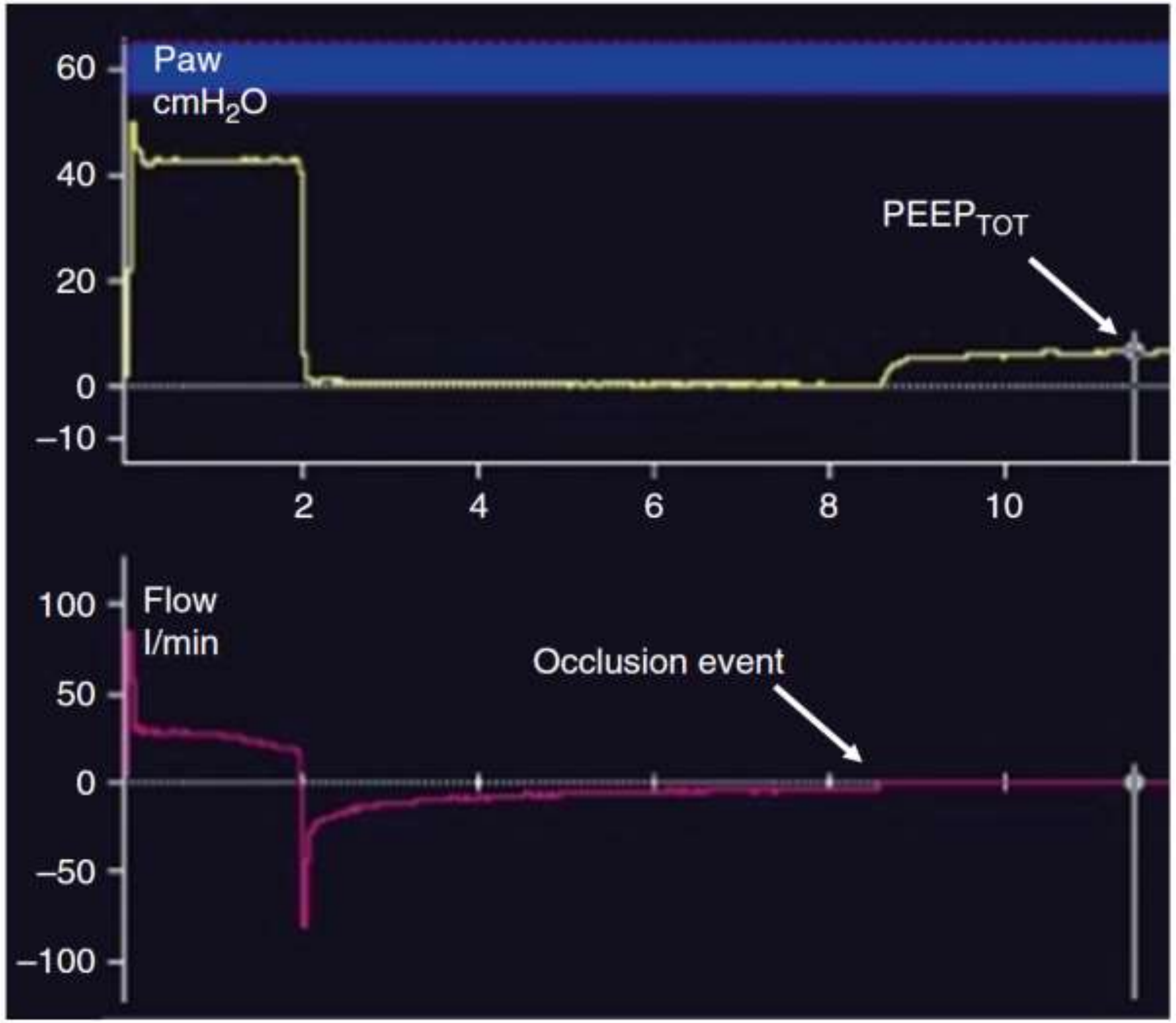
Auto PEEP consequences

- Ineffective triggers
- Increased WOB
- Hypoxia
- Barotrauma
- Hemodynamic instability

Auto PEEP detection

- End-expiratory occlusion is used to measure auto PEEP
- Pressure in the lungs equilibrates with the pressure ventilator circuit
- Pressure measured at the proximal airways is equal to the end-expiratory alveolar pressure
- Auto PEEP is the difference between total PEEP and set PEEP

Auto PEEP detection



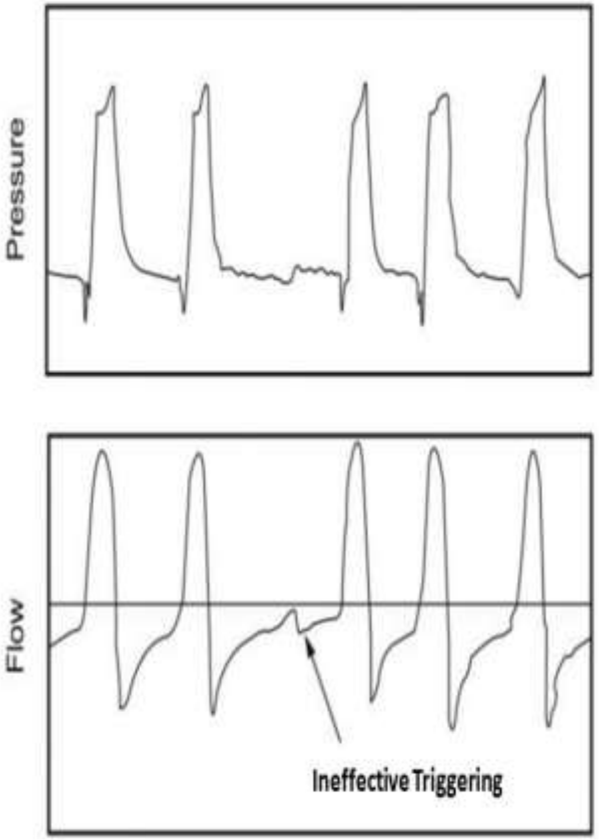
Overcoming Auto PEEP

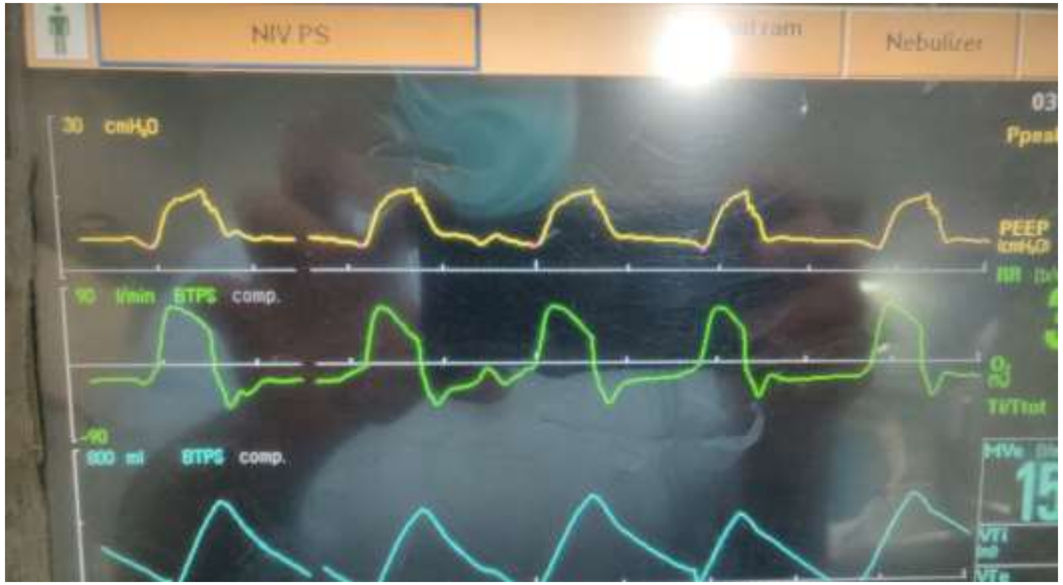
- Decrease
  - Insp time
  - RR
  - Vt
  - Resp demand – pain fever anxiety
- Bronchodilator use
- External PEEP

Ineffective trigger

- Respiratory muscular effort which is insufficient to initiate mechanical breath
- Manifests as a decrease in airway pressure associated with a simultaneous increase in airflow
- Ventilator factors– effort not able to meet the set trigger, large pressure drops across smaller tubes
- Patient related- Auto PEEP, resp muscle weakness and decreased drive

Ineffective trigger





Auto trigger

- Assisted breaths delivered which were not patient triggered
- Cause
  - Fluid in circuit, leak, cardiac oscillations, low trigger threshhold

Double trigger

- Patients inspiration continues after the ventilator inspiration and triggers another breath immediately after the inspiration
  - High ventilatory demand of the patient (ARDS)
  - Inappropriate settings (Low tidal volume, short inspiratory time, high ETS)

