Monitoring of mechanical ventilation
－wave forms, synchronization and others

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Outline

- Basic waveform in mechanical ventilator
- Patient-ventilator asynchrony
- Others for clinical care
- Conclusions

Goals of artificial ventilatory support

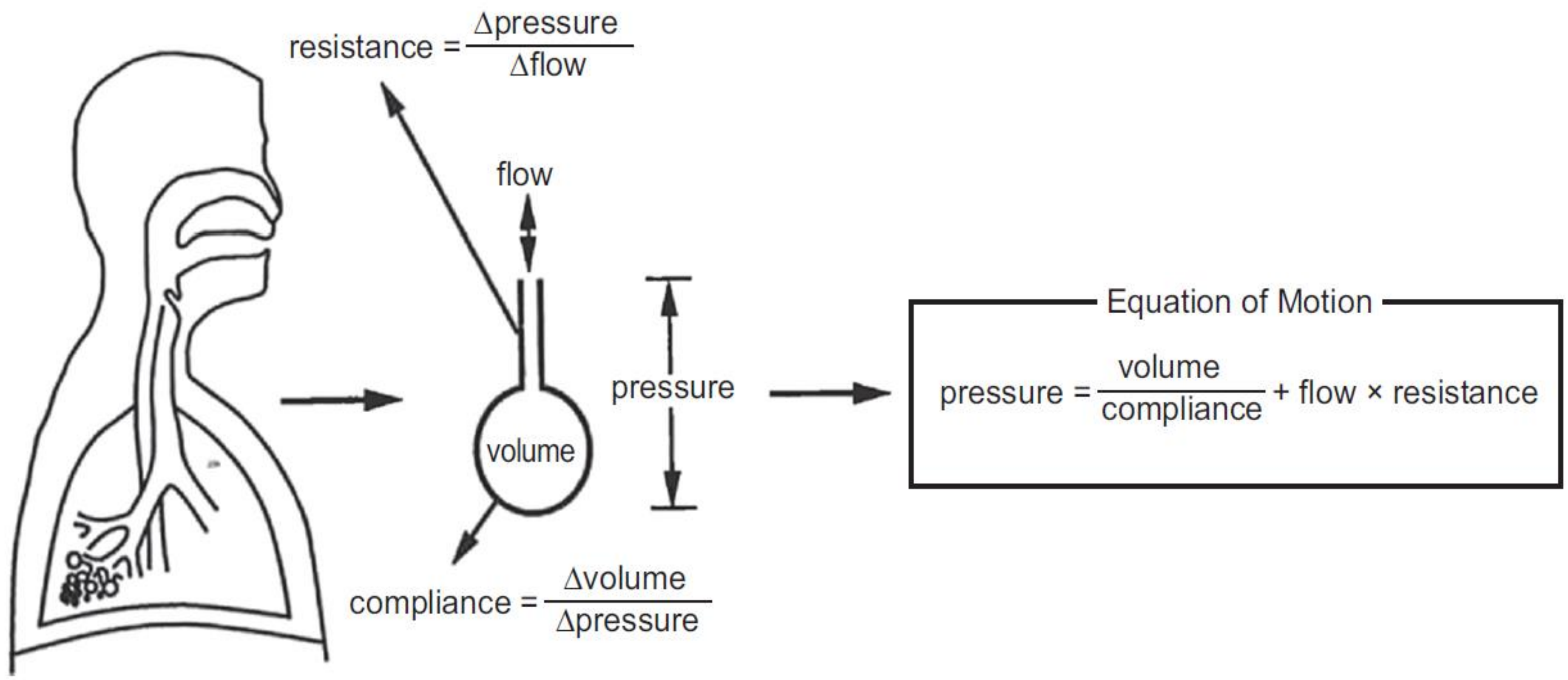
- Support gas exchange
  - alveolar ventilation (PCO_2, pH)
  - arterial oxygenation (PaO_2, SaO_2)
- Increase lung volume
  - end inspiratory lung inflation
  - functional residual capacity (FRC)
- Reduce the work of breathing

Goals of artificial ventilatory support

- **Prevent ventilator induced lung injury**
- **Improve patient comfort**
- **Liberate the patient from mechanical ventilation as soon as possible**

Cleveland Clinic Journal of Medicine July 2009

Single-compartment model of the respiratory system



Respir Care 1992;37

How ventilators deliver breaths

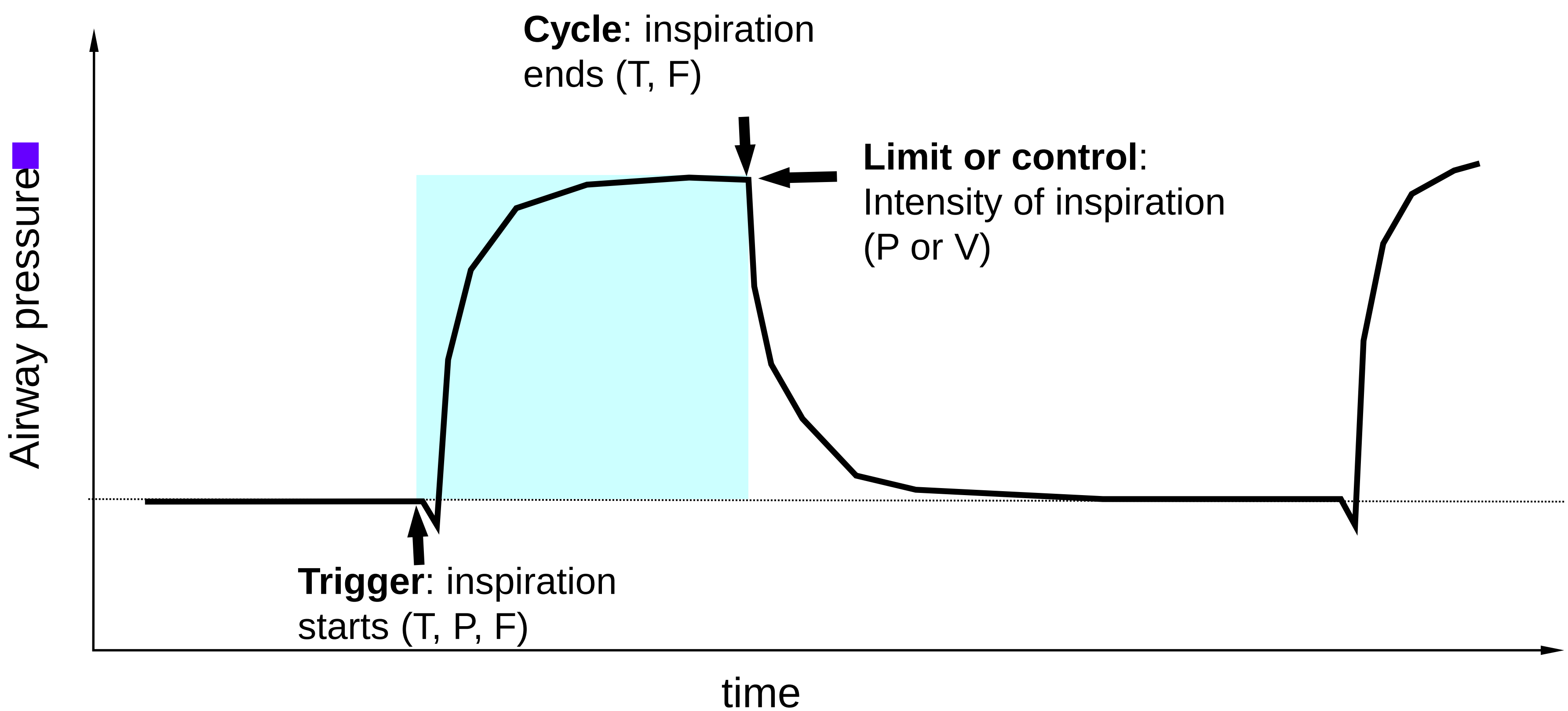
- Based on three main variables
  - how the breath starts
  - how the breath is delivered by the machine
  - how the breath is stopped

Current Pediatrics Reports (2021)

Concept of MV - trigger, target, cycle

- Trigger
  - Initiate the breath
  - Time, flow, pressure
- Target (Limit)
  - Parameter is sustained at a preset level during the breath
  - Volume, Flow, Pressure
- Cycle (Termination)
  - Causes the breath to end
  - Time, Flow, Pressure

Concept of MV



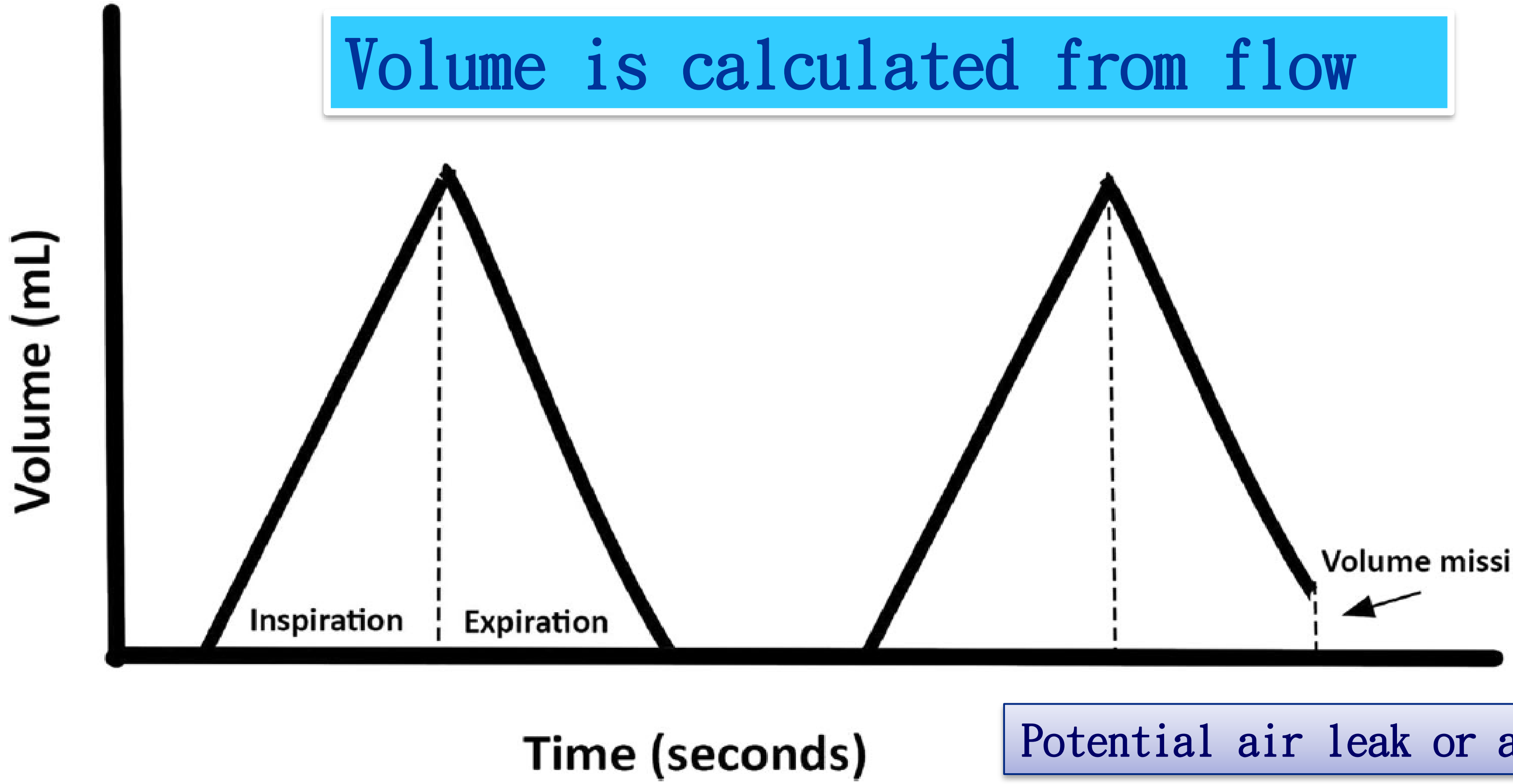
T = time **P = pressure** **F = flow** **V = volume**

Basic graphics

- Three scalars
  - Volume-time
  - Pressure-time
  - Flow-time
- Two loops
  - Pressure-volume
  - Flow-volume