Double trigger

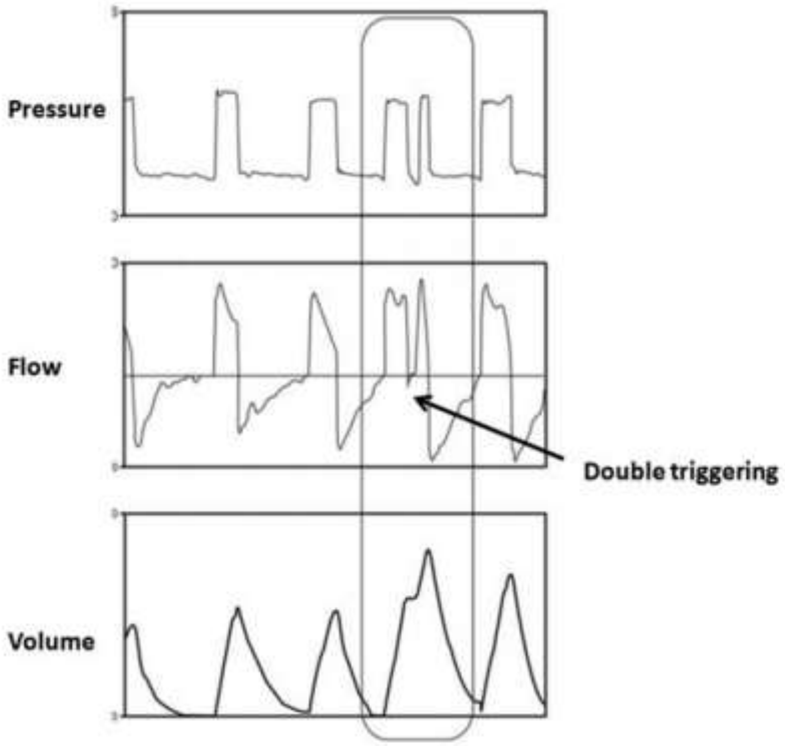


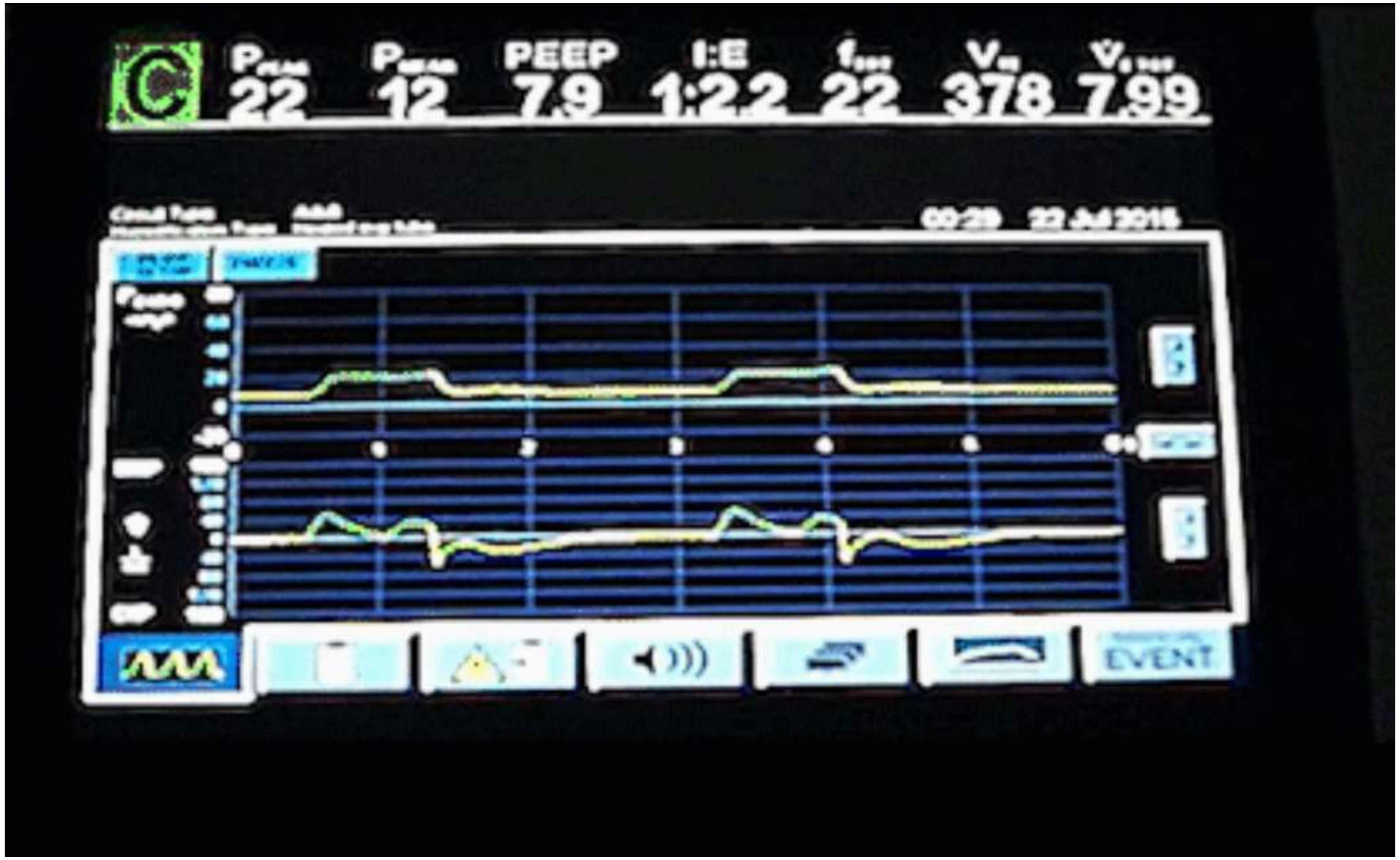
Fig. 27. An example of double triggering in pressure support ventilation. Patient demand continues beyond the set inspiratory time, resulting in triggering of a second mandatory breath during the same patient effort.

Reverse triggering

- Unique type asynchrony in which diaphragmatic muscle contractions triggered by ventilator insufflations constitute a form of patient-ventilator interaction referred to as “entrainment”
- In heavily sedated patients it is suggested that patients had entrainment of neural breaths within mandatory breaths.
- This entrainment occurred at a ratio of 1:1 up to 1:3. They occur at the transition from the ventilator inspiration to expiration.
- Breath stacking , overdistention and VIDD

Mechanical ventilation-induced reverse-triggered breaths: a frequently unrecognized form of neuromechanical coupling. Chest. 2013 Apr; 143(4):927-38

Reverse triggering



Reverse triggering

Flow asynchrony

- Causes :
  - High ventilatory demand (ALI/ARDS)
  - Low ventilatory settings (flow rate, Vt, Pramp)
- Treat:
  - Treat reversible causes (fever, acidosis)
  - Increase the Vt
  - Increase the flow rate (directly, or by decreasing inspiratory time, increasing pause)
  - Change to pressure control mode with variable flow

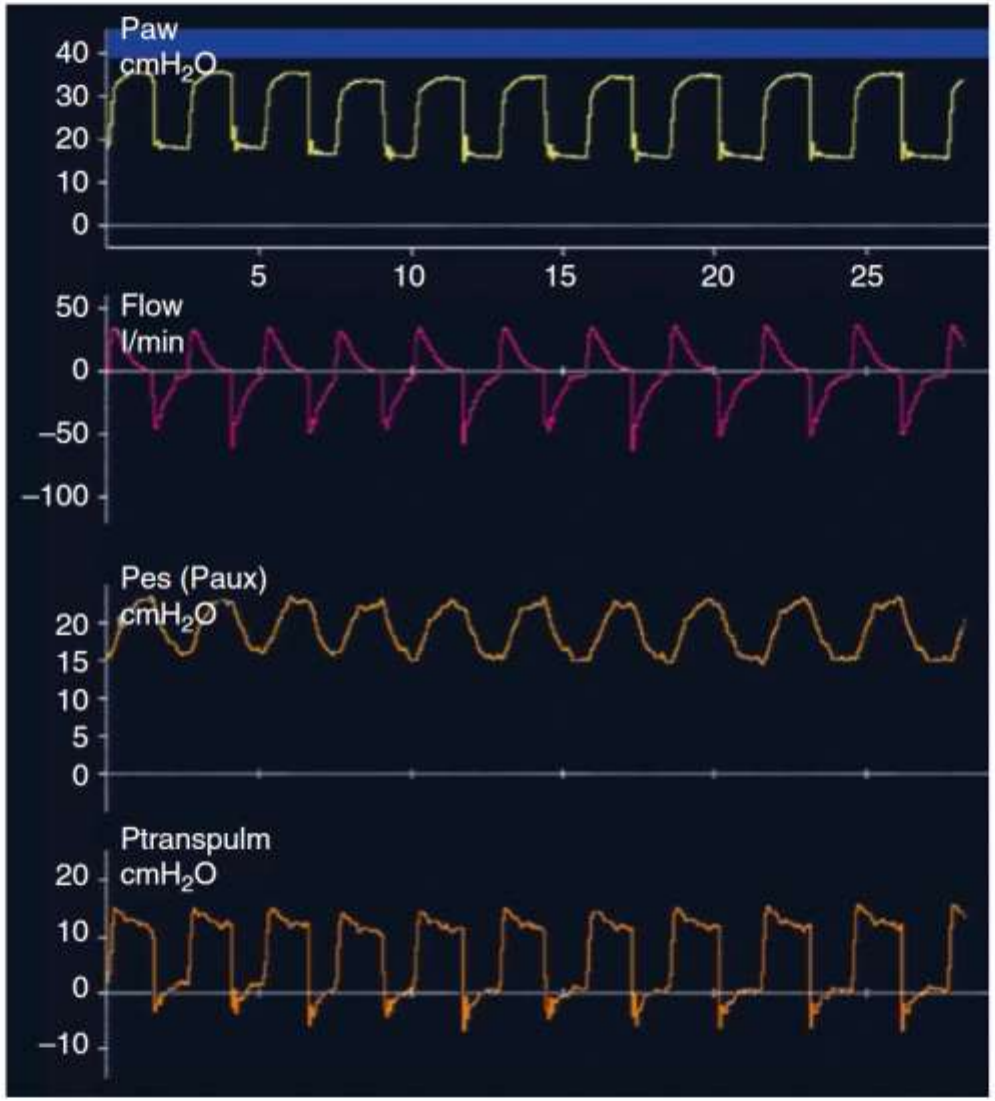
Flow asynchrony

Patient with ARDS weaning

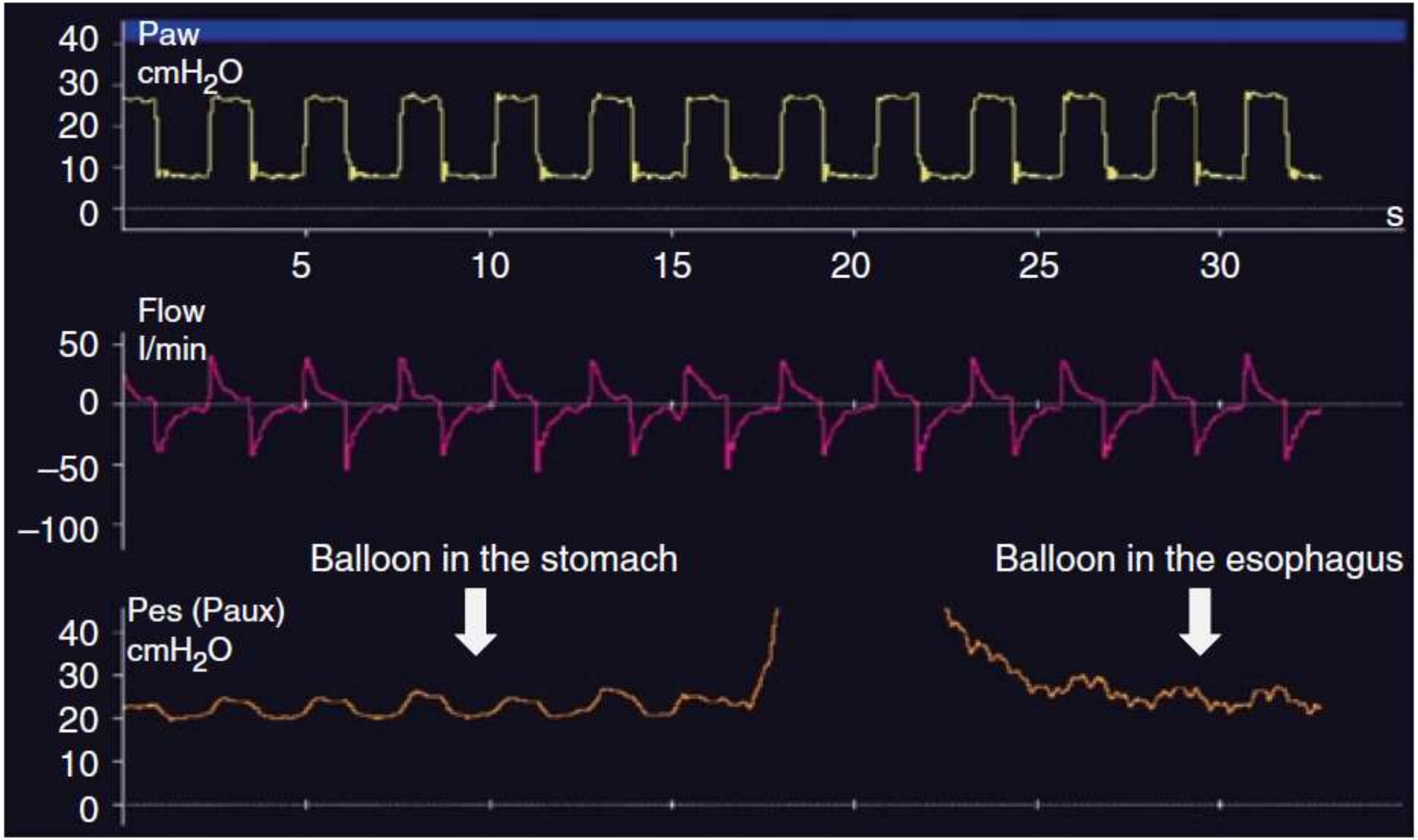
Esophageal pressure curve

- Esophageal pressure is measured by a catheter with a balloon that is placed at the lower end of the esophagus
- Estimate the pleural pressure
- Passive patient esophageal pressure increases with each mechanical insufflation
- Spontaneously breathing patients esophageal pressure becomes negative during insufflation
- Positioning is key

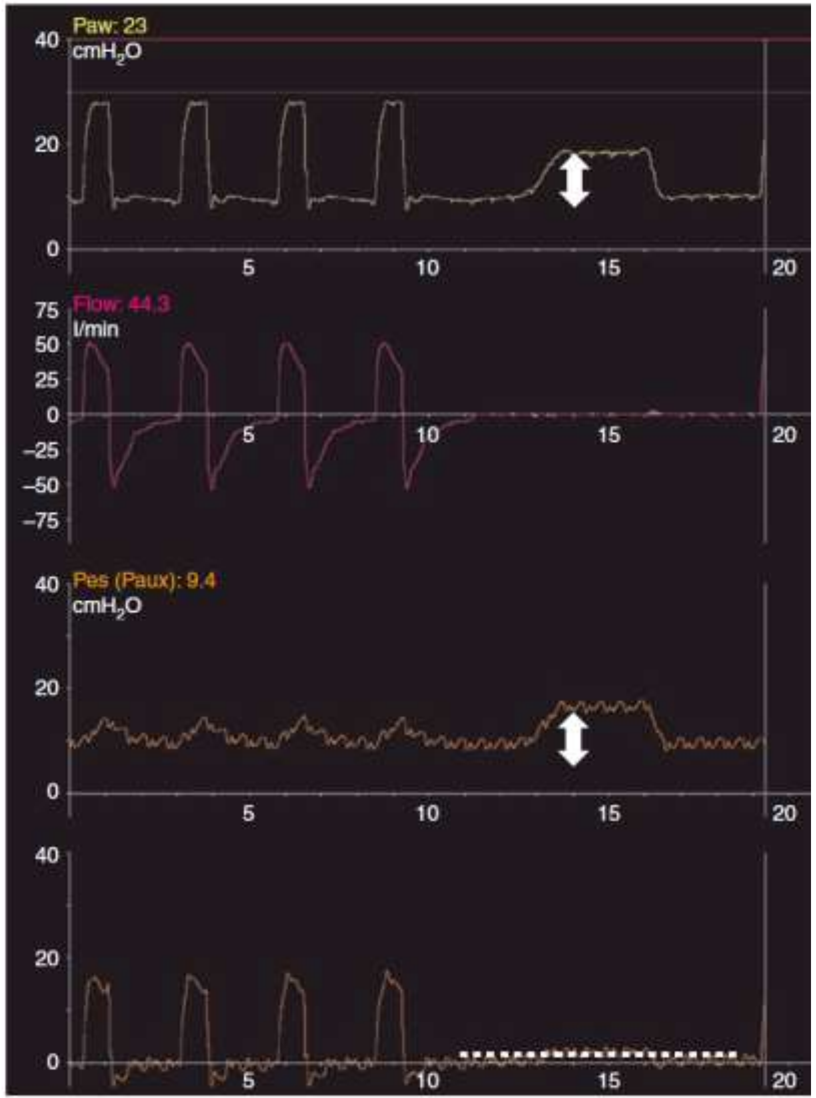
Esophageal pressure curve



Positioning esophageal balloon



Positioning esophageal balloon



Esophageal waveform in passive patient

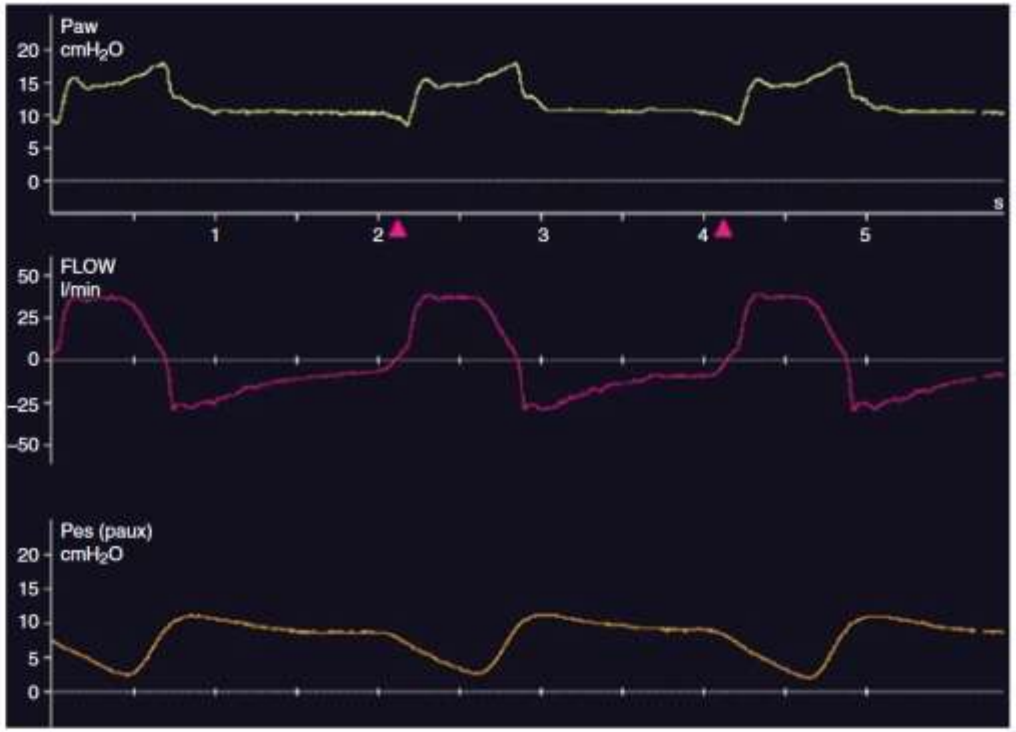
High Pes and Ptp

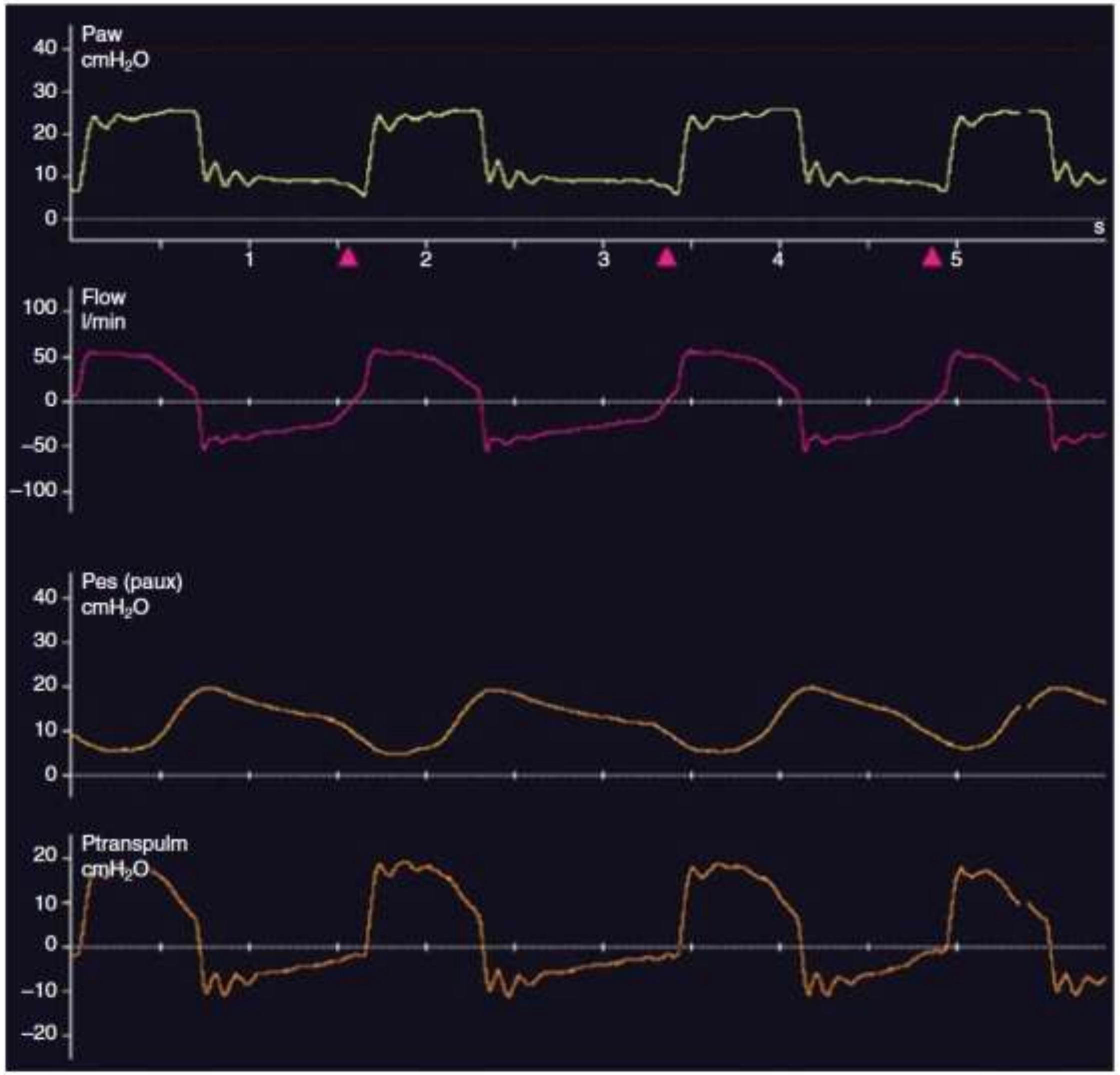
Ideal Ptp


MAIN
VOLUME A/C
CIRCUIT DISCONNECT
38
Ppeak
11.3
Total Ve
4
Ptp PEEP
18
Ptp Plat
32
Rate
Flow (L/min)
Vt (mL)
35
0.35
55
0.00
10
2.0
60
12.3
1:2.4

Esophageal waveform in spontaneously breathing individuals

- Starts decreasing at the onset of the patient's inspiratory effort and drops to a minimum pressure at the end of the inspiratory effort





Paw
cmH2O
40
30
20
10
0
s
1
2
3
4
5
Flow
l/min
100
50
0
−50
−100
Pes (paux)
cmH2O
40
30
20
10
0
Ptranspulm
cmH2O
20
10
0
−10
−20

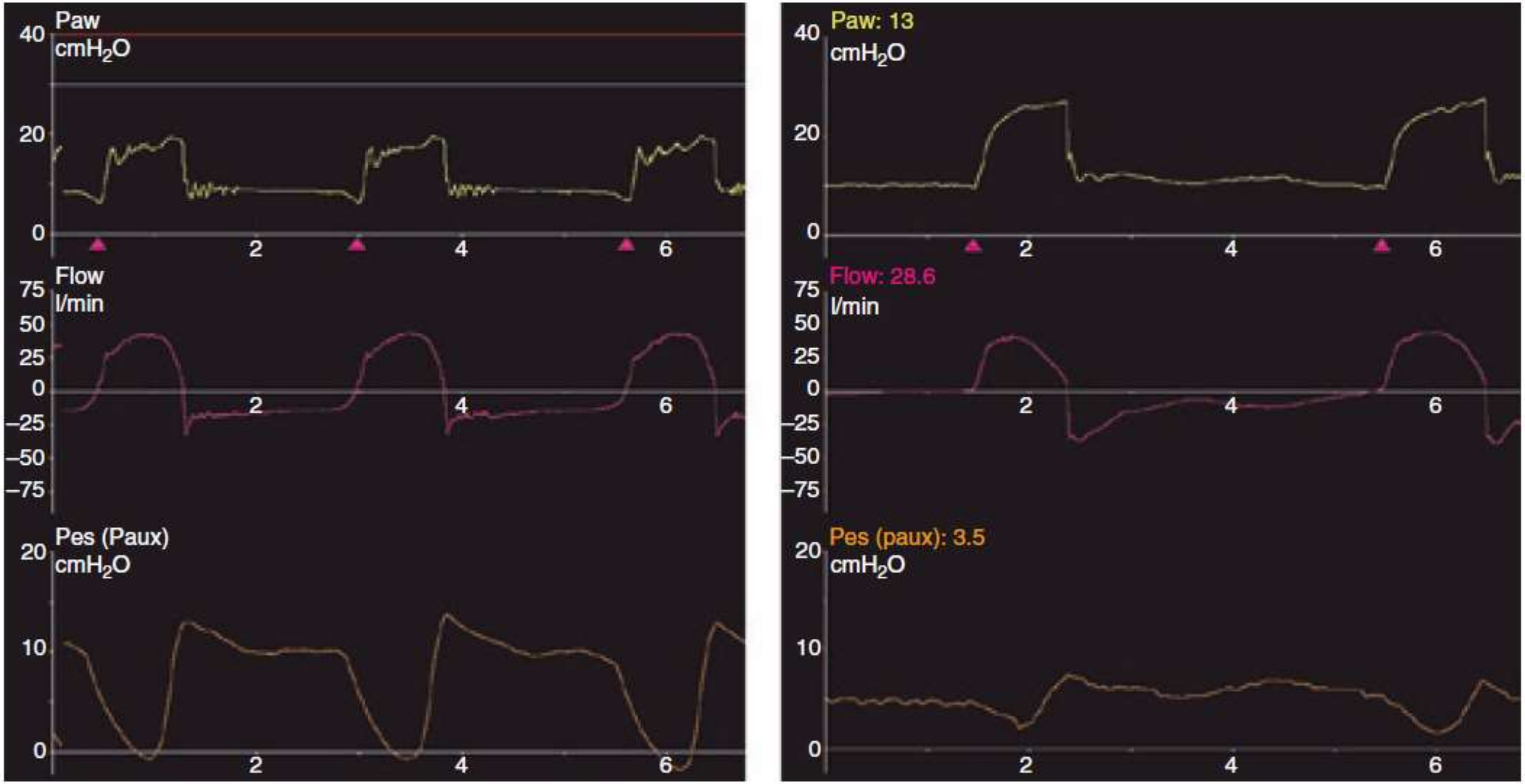
Esophageal and transpulmonary pressure waaveforms spontaneous breathing