Volume-time

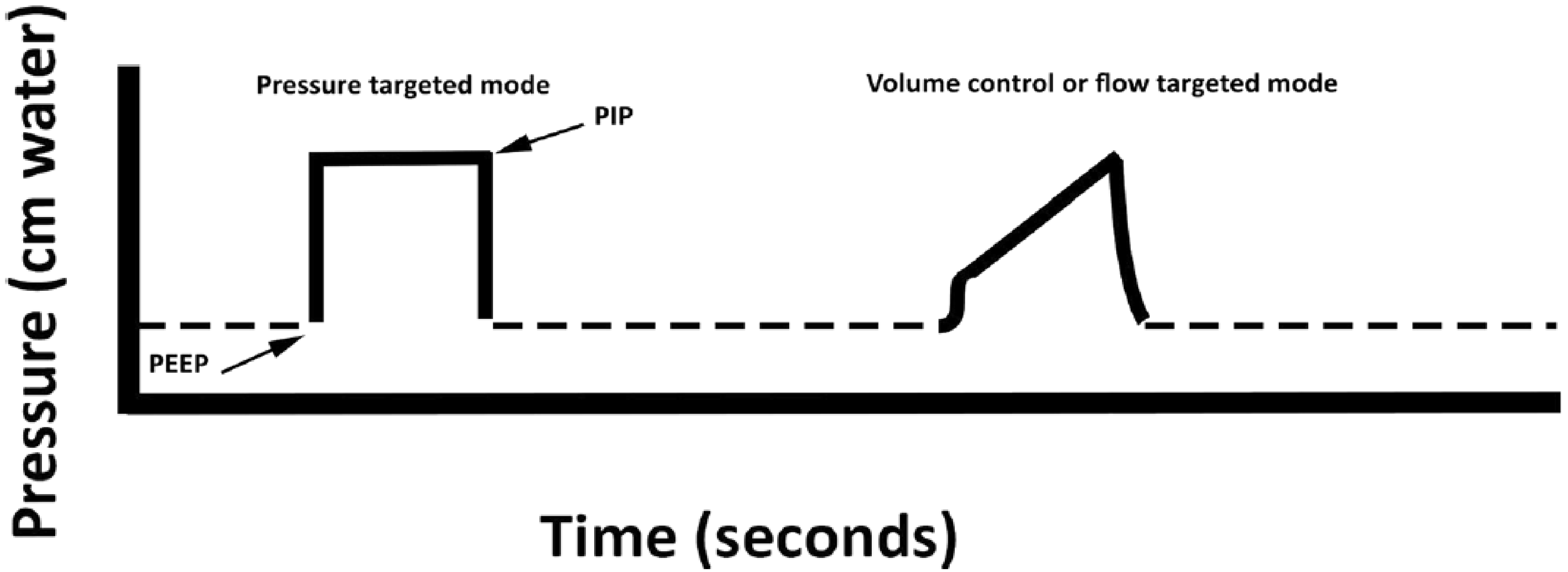
Volume is calculated from flow



Potential air leak or auto-PEEP

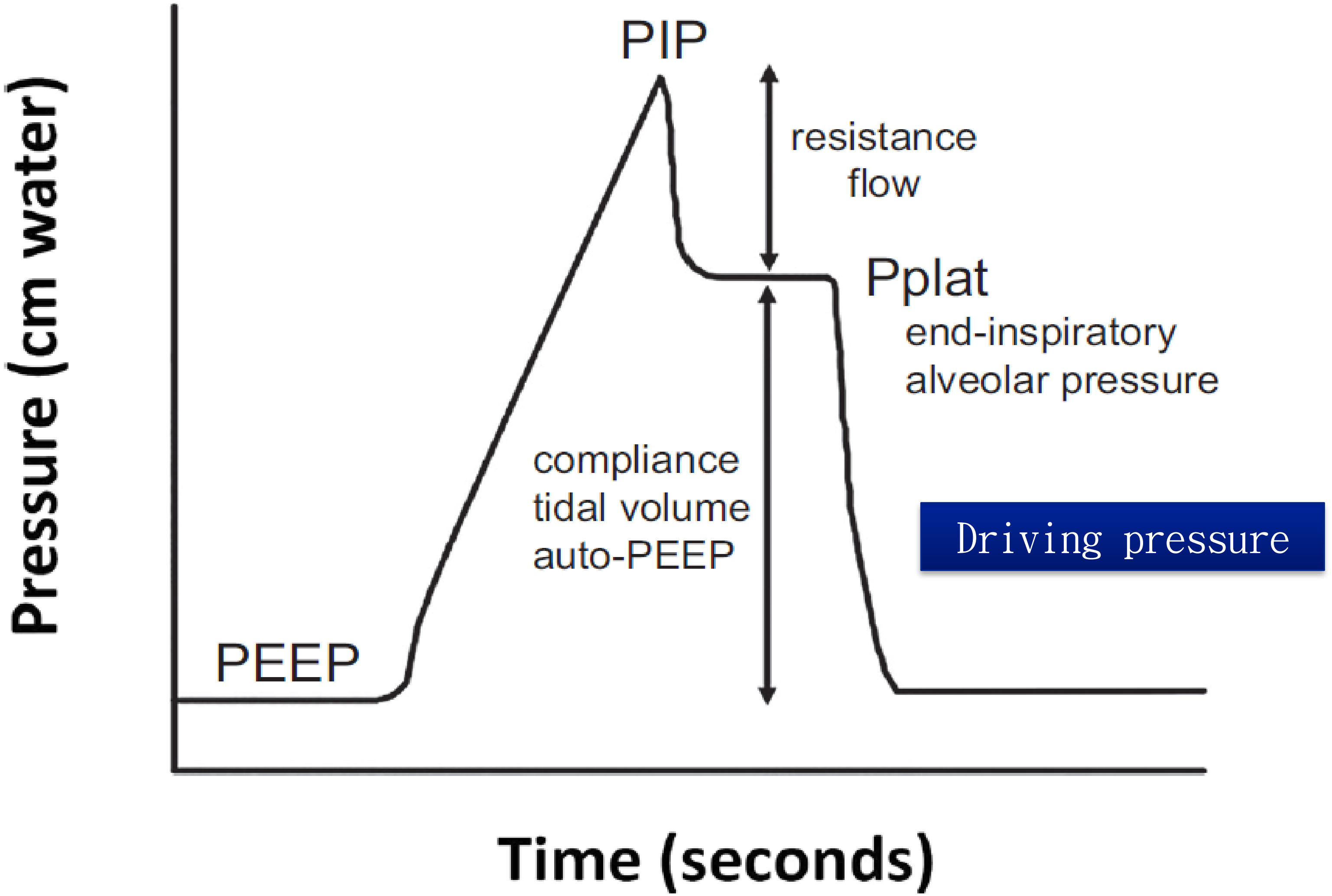
Current Pediatrics Reports (2021)

Pressure-time



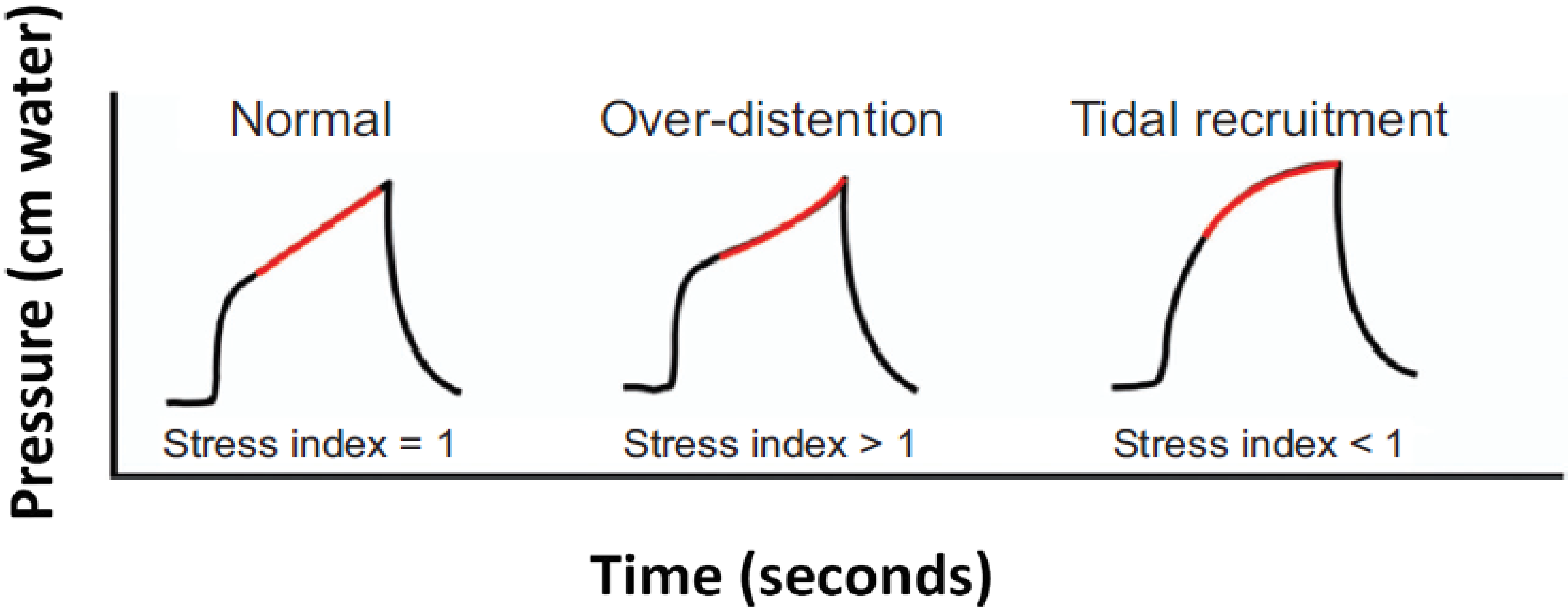
Current Pediatrics Reports (2021)