Clinical application

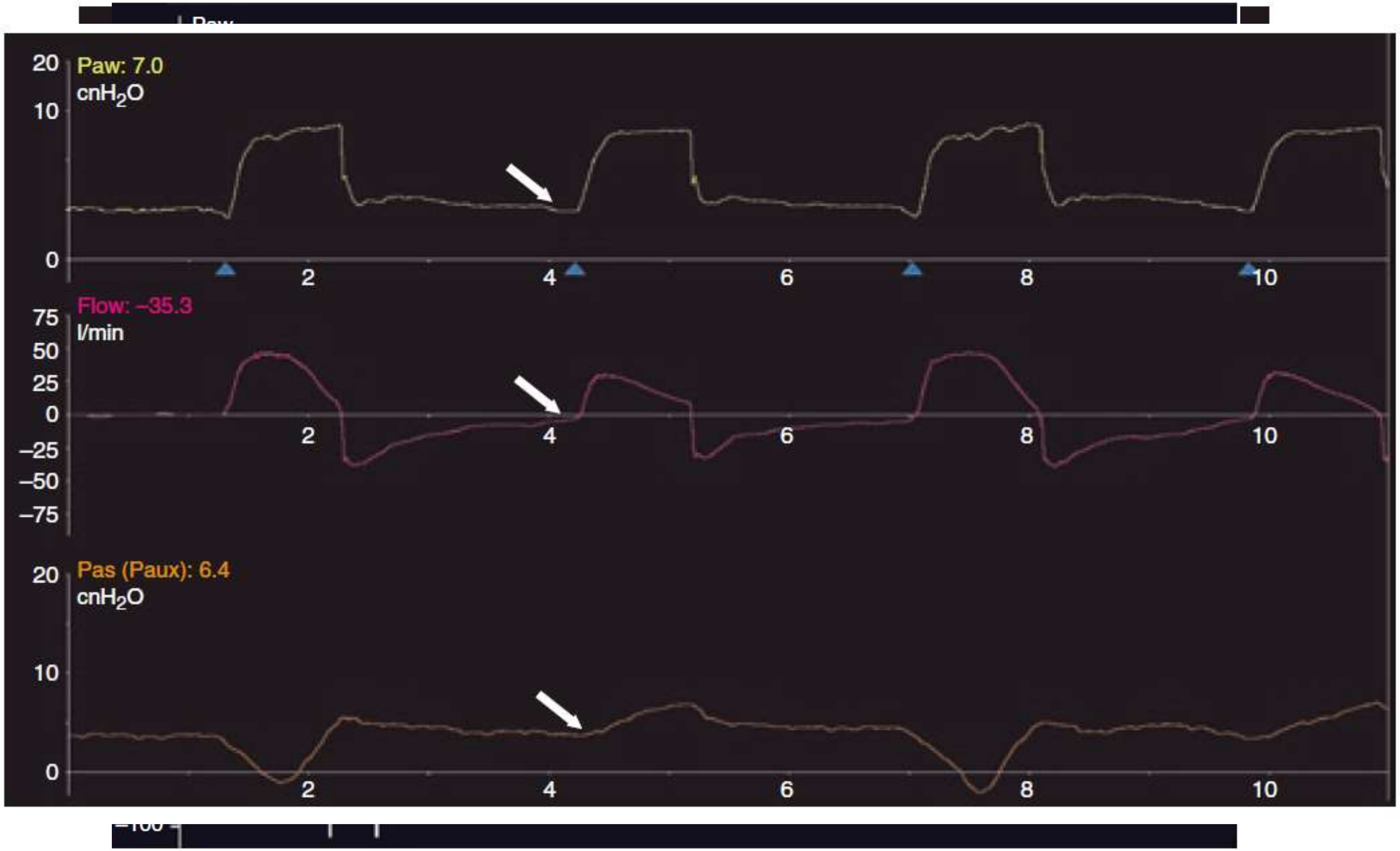
- Measuring transpulmonary pressure at end inspiration and expiration
- Open lung strategy in ARDS ventilation and prevention of lung injury
- End inspiratory transpulmonary pressure ≤ 25 (≤ 20 cm)
- End expiratory transpulmonary pressure 0-5 cm
- Spontaneously breathing
    - Inspiratory effort
    - AutoPEEP
    - Asynchrony assessment

Strong inspiratory effort

Weak inspiratory effort



Asynchrony



Paw: 7.0
cnH2O
20
10
0
2
4
6
8
10
Flow: −35.3
l/min
75
50
25
0
−25
−50
−75
Pas (Paux): 6.4
cnH2O

PEEPi

The most accurate method to quantify PEEPi is to measure the drop in esophageal pressure at end expiration at the point of the contraction of the inspiratory muscles until inspiratory flow starts

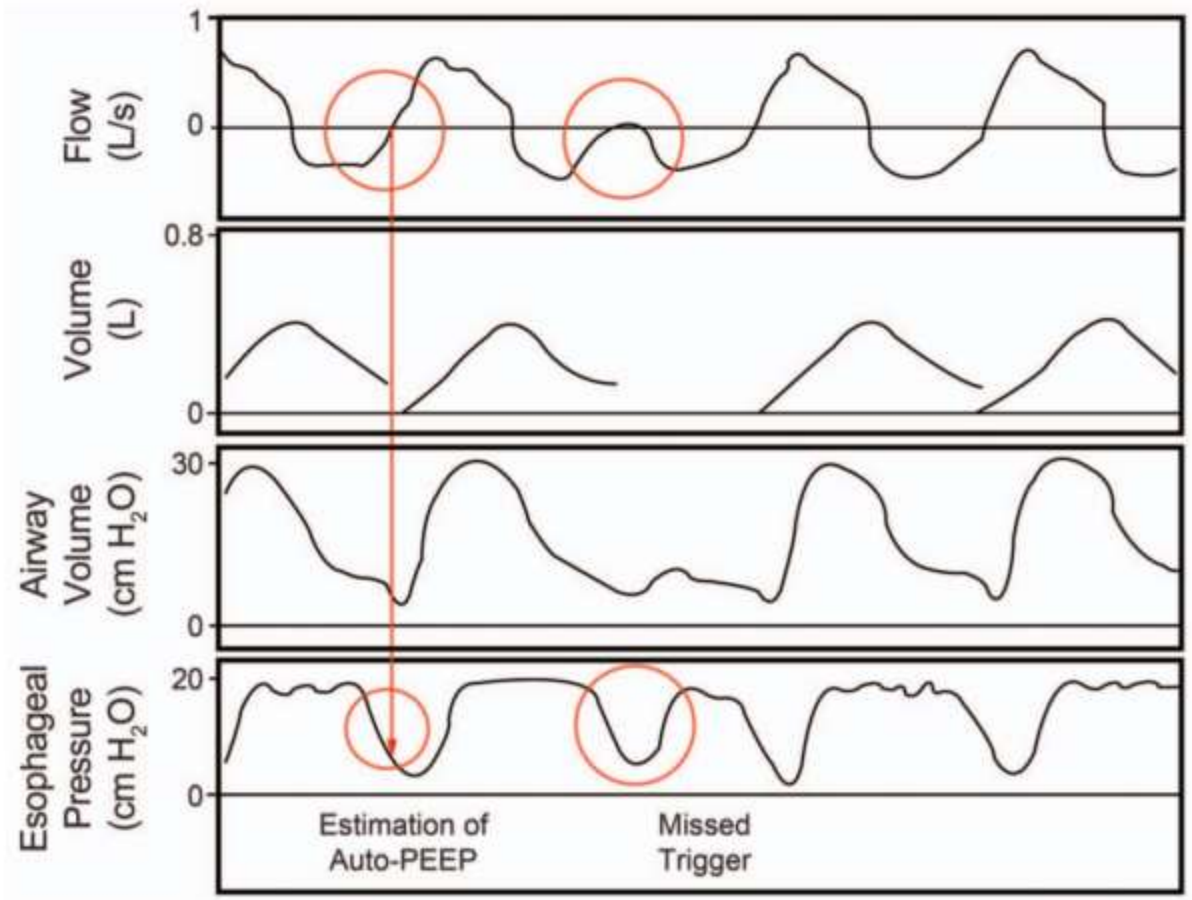


Fig. 4. Airway pressure, flow, volume, and esophageal pressure (P_{es}) waveforms in a patient with auto-PEEP. Note the decrease in P_{es} required to trigger the ventilator, which represents the amount of auto-PEEP. Also note that flow does not return to zero at the end of exhalation, and the inspiratory effort does not trigger the ventilator.

Akoumianaki *et al.* American Journal of Respiratory and Critical Care Medicine Volume 189 Number 5 | March 1 2014

Pressure volume loop

- Positive pressure ventilation
  - Tracing begins in the lower left hand corner of the graph and moves counterclockwise
  - At end expiration, returns to the point of initiation
  - The highest point of the PV loop read off on the *y*-axis represents the tidal volume
  - The same point read against the *x*-axis represents the Ppeak
  - With exhalation, the tracing follows the expiratory curve downward, culminating at the point representing zero tidal volume and zero pressure (in the absence of set PEEP)
  - Change in volume per unit change in pressure - compliance

Pressure volume loop

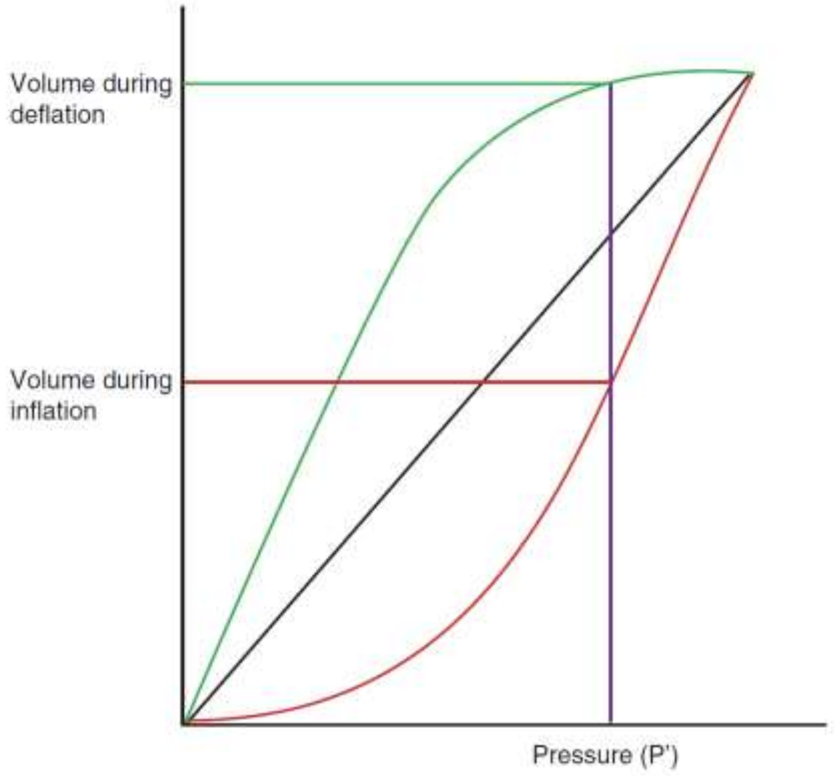


FIGURE 8.16. The pressure–volume loop: lung volume during inflation and deflation.

Air–fluid interfaces within the lung generate forces of surface tension and the inspiratory and expiratory tracings follow different paths – tracing out a loop

Pressure volume loop

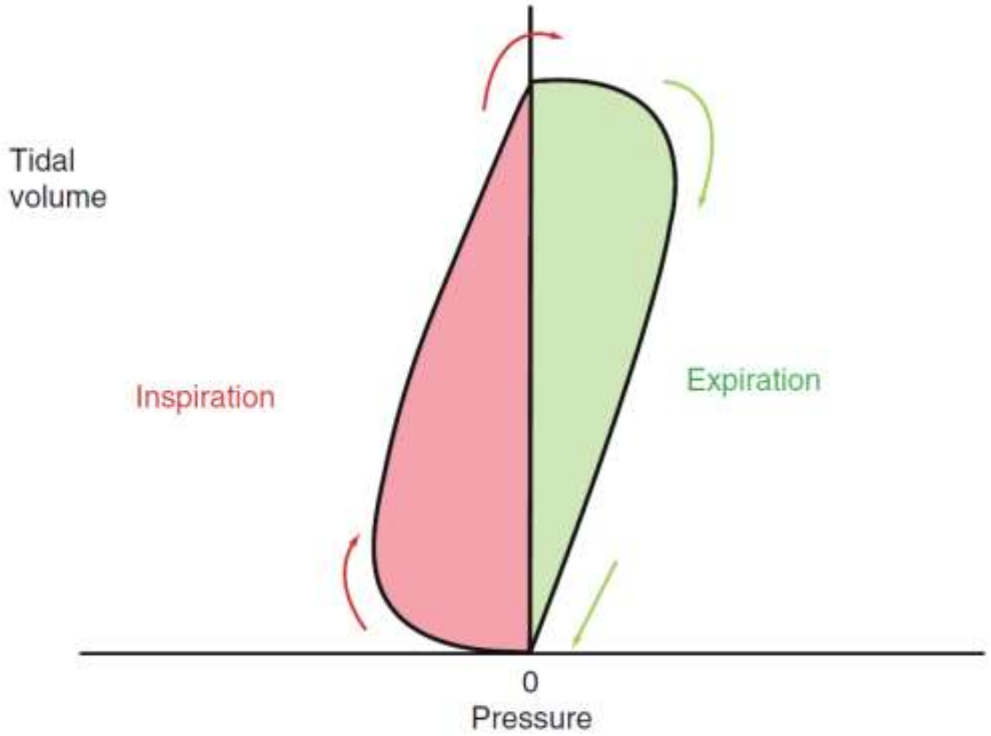


FIGURE 8.15. The pressure–volume loop during spontaneous breathing.

- Traced clockwise
- Inspiration intrapleural pressure becomes negative → the tracing moves to the left of the *y*-axis and air is drawn into the lungs
- As TV is reached the lungs fill up with air and the negativity of the intrapleural pressure decreases the tracing returns to the zero pressure line

Pressure volume loop patient vs machine trigger

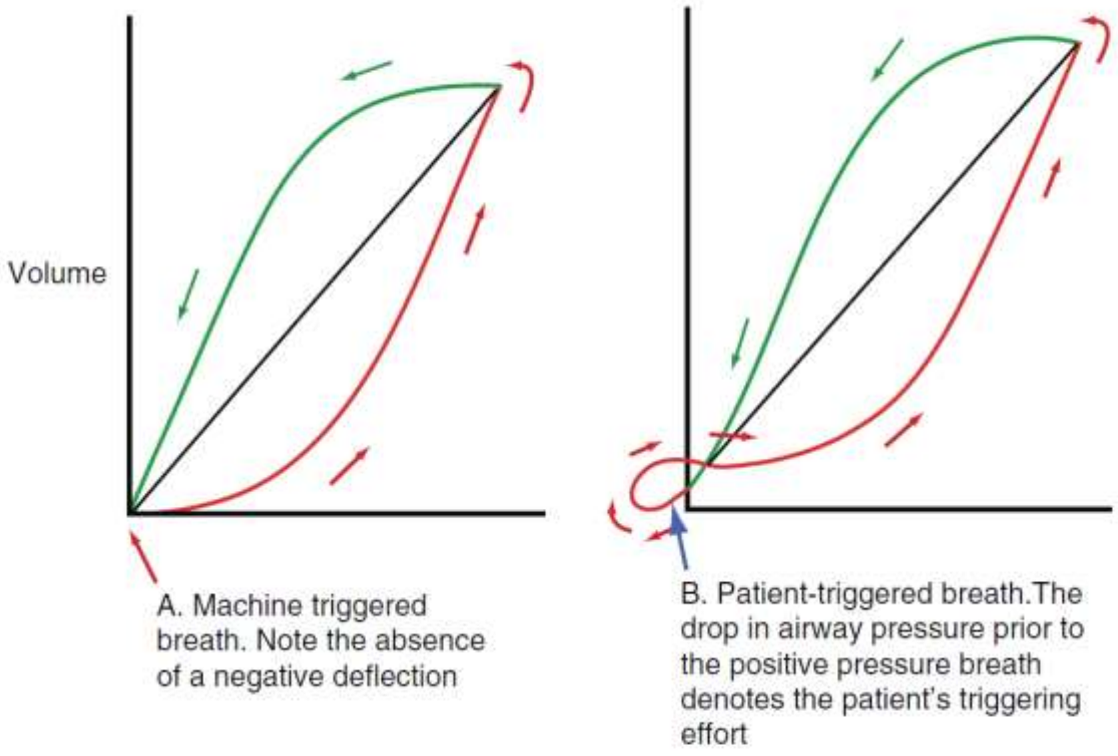


FIGURE 8.19. The pressure–volume loop: triggering.

Pressure volume loop

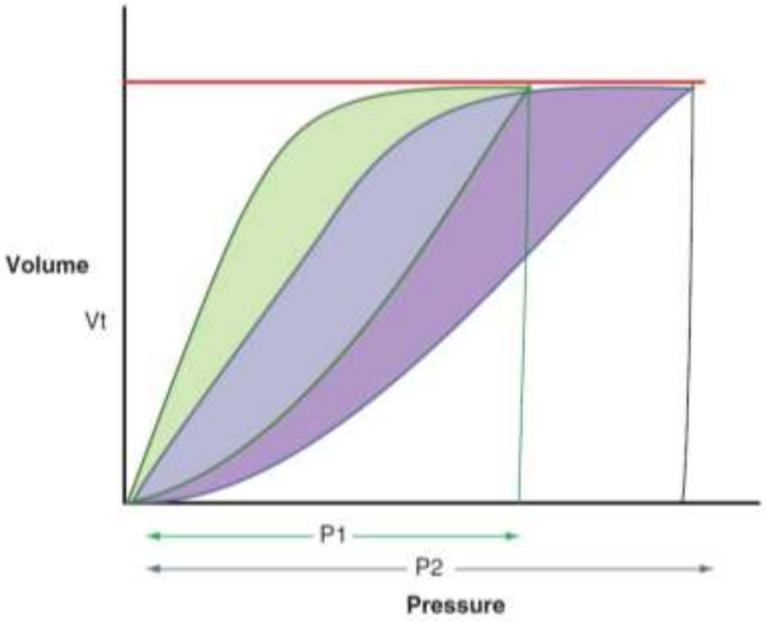


FIGURE 8.22. Effect of decreased compliance on the PV loop during volume-targeted ventilation.

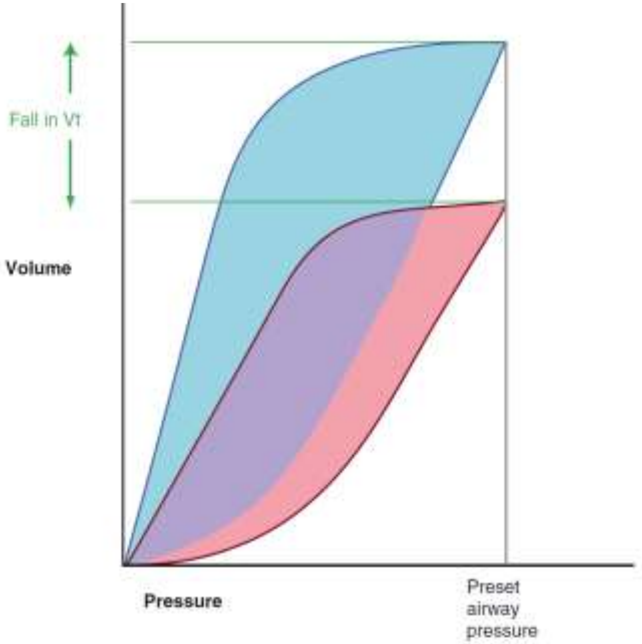


FIGURE 8.23. Effect of decreased compliance on the PV loop with pressure-targeted ventilation.

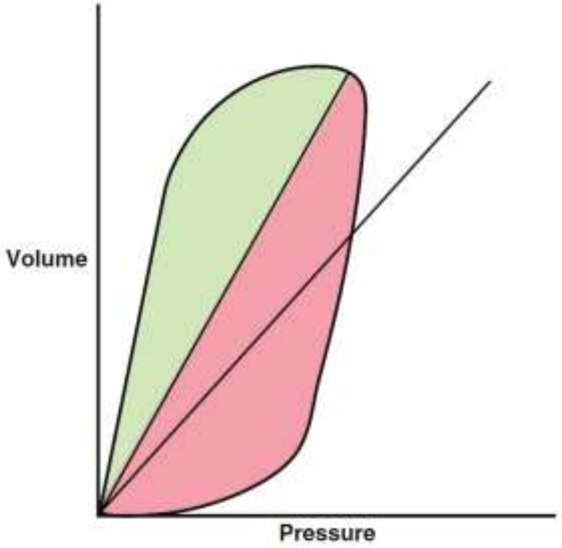


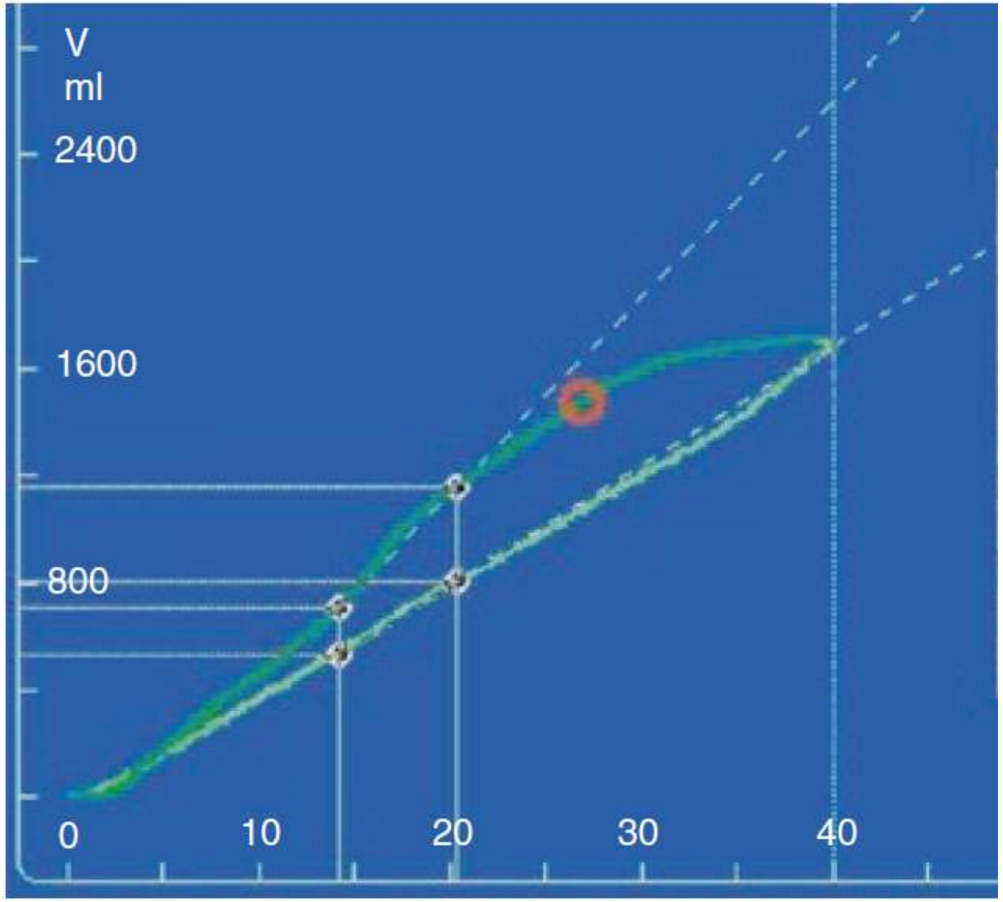
FIGURE 8.25. Pressure–volume loop of a highly compliant lung.