Pressure-time



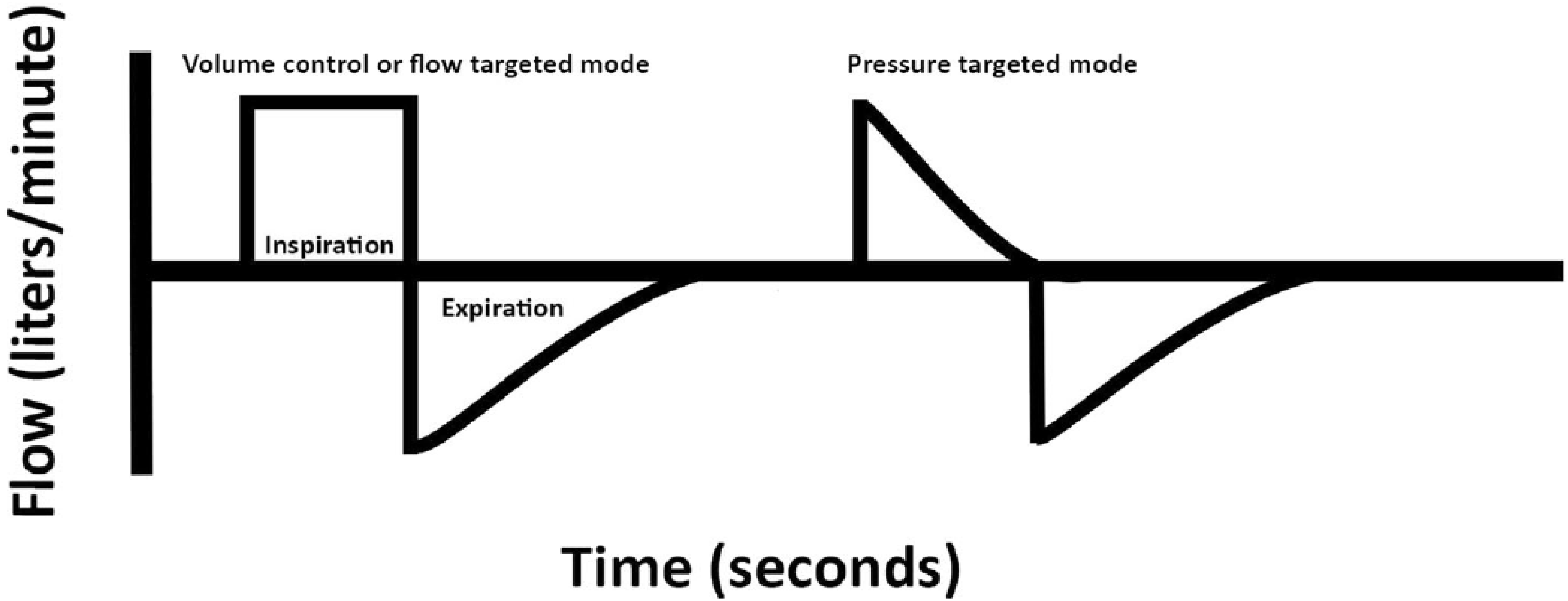
Respir Care 1992;37

Pressure-time



Respir Care 1992;37

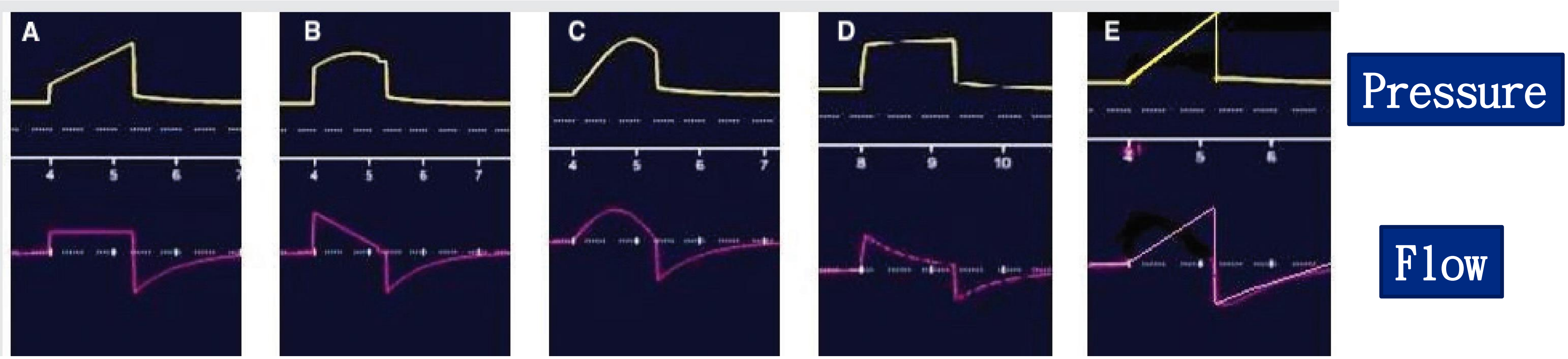
Flow-time



Current Pediatrics Reports (2021)

Flow-time

- Five different inspiratory flow waveforms

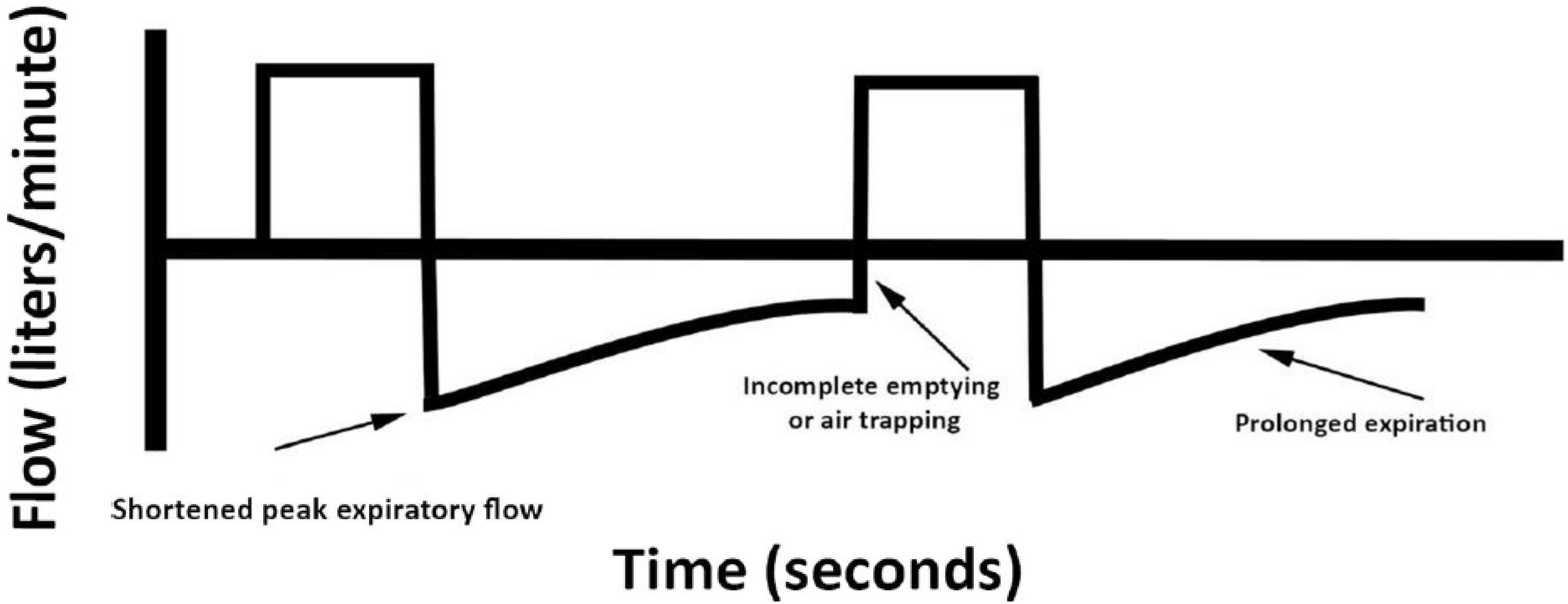


Can J Respir Ther 22 July 2020

Flow-time

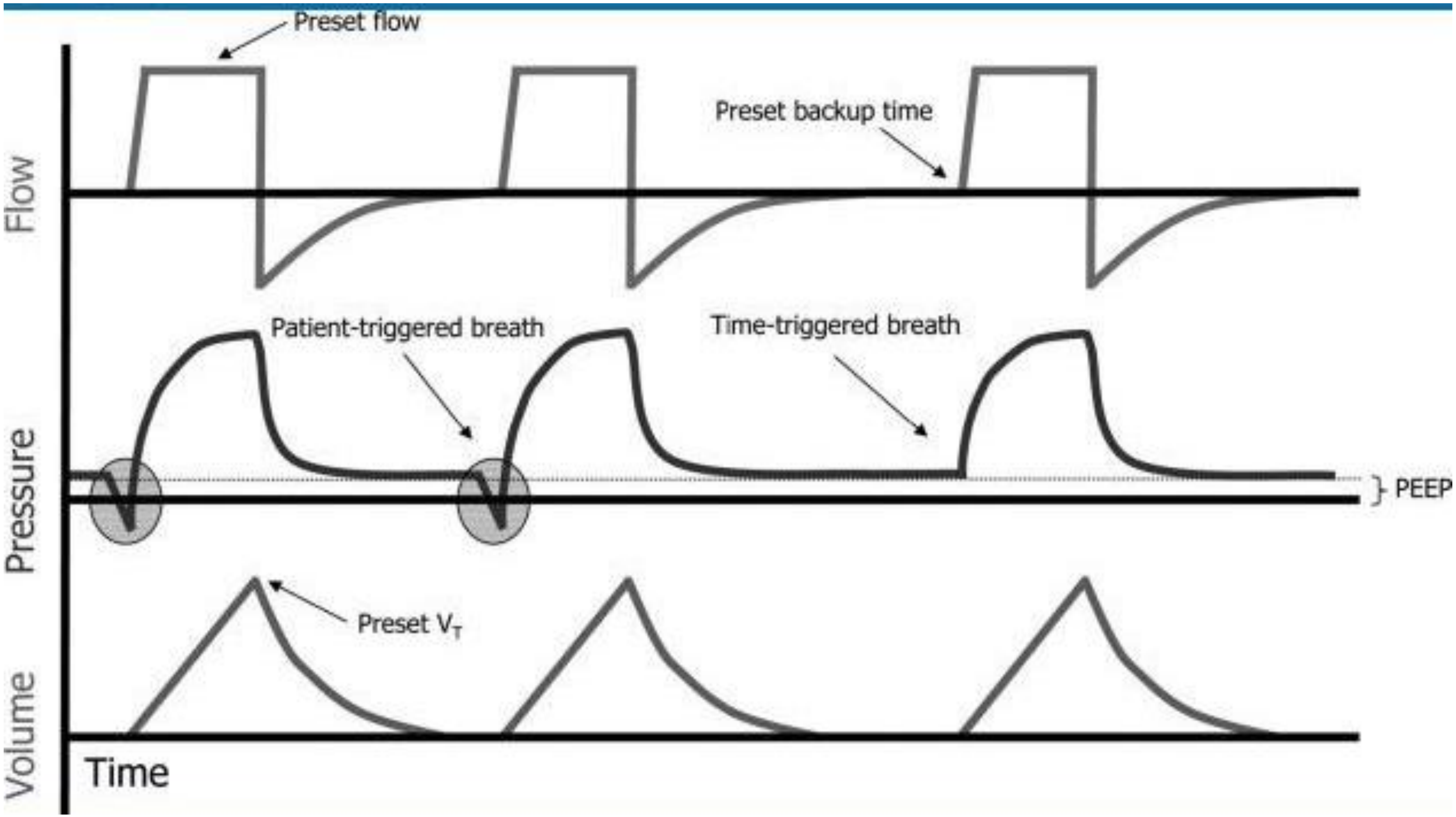
- Waveform affect the peak inspiratory airway pressure (PIP), mean airway pressure (Paw), and inspiratory time
- Most pressure-controlled modes use the decelerating or descending waveform
- Square waveform used mainly on the volume-controlled mode
- Decelerating waveform was also reported to reduce the dead space, the alveolar - arterial gradient and the WOB

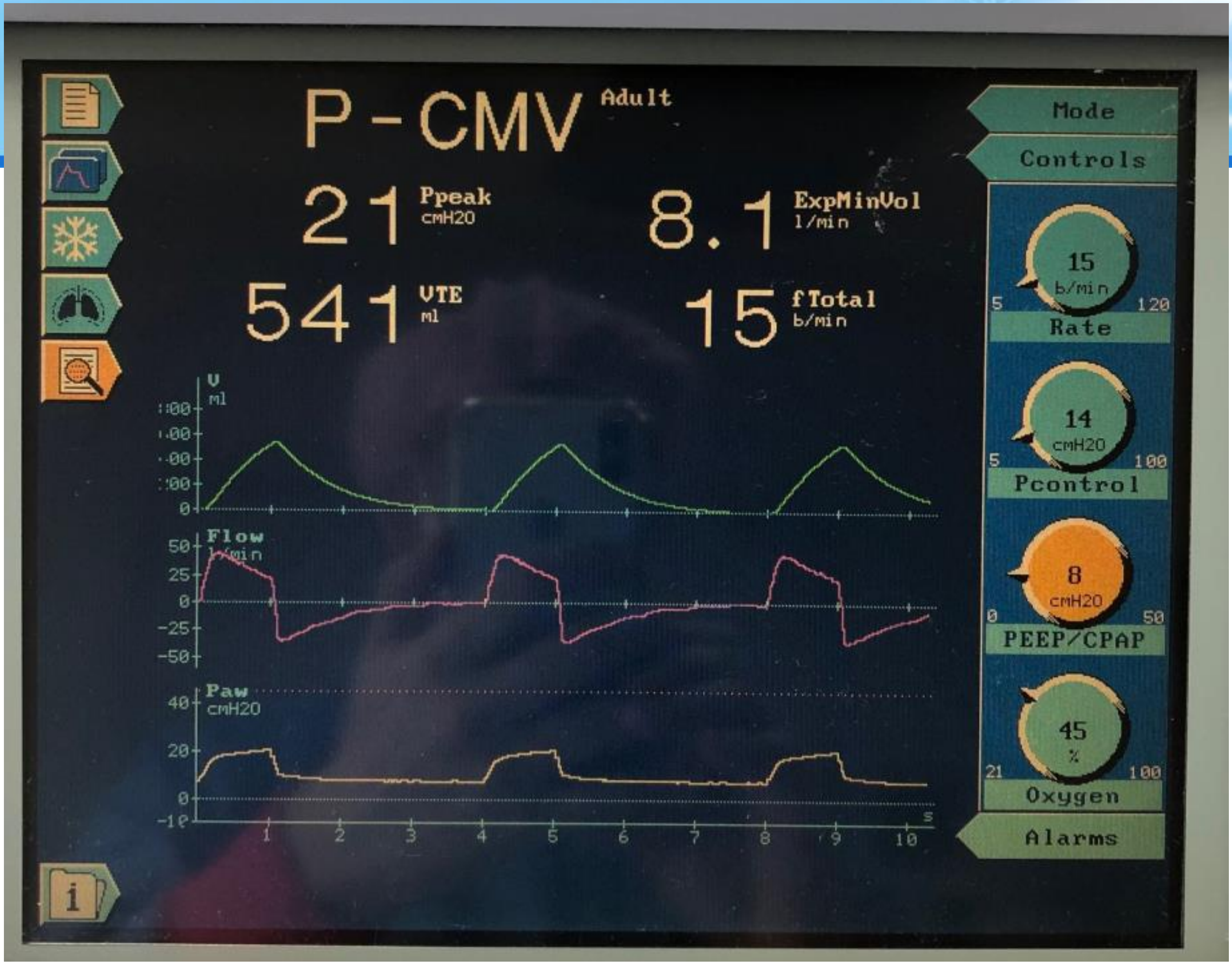
Flow-time



Current Pediatrics Reports (2021)

Basic graphics

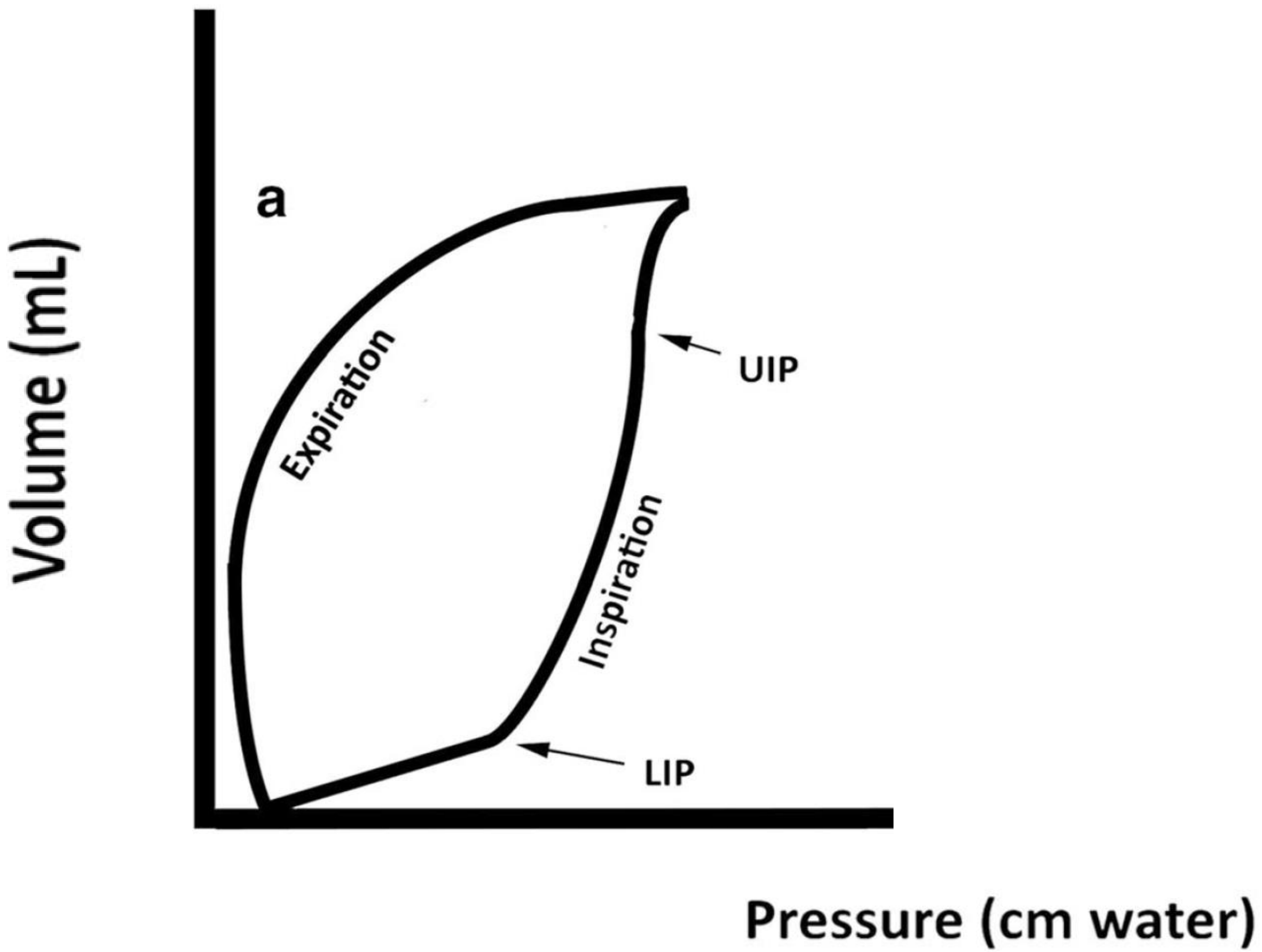



P-CMV
Adult
21
Ppeak
cmH2O
8.1
ExpMinVol
l/min
541
VTE
ml
15
fTotal
b/min
Mode
Controls
15
b/min
Rate
14
cmH2O
Pcontrol
8
cmH2O
PEEP/CPAP
45
%
Oxygen
Alarms
V
ml
Flow
l/min
Paw
cmH2O

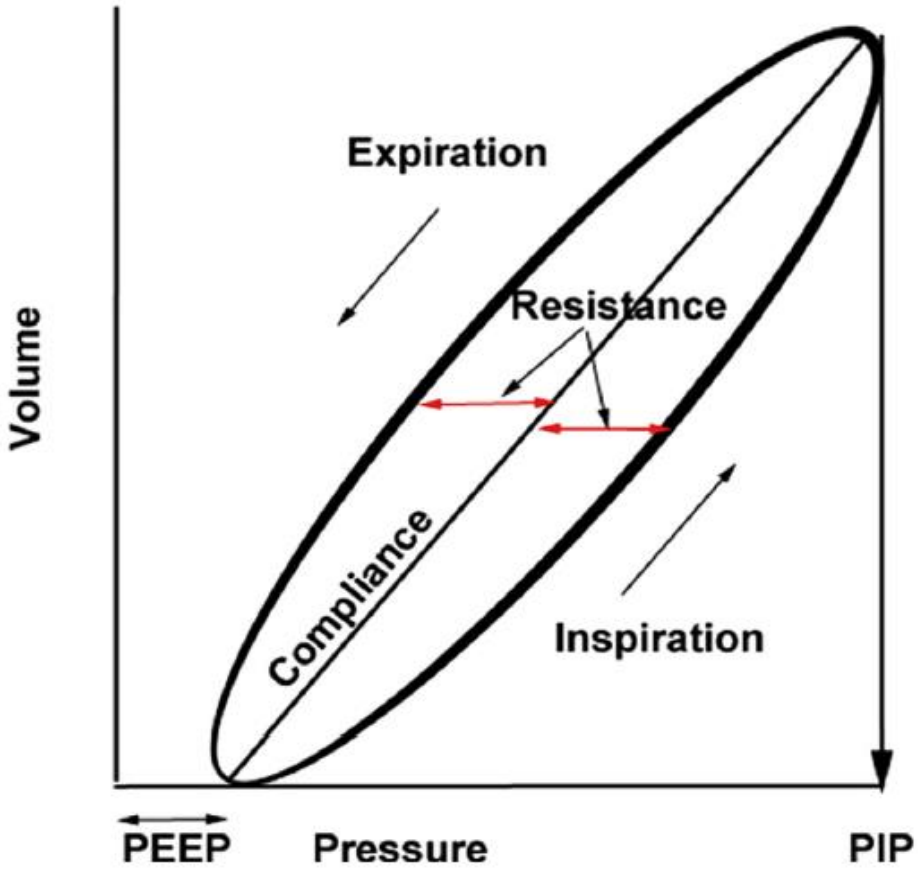
Basic graphics

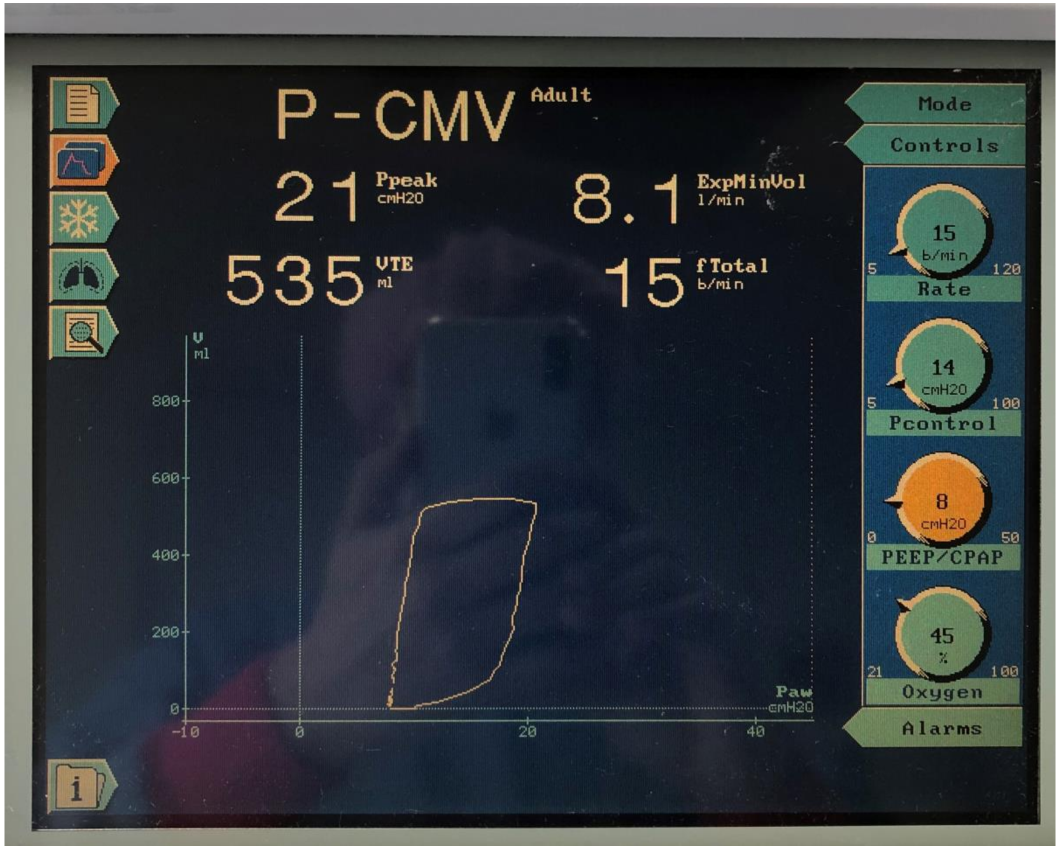
- Three scalars
  - Volume-time
  - Pressure-time
  - Flow-time
- Two loops
  - Pressure-volume
  - Flow-volume