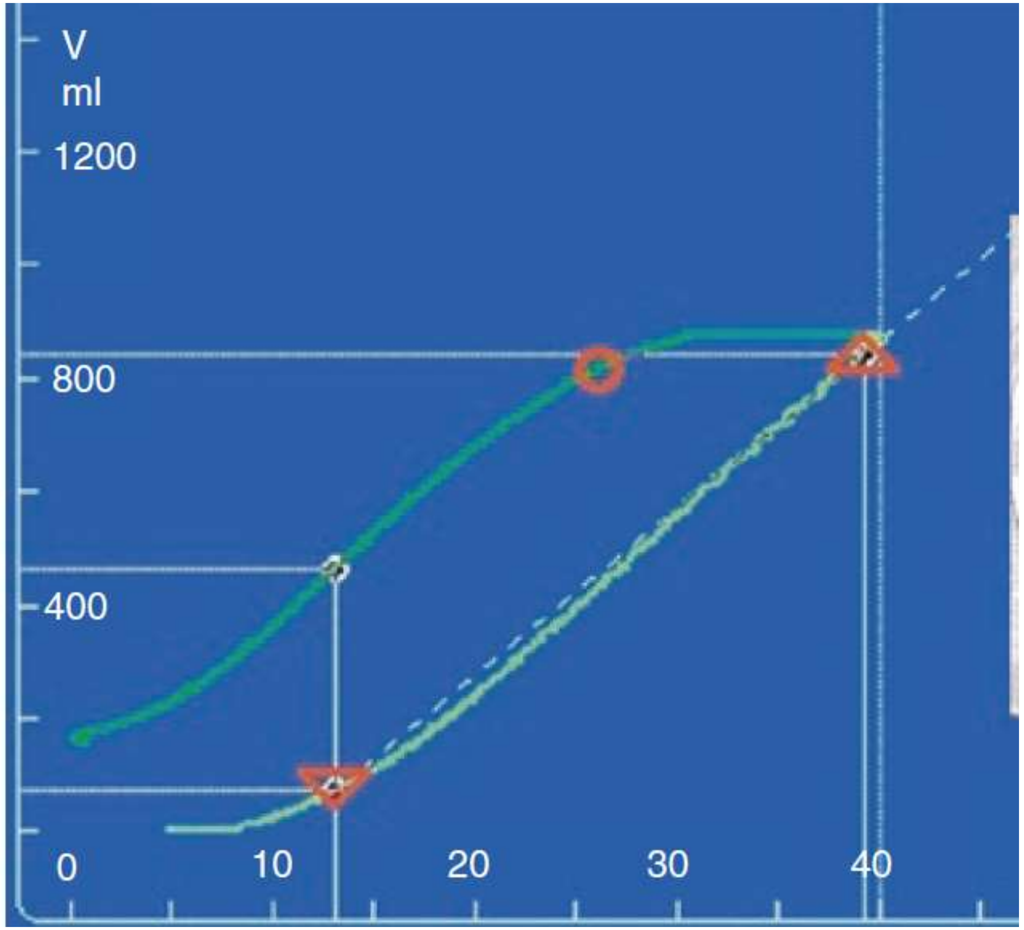
PV Loop high compliance COPD

Assessing recruitment using PV curve

- Normal lung – the PV curve is linear and the inflation and deflection curves are separated by small area of hysteresis
- Compliance remains constant
- Early ARDS the shape of the PV loop may differ
- The inflation and deflation limbs demonstrate a change in slope,
- Implication - respiratory-system compliance varies at different levels of pressure
- Hysteresis is greater than in normal-lung patients due to recruitment occurring during inflation and derecruitment occurring during deflation

Assessing recruitment using PV curve





Assessing recruitment using PV loop

- Linear compliance or midrange compliance
  - The compliance of the recruiting part of the inflation limb, i.e., between the two changes in the slope
  - The more vertical the slope, the more recruitment takes place
  - High linear compliance equates to high potential for recruitment
  - Lin Compliance of >50ml/cm H2O = recruitment maneuver
- Difference in volume between the inflation and deflection limb of curve at 20 cm H2O >400mL
- Concave inflation curve

Assessing recruitment using PV loop

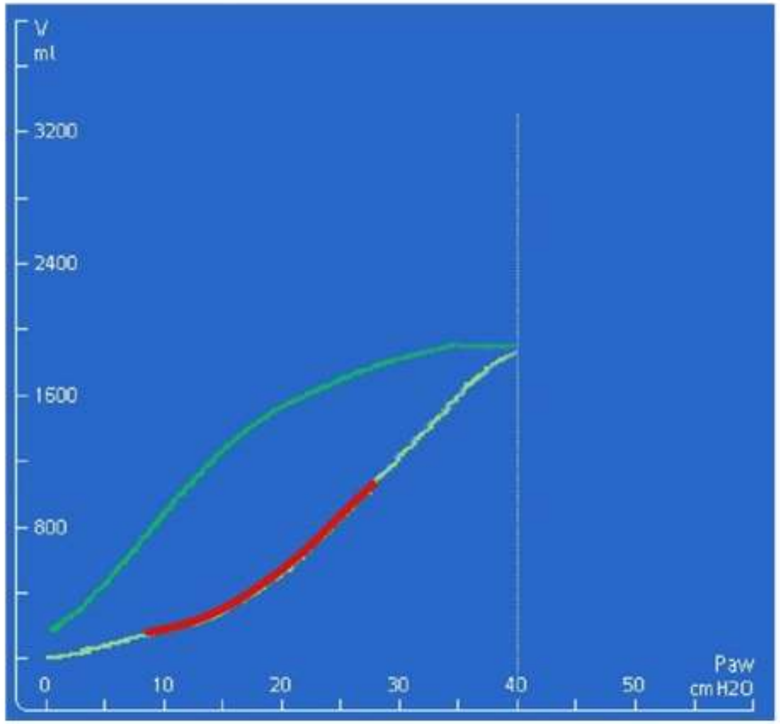


Figure 4: Inflation limb showing upward concavity, indicating high potential for lung recruitment

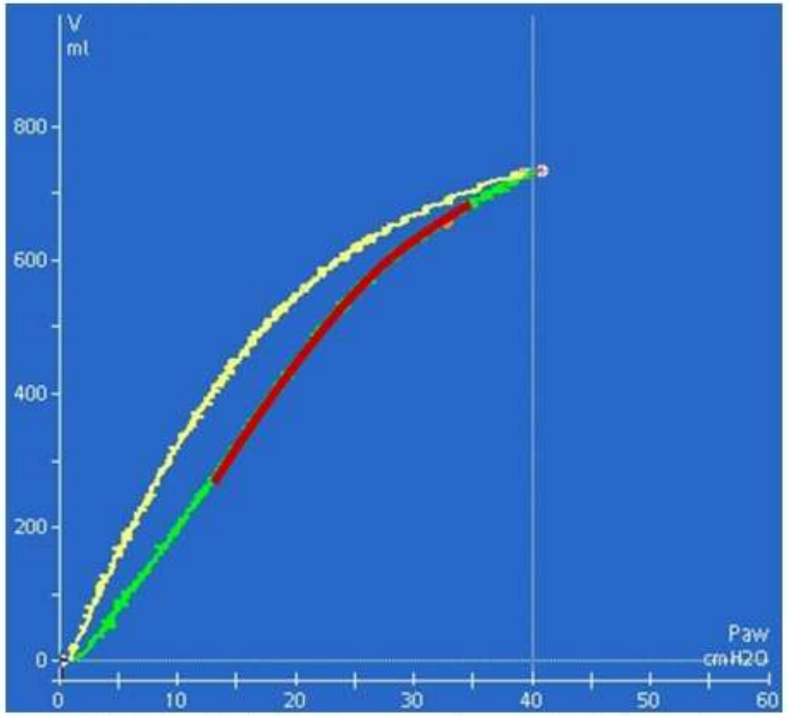
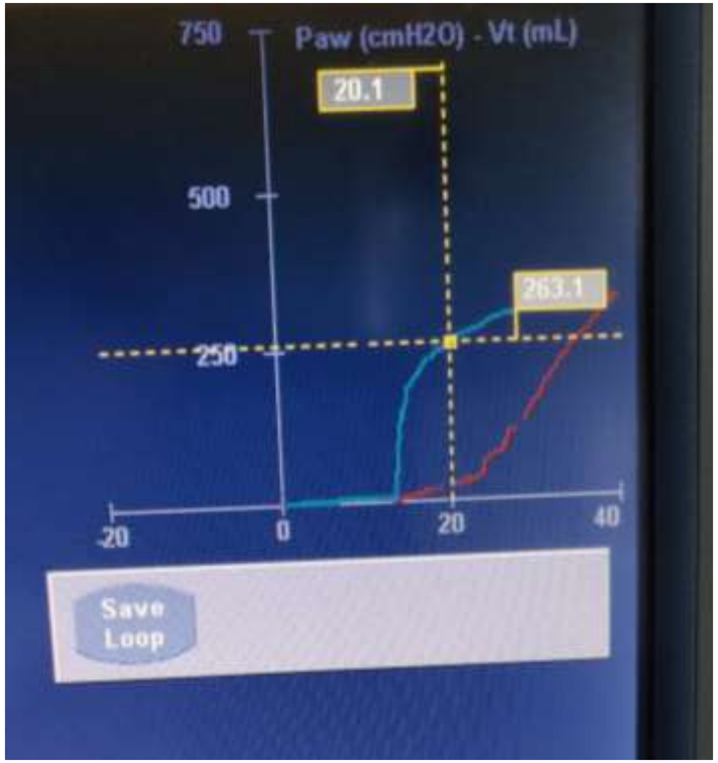
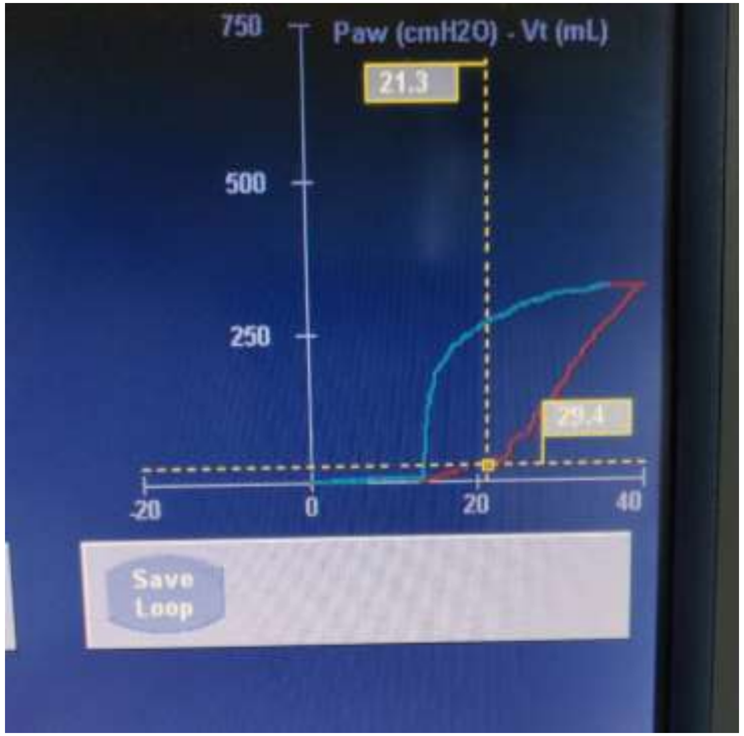


Figure 3: Inflation limb showing upward convexity, indicating low potential for lung recruitment

PV Loop Difference at 20 cm less than 400



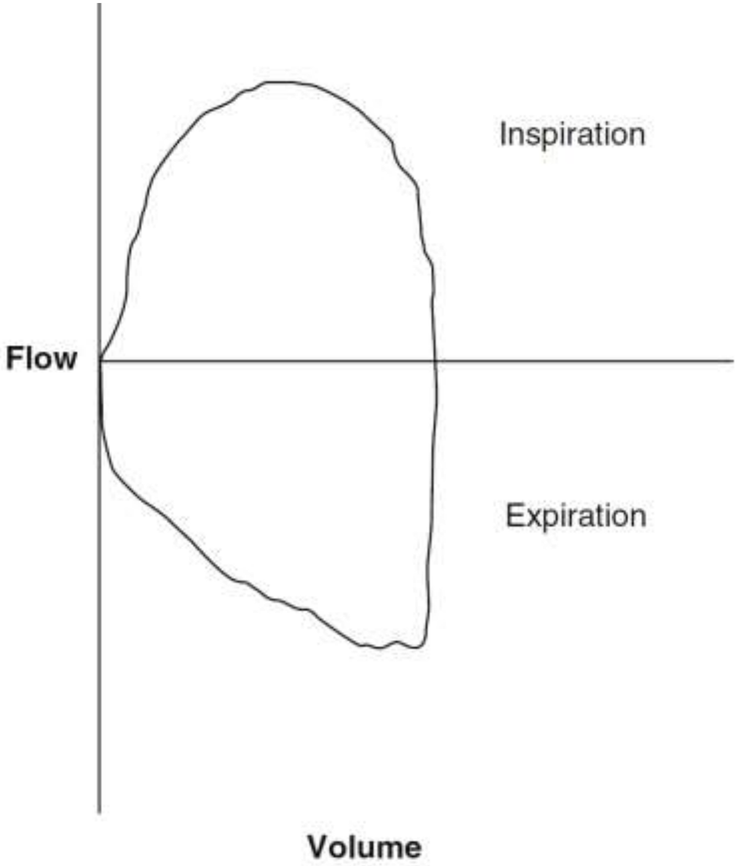


Flow-volume loop

- Loops with flow as a function of volume
- Inspiratory curve displayed above on ventilators
- Inspiratory flow rate is set and expiration is passive
- During inspiration - shape of the flow-volume loop is determined by the flow setting on the ventilator with volume-controlled ventilation
- During exhalation, the shape of the flow-volume loop is determined by respiratory mechanics
- Spontaneous breath is recognised by the slightly irregular contour of the inspiratory portion