Pressure-volume



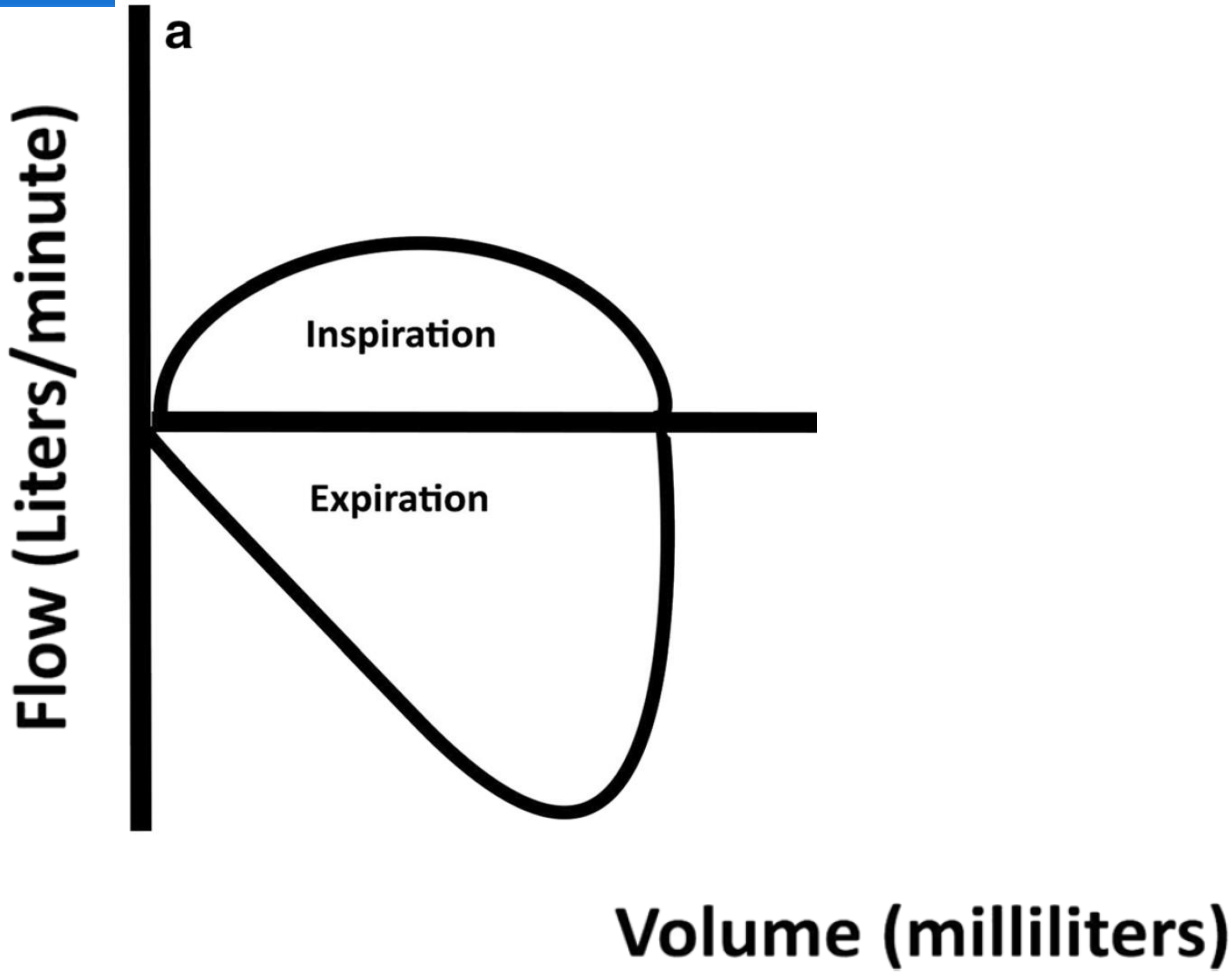
Pressure-volume





Seminars in Fetal & Neonatal Medicine (2015)

Flow-volume


a
Flow (Liters/minute)
Inspiration
Expiration
Volume (milliliters)

Six Steps for Interpretation of Ventilator Graphics

Step	Description/Application
Identify the type of breath.	Volume or pressure.
Differentiate the pulmonary measurements.	The assessment of respiratory mechanics plays a central role in the management of critically ill patients on mechanical ventilation.
Interpret the ventilator plots.	The concept of gentle ventilation, or avoiding ventilator-induced lung injury, has made analysis and careful monitoring of pressure-volume and flow-volume plots an integral part of optimal care management.
Identify display images of the common modes of mechanical ventilation.	All modes can be divided into 1 of 3 control variables: pressure, volume, or time; the vast majority of modes are either volume control or pressure control.
Interpret inspiratory and expiratory graphics.	Graphical displays are informative in assessing the adequacy of ventilatory support provided.
Identify signs of asynchrony.	Asynchrony is disharmony in the patient–ventilator interaction, which can lead to deleterious effects; clinicians must be able to identify and understand asynchrony so that necessary interventions can be performed to optimize patient care.

Volume-control ventilation

Time triggered, Flow limited, Time cycled Ventilation

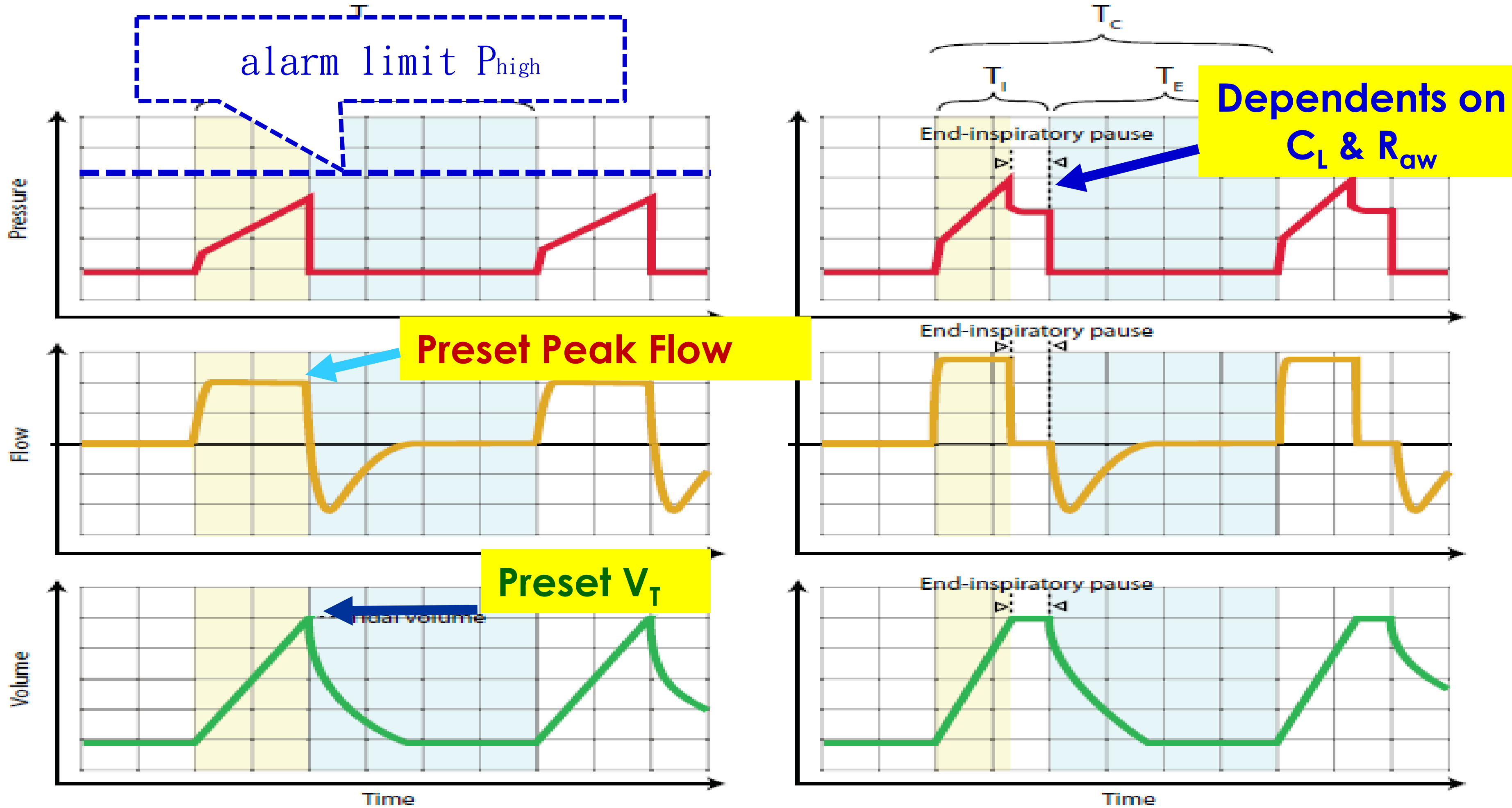


Figure 5.8 Volume-controlled inflation.

Pressure-control ventilation

Time Triggered, Pressure Limited, Time Cycled Ventilation

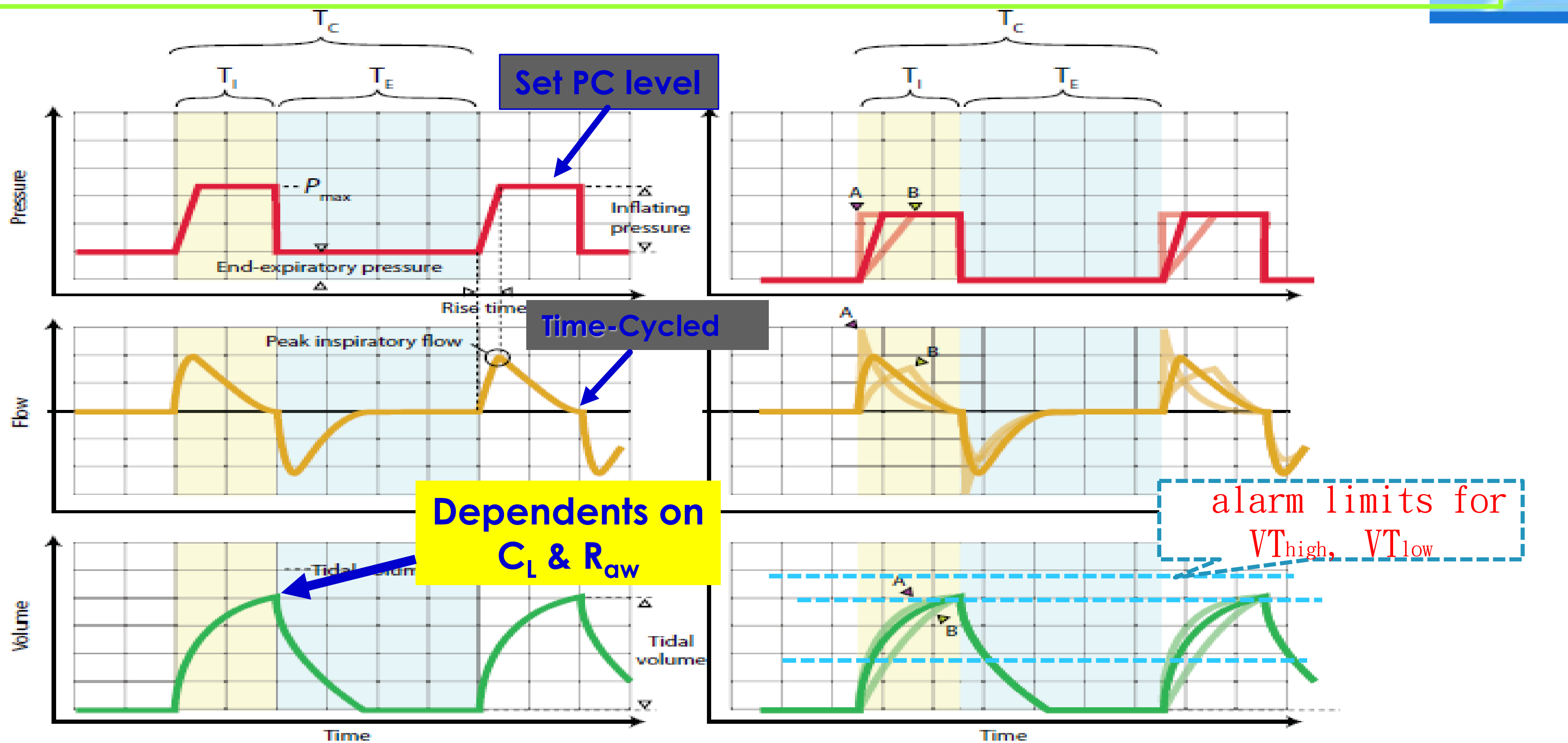
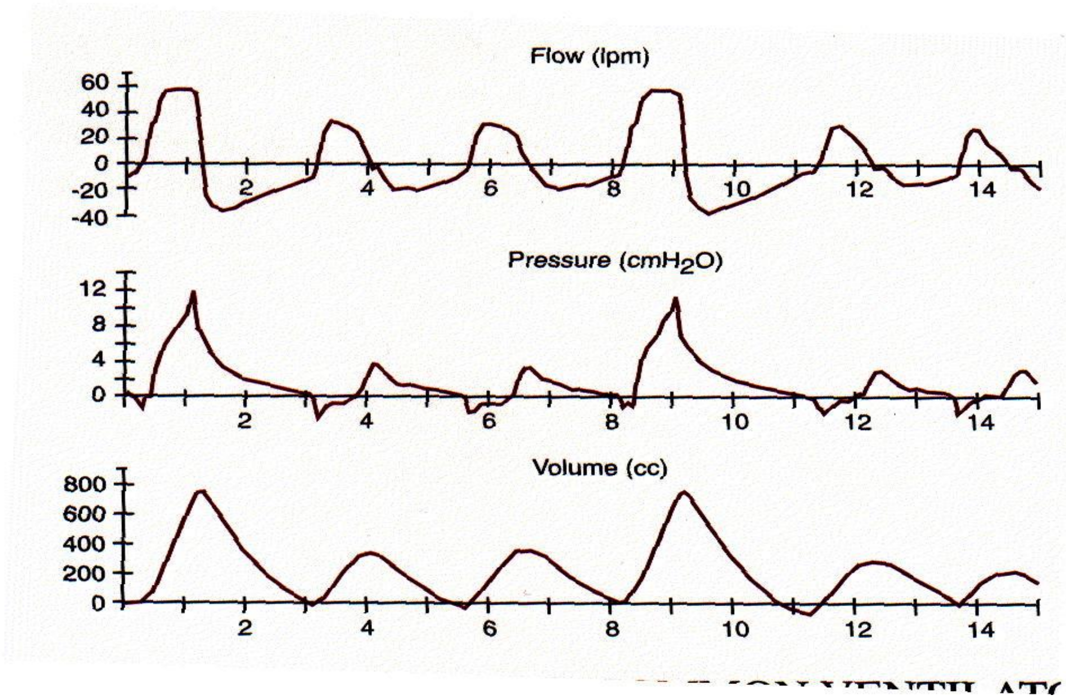