Hasan *et al.* Understanding Mechanical Ventilation A Practical Handbook; 2nd ed; 2010; Springer

Flow volume loop



Spontaneous breath is recognizable by
the slightly irregular contour of its inspiratory portion

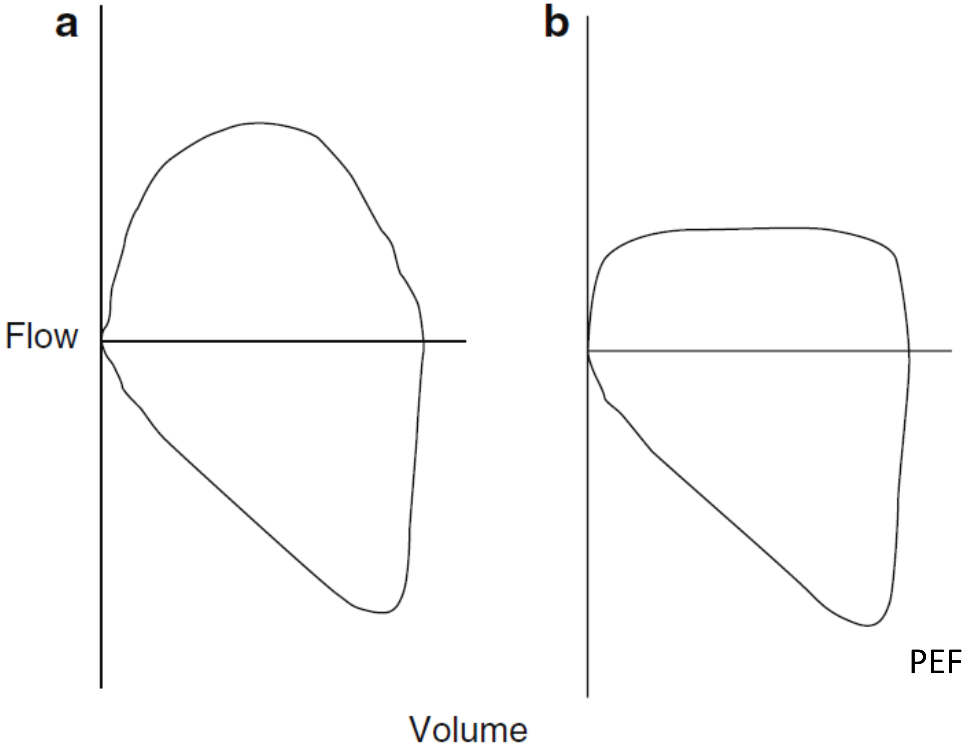


FIGURE 8.31. Flow–volume loop during volume controlled ventilation. (a) Sine-wave flow pattern. (b) Square-wave flow pattern.

Hasan *et al.* Understanding Mechanical Ventilation A Practical Handbook; 2nd ed; 2010; Springer

Flow volume loop

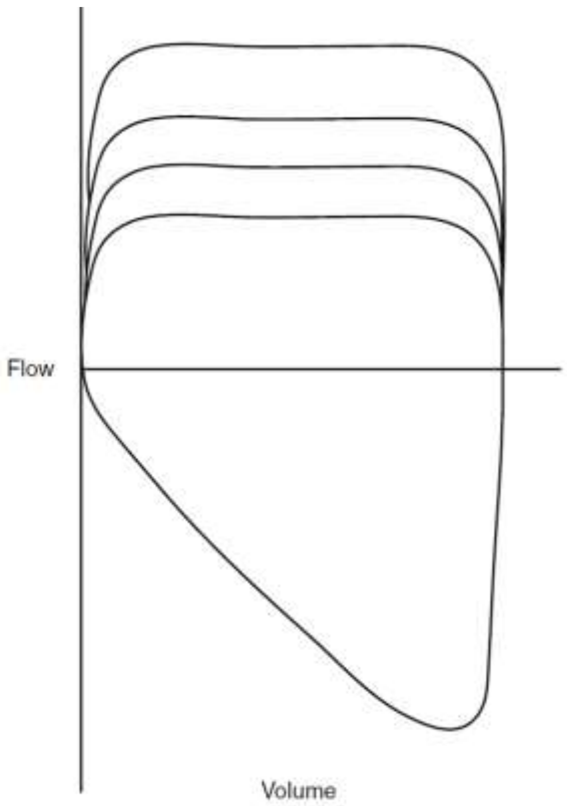


FIGURE 8.32. Flow–volume loop: the effect of varying the set inspiratory flow rate during square-wave volume-targeted ventilation.

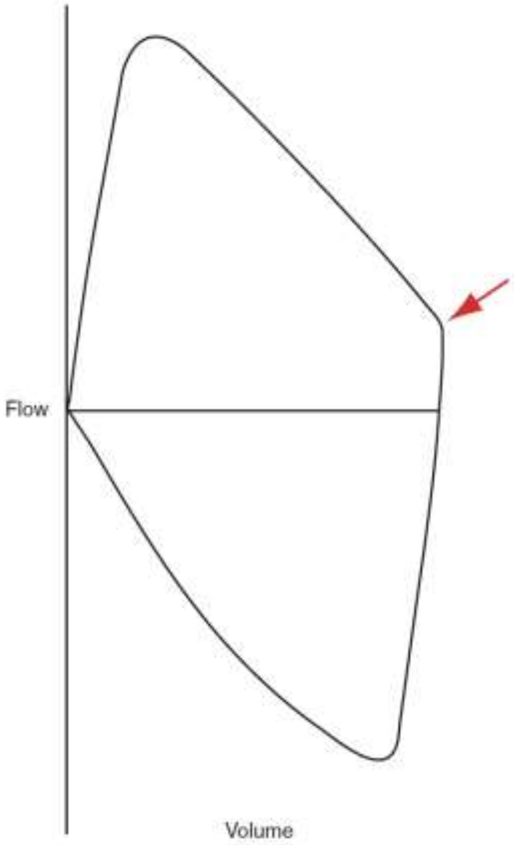


FIGURE 8.34. Flow–volume loop in pressure support ventilation. Note the abrupt decline in flow toward the end of ventilation as the ventilator cycles from inspiration to expiration (*red arrow*).

Hasan *et al.* Understanding Mechanical Ventilation A Practical Handbook; 2nd ed; 2010; Springer

Flow volume loop

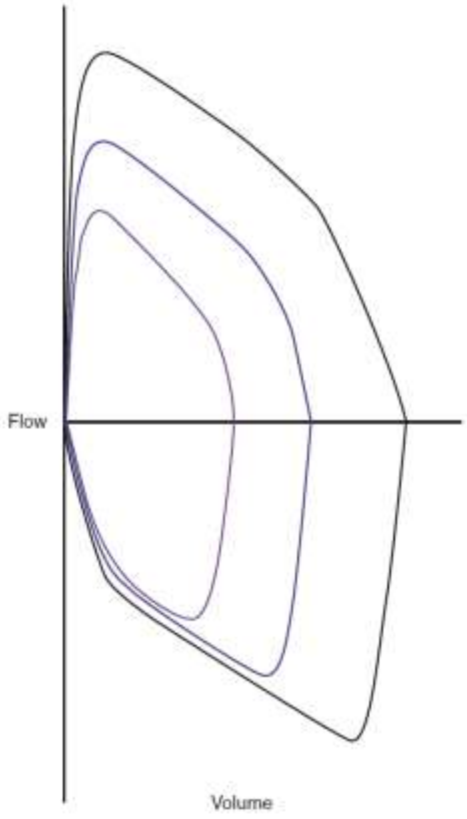


FIGURE 8.33. Flow–volume loop: the effect of varying the set airway pressure during a pressure-targeted ventilation. Shown in purple is

PCV*:* the peak flow is attained early during inspiration and the waveform shows a decelerating flow that is a defining characteristic of any pressure-targeted mode
The waveform retains its typical morphology at all the levels of the pressure level

Flow volume loop

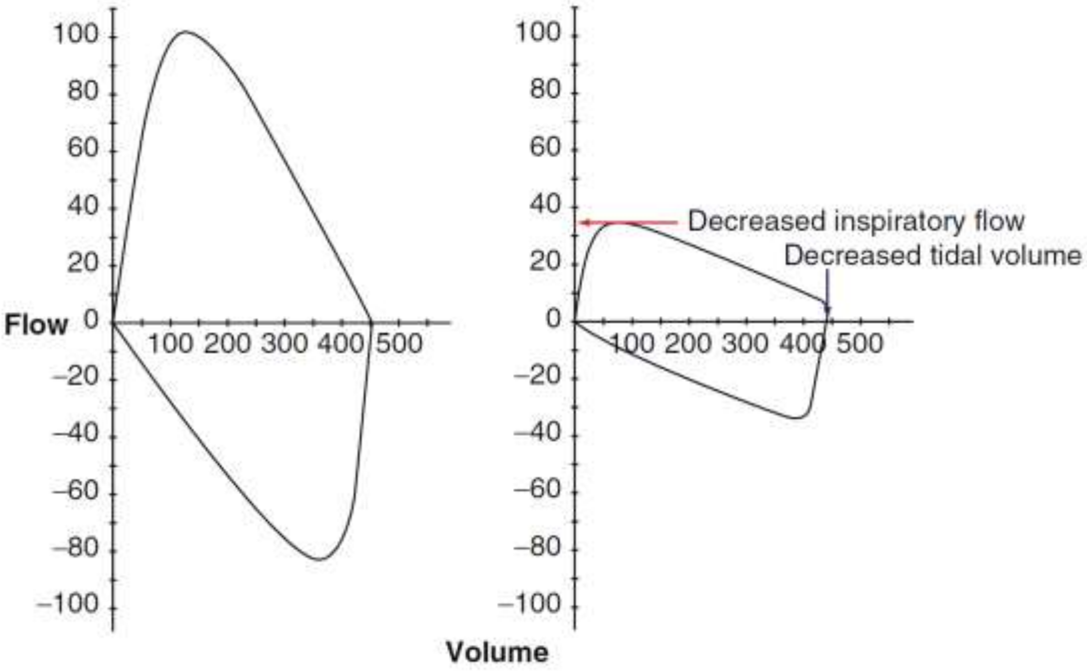


FIGURE 8.35. Flow–volume loop: effect of increased airway resistance on flow and volume. Shown in the panel on the left is a normal looking flow–volume loop obtained during pressure-targeted ventilation. The effect of increased airway resistance is shown in the panel on the right. Both flow and volume have decreased.

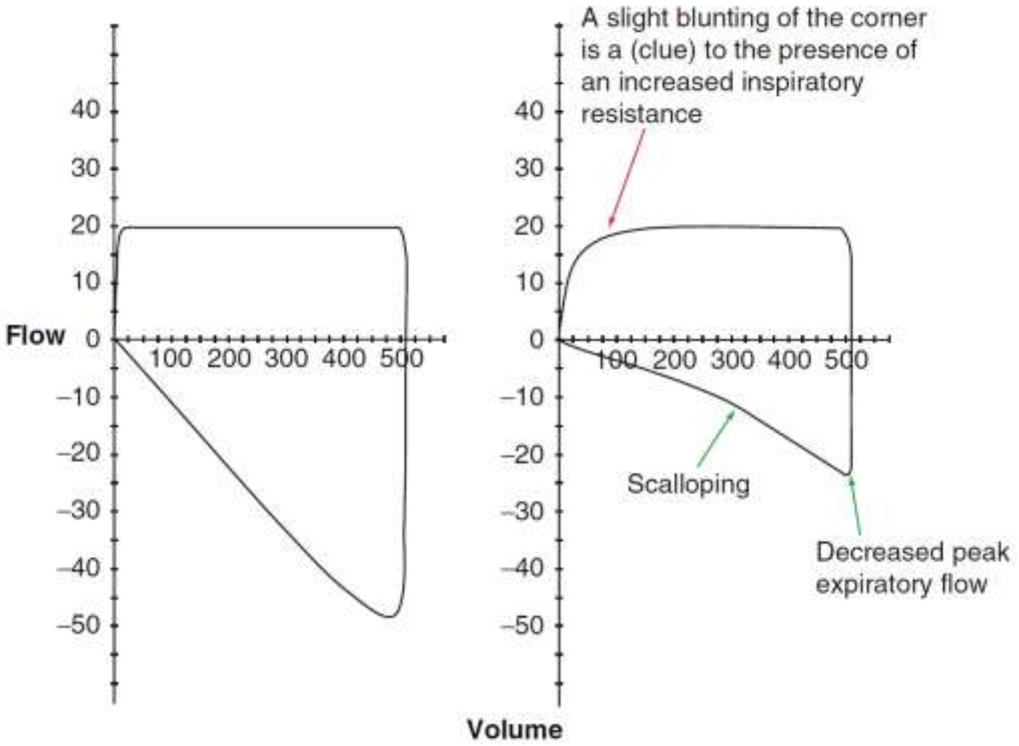


FIGURE 8.36. Flow–volume loop: effect of increased inspiratory and expiratory resistance.

Hasan *et al.* Understanding Mechanical Ventilation A Practical Handbook; 2nd ed; 2010; Springer

Flow volume loop

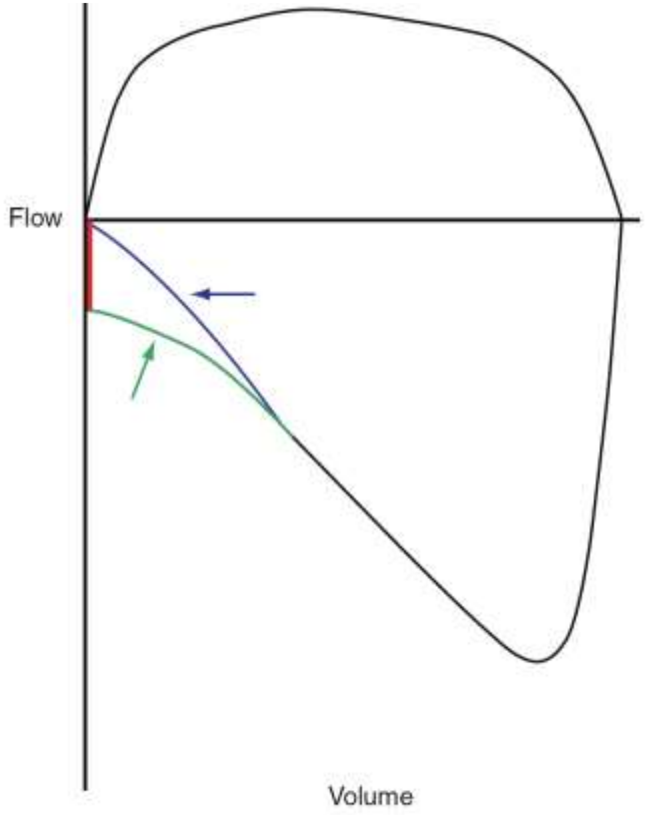
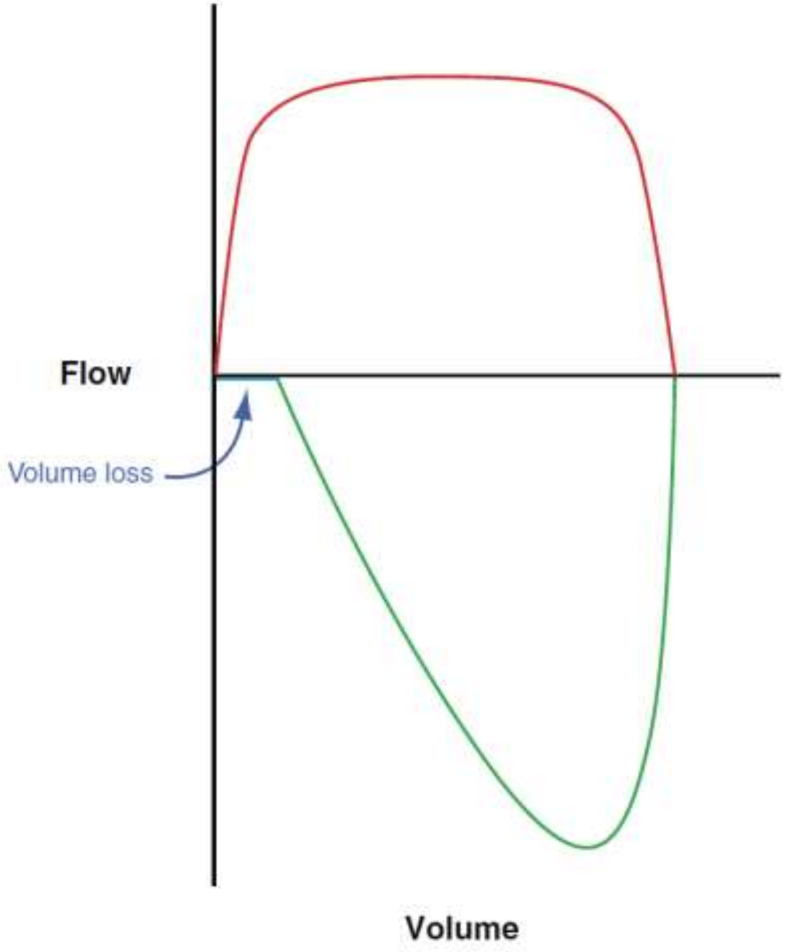


FIGURE 8.37. Flow–volume loop: dynamic hyperinflation (*see text*).

The expiratory flow tracing fails to return to the baseline at the end of exhalation (green line). The normal terminal part of the expiratory tracing is shown in blue



The expiratory tracing stops well short of they-axis this can happen when there is air leakage ET cuff leak Volume of leak can be quantified from graph

Air trapping and Leak

Flow volume loop

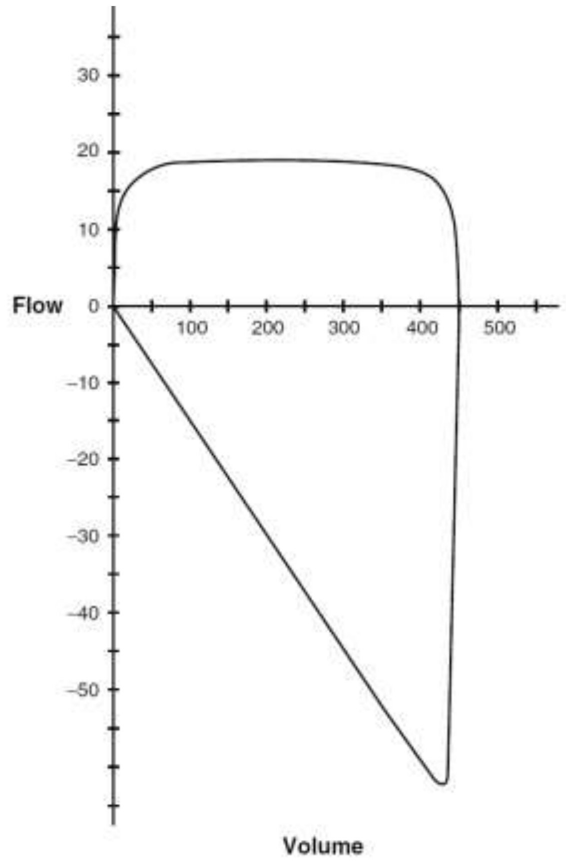


FIGURE 8.38. Flow–volume loop: effect of a decrease in compliance.

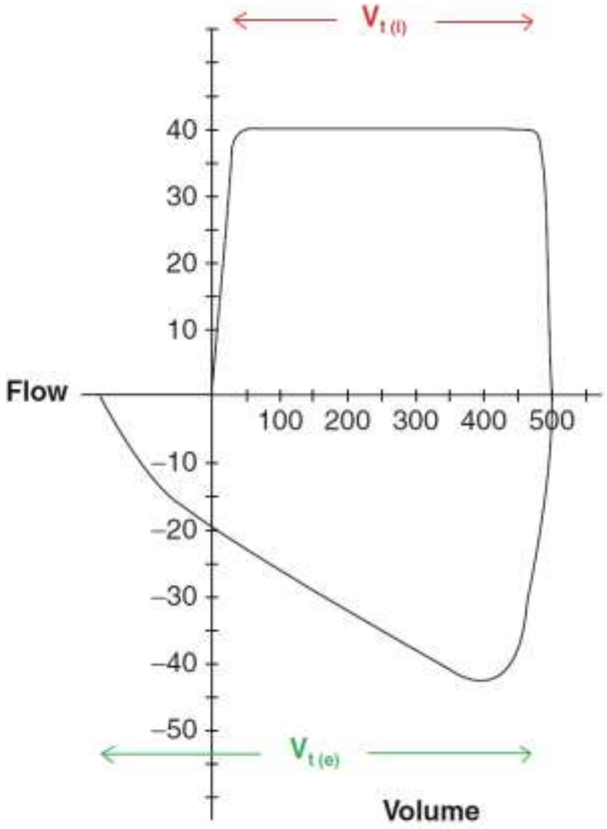
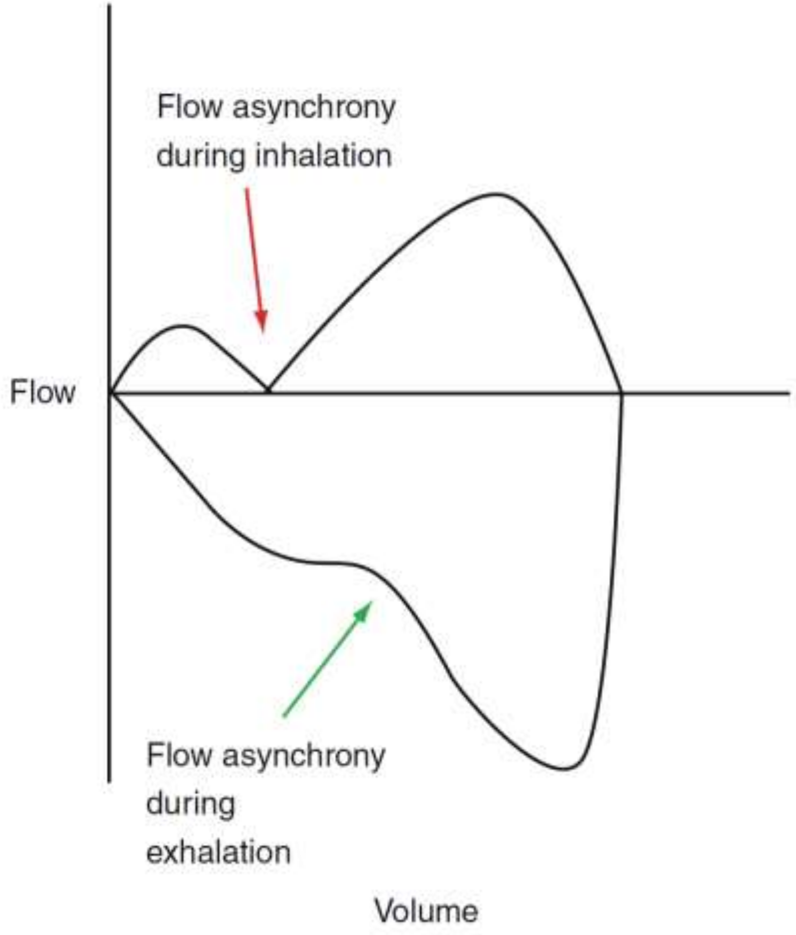


FIGURE 8.52. Flow–volume loop: active exhalation. Inspiratory tidal volume ($V_{t(i)}$) is shown by the red arrow, and expiratory tidal volume $V_{t(e)}$ by the *green arrow*.

Flow volume loop



Summary

- Ventilator waveform analysis is a very integral and important component in the management of a mechanically ventilated patient
- Significance of scalars vary based on the mode of ventilation, the independent and dependent variable
- Overall scalars and loops provide valuable information wrt the ventilator patient interaction includes synchrony, respiratory system mechanics and circuit related issues (secretions,leaks)
- Early interpretation and corrective measures essential for optimal ventilation