Figure 5.10 Pressure-controlled inflation.

同步間歇強制通氣(SIMV)

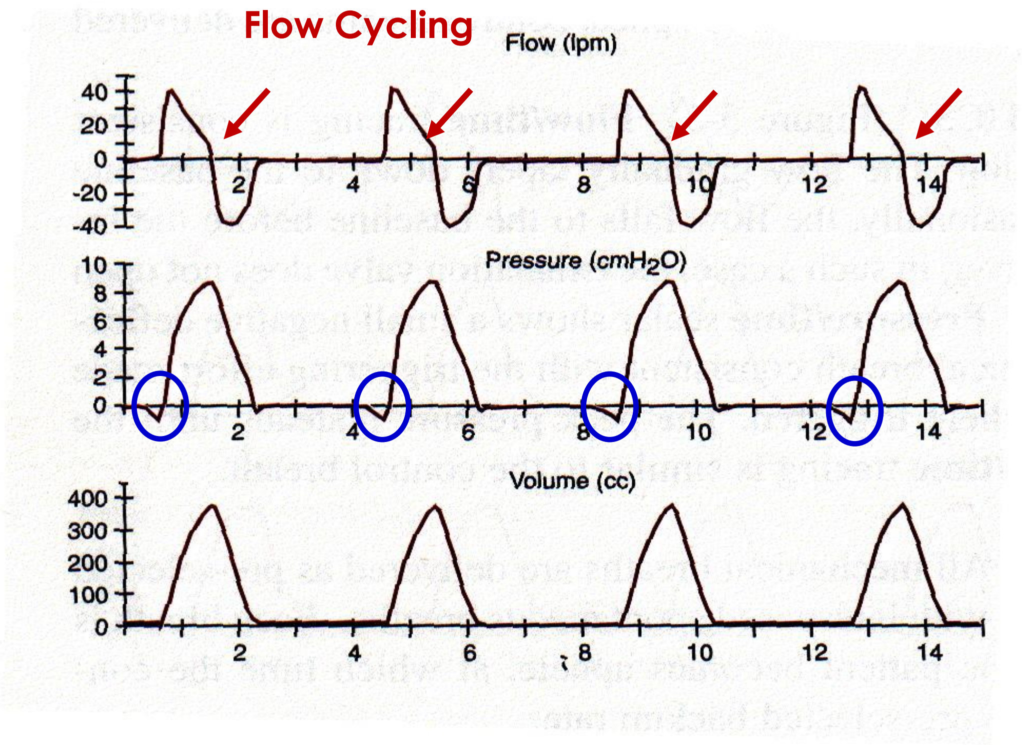
預先設定強制換氣的容積或壓力及頻率，強制換氣時有等待時間以達同步作用，兩次強制換氣中，病人可經由呼吸器自行呼吸。



壓力支持通氣
Pressure support ventilation

P’t Triggered, Pressure Limited, Flow Cycled Ventilation

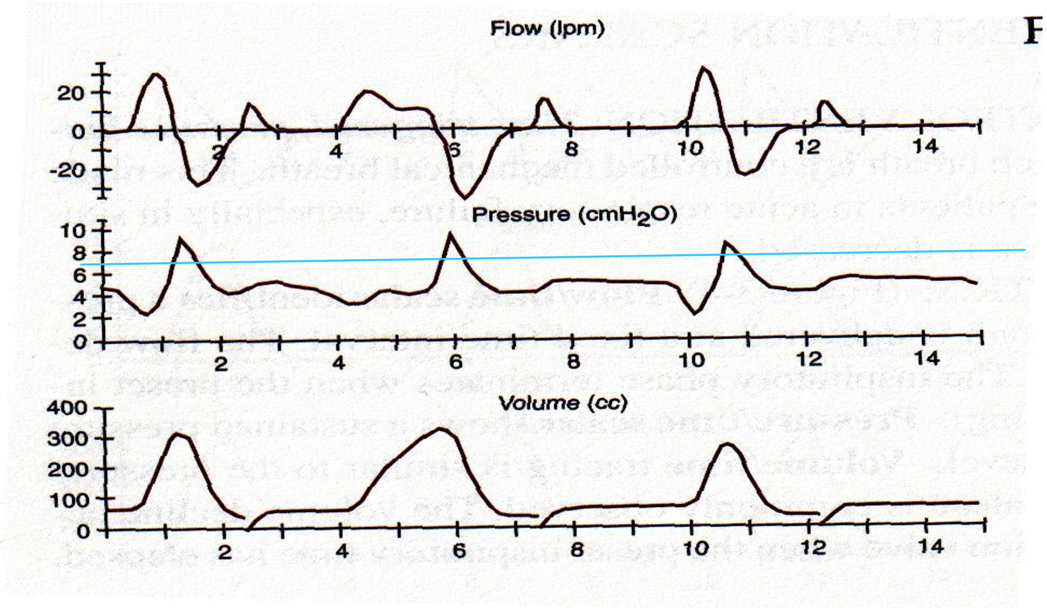
- 每次呼吸均由病人驅動，由呼吸器提供一設定壓力支援可以克服氣道阻力，降低呼吸做功；常用于呼吸器脫離時。
- 較為舒適。
- 不適用于病人無自主呼吸或使用鎮靜麻醉藥物。
- 無法保證潮氣容積。



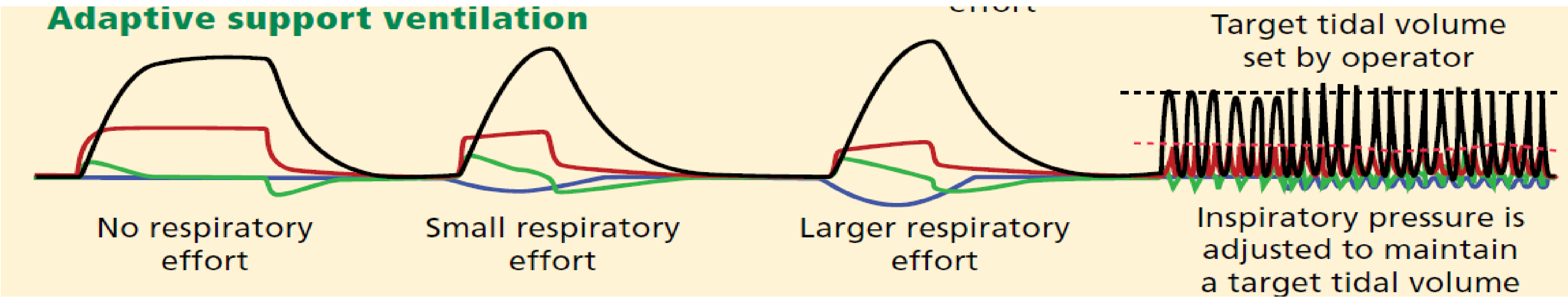
持續氣道正壓
Continuous positive pressure ventilation

P't Triggered, Pressure Limited, Pressure Cycled Ventilation

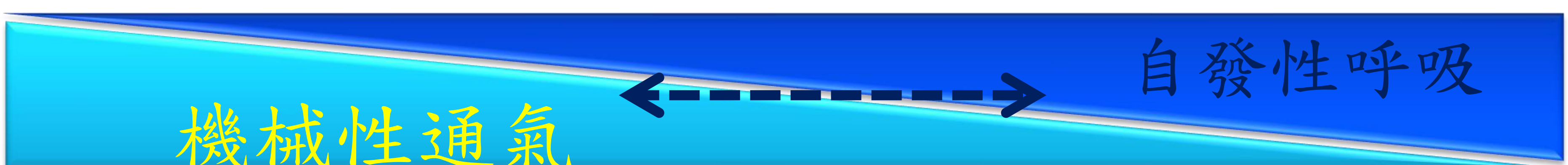
- 病人完全自主呼吸，呼吸器只提供連續氣流，維持呼吸道保持高於大氣壓的預設壓力。
- 增加FRC改善肺部之氣體交換作用。
- 適用- 有正常的換氣能力，但肺的氧合作用不好，如：肺塌陷不良，需PEEP來改善病人的氧氣。



適應性支持通氣
Adaptive support ventilation



- 每分鐘肺泡通氣量為目標的基礎上自發性呼吸
  - –呼吸器計算呼吸做功最小之最佳的呼吸頻率。
  - –自動適應不斷變化的病人肺力學
  - –減少人員操控機器
  - –提高了同步性，並自動脫離呼吸機。



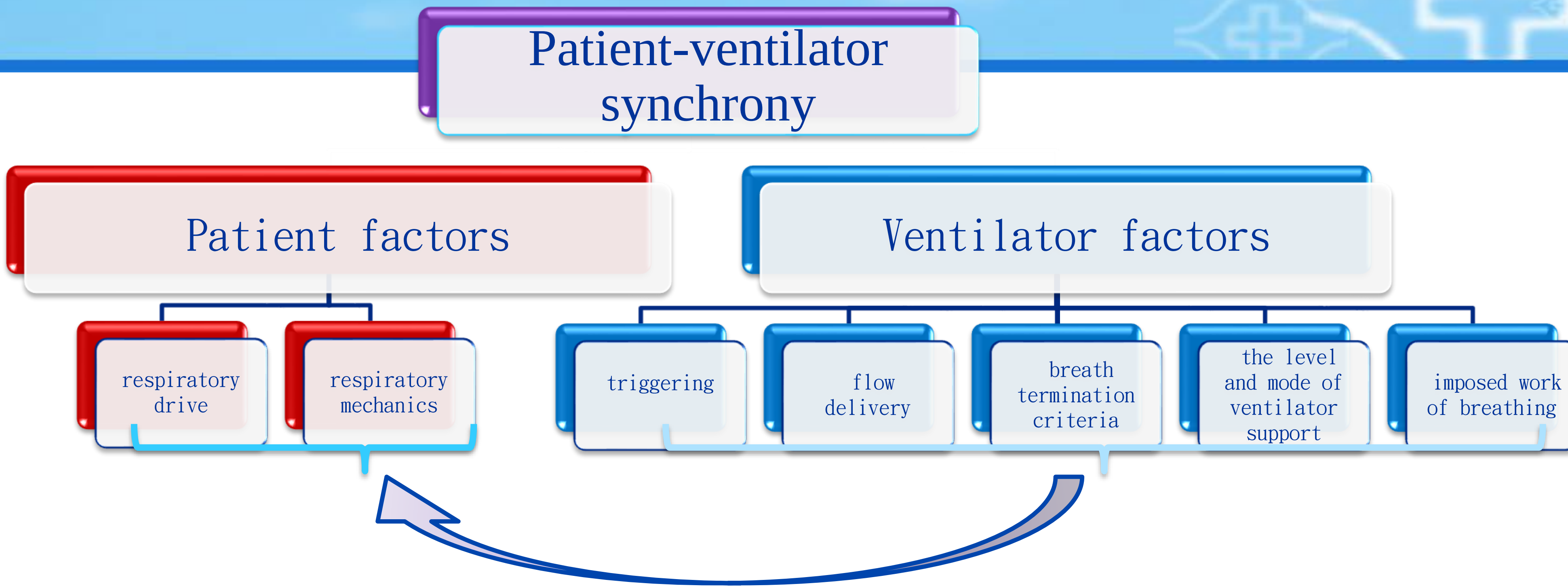
The evolution of ventilation modes

Conventional ventilation modes	➢ Controlled mechanical ventilation (CMV) ➢ Assist-control mechanical ventilation (A/CMV) ➢ Synchronized intermittent mandatory ventilation (SIMV or IMV) ➢ Pressure support (PS) ➢ CPAP
Advanced ventilation modes	➢ Mandatory Minute Volume Ventilation(MMV) ➢ Biphasic positive airway pressure(BiPAP) ➢ Airway pressure release ventilation (APRV) ➢ High-frequency ventilation (HFV)
Closed loop ventilation	➢ Pressure-regulated volume control (PRVC) ➢ Adaptive support ventilation (ASV) ➢ Volume support / Automatic Pressure Ventilation(APV) ➢ Proportional Assisted Ventilation(PAV) ➢ ….

模式沒有好壞！看如何運用！！

Patient-Ventilator interaction

Patient-Ventilator interaction



呼吸器調整符合病人的需求

- 操作者調整
- 自動化調整
- 智能化調整

Patient-ventilator asynchrony

- Patient focus, ventilator meet patient requirement
- Right tool for the right job
  - no one "tool" (ie, set of ventilator parameters) satisfies the needs of different patients
- Sedation and neuromuscular blocking agents should not be used routinely to improve patient-ventilator synchrony

Complication of Patient-ventilator asynchrony

- Increased sedation needs
- Increased work of breathing
- Ventilation-perfusion mismatch
- Increased dynamic hyperinflation
- Increased length of mechanical ventilation
- Increased length of stay
- Increased mortality

Asynchrony Related to Trigger

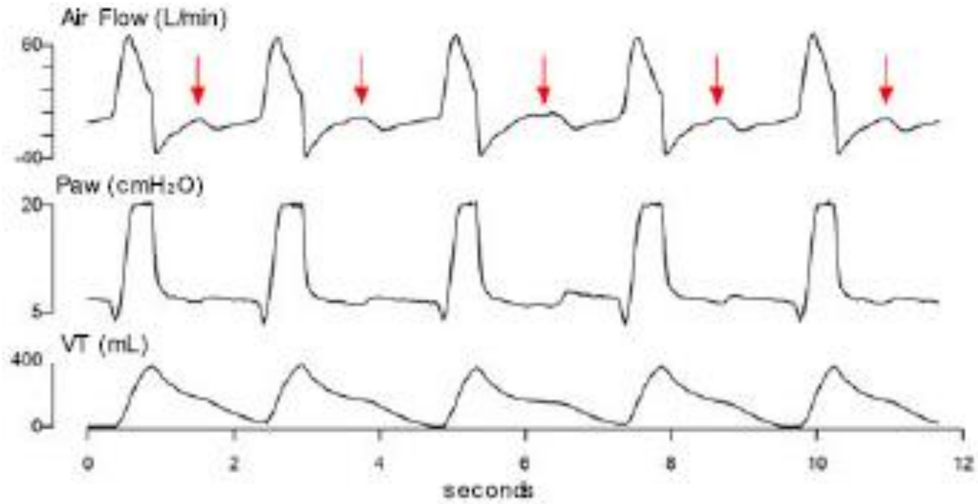
- Ineffective triggering
- Double triggering
- Auto-triggering
- Reverse triggering

Ineffective triggering

- Patient attempts to initiate a breath but the trigger threshold is not reached
- Ineffective triggering
  - increases patient WOB
  - result in respiratory muscle fatigue
  - increased duration of mechanical ventilation
  - increased weaning failure

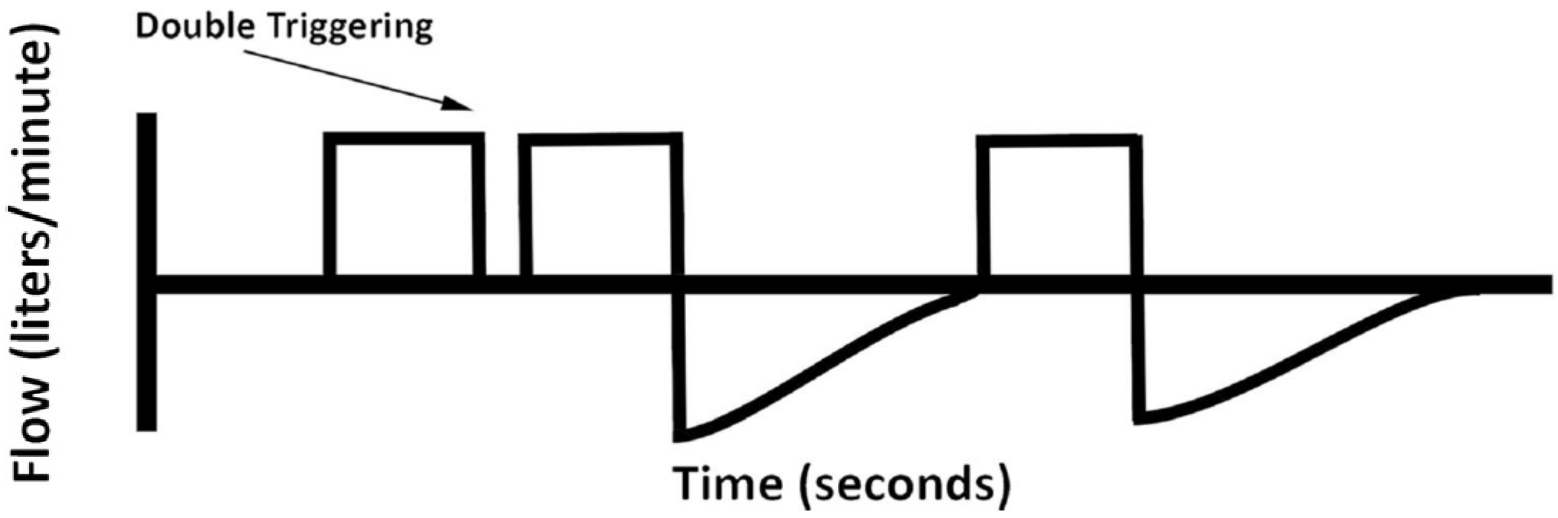
Causes of ineffective triggering

- Improper triggering threshold
- Airtrapping (auto-PEEP)
- Muscle weakness
- Low respiratory drive
- Oversedation



Double triggering

- Second breath being triggered immediately after the first
- Patient receives double V_T with risk of lung over-inflation

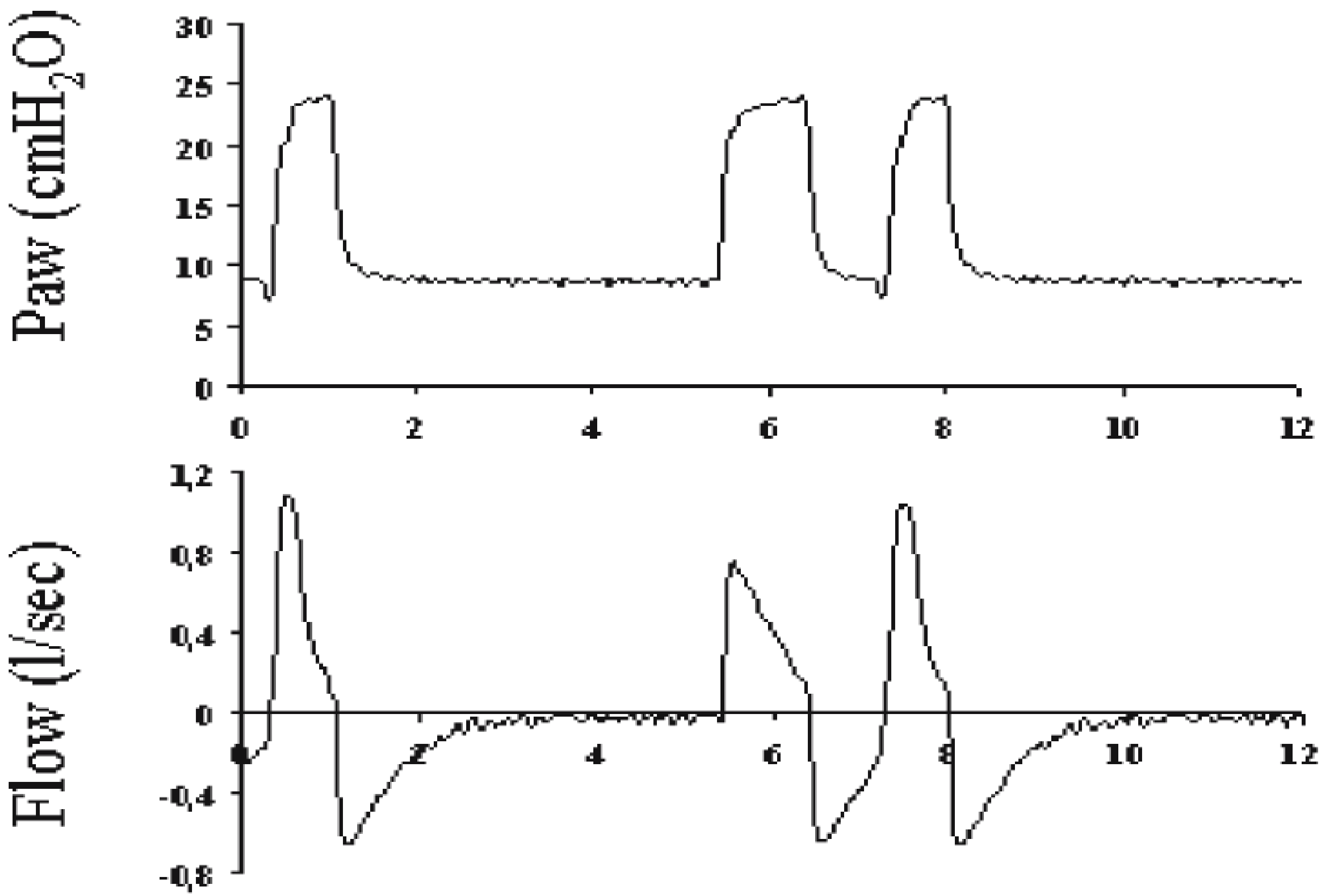


Causes of double triggering

- High patient ventilatory demand
- Inappropriate cycle threshold set
  - V_T too small
  - inspiratory time too short
  - flow-cycle threshold too high
- Troubleshoot:
  - Match patient inspiratory demand
    - increase inspiratory time
    - increase tidal volume

Auto-triggering

- Multiple breaths delivered by the ventilator
- Causes
  - Air leaks in the system
  - Inappropriately set trigger sensitivity
  - Condensation in the ventilator tubing
  - Detection of cardiac movement



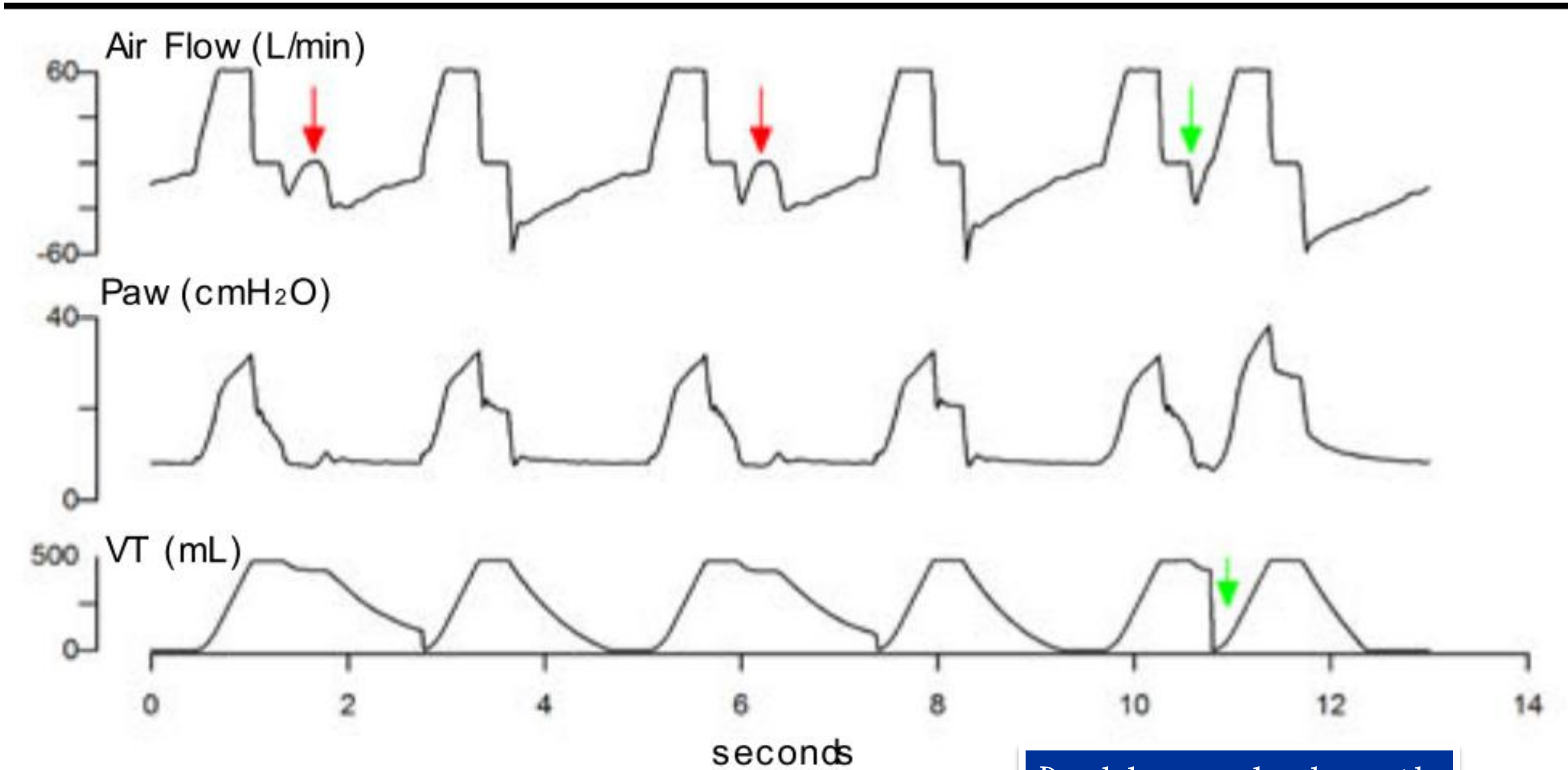
Intensive Care Med (2006)

Reverse triggering

- Frequently under-recognized
- Passive insufflation of the lungs activates the patient' s neurological respiratory center trigger respiratory muscle contractions
- Main occur in patients with acute respiratory distress syndrome or diagnosed of brain death

Intensive Care Medicine Experimental 2019

Reverse triggering



Double cycle breath

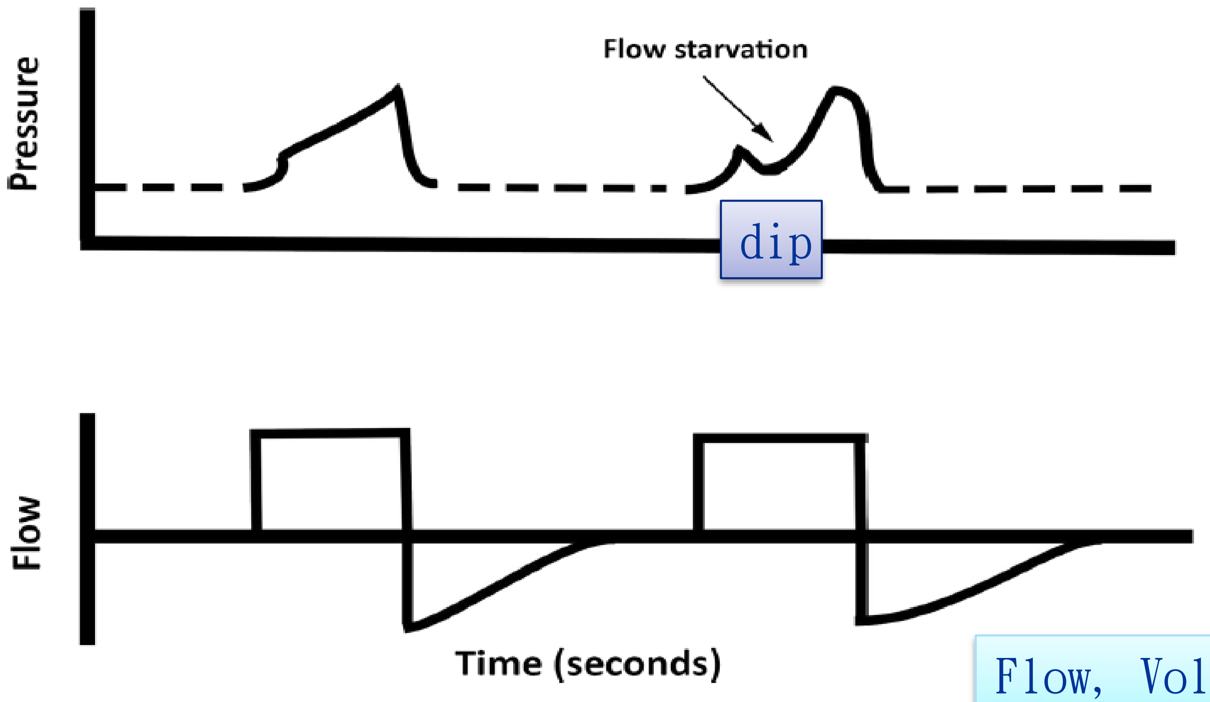
Reverse triggering

- Reverse triggering could be associated with lung or diaphragm injury
  - stretching in the dependent lung equivalent to apply 15 ml/kg tidal volume

- Mechanisms poorly understand
  - the best treatment remains to be determined

Asynchrony Related to Flow

- Flow starvation
  - flow from ventilator unmet the patient need



Flow, Volume no change

Current Pediatrics Reports (2021)

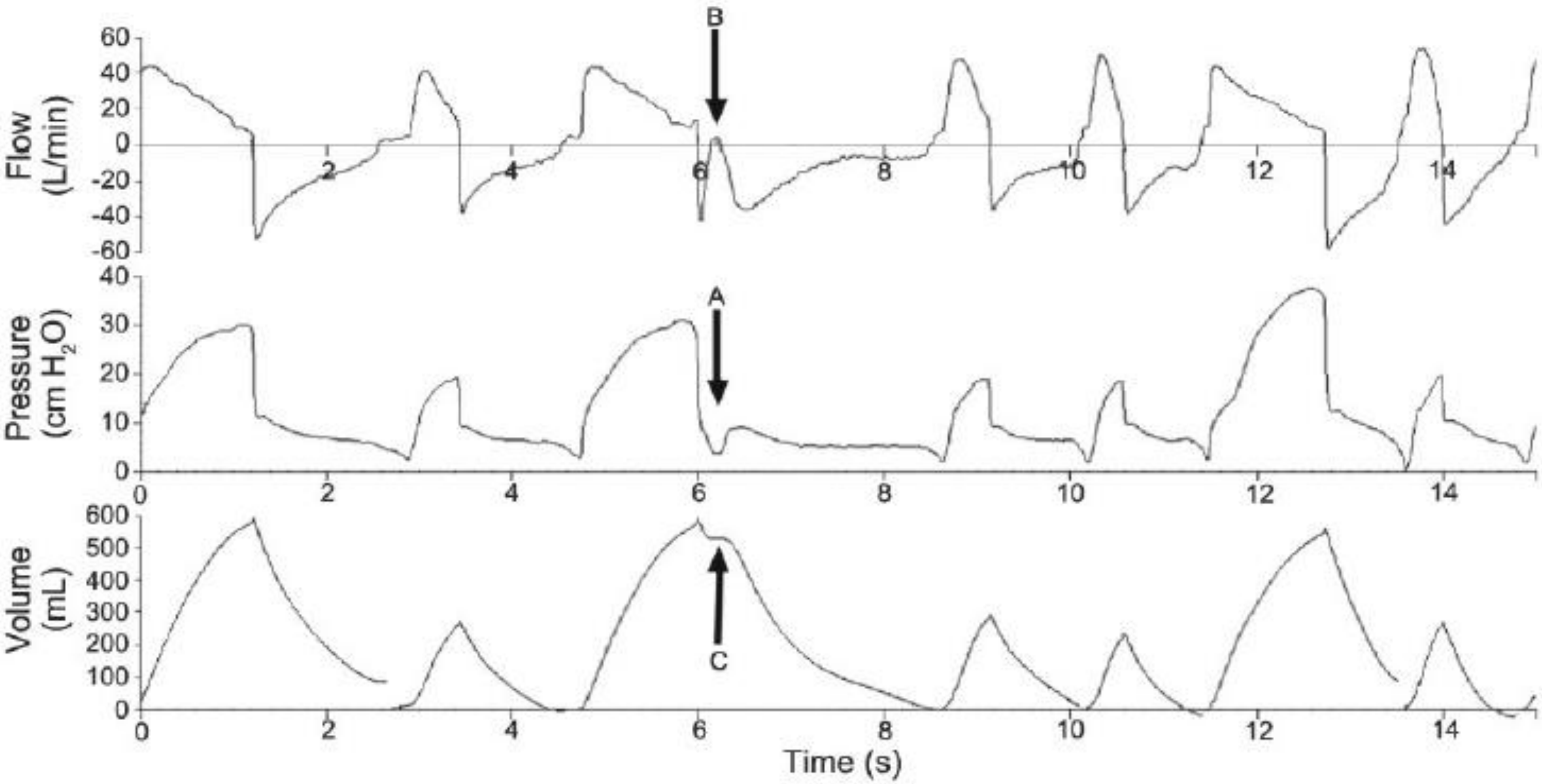
Asynchrony Related to Flow

- Cause
  - inadequately set flow on the ventilator
  - more often in modes with constant flow (volume control modes)
- Troubleshoot
  - increase the set flow
  - change to non-constant flow pattern

Asynchronies Related to Cycling

- Related to the inspiratory time either being too short or too long
  - premature and delayed
- Premature cycling
  - Ventilator stops before patient’s inspiratory effort finish
  - an additional upward deflection after inspiration on the flow-time scalar

Premature cycling

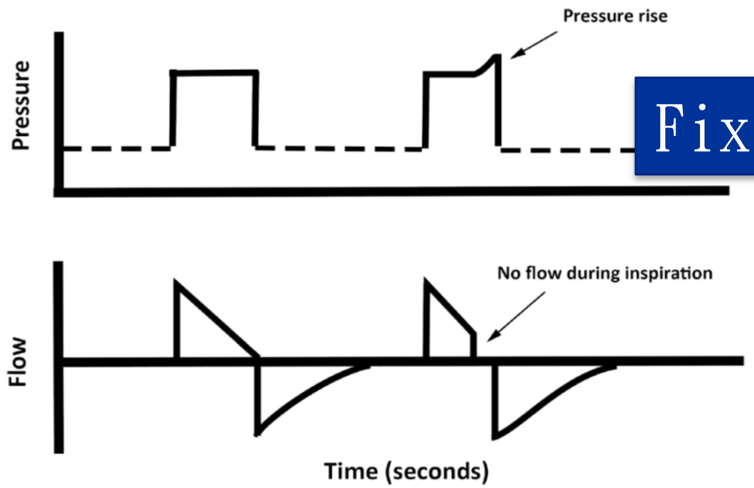


Fix: changes to the delivered flow or inspiratory time

r Care 201

Delayed cycling

- Patient trying to exhale while inspiration is still occurring
  - rise in pressure at the end of the pressure – time
  - a period of zero flow during inspiration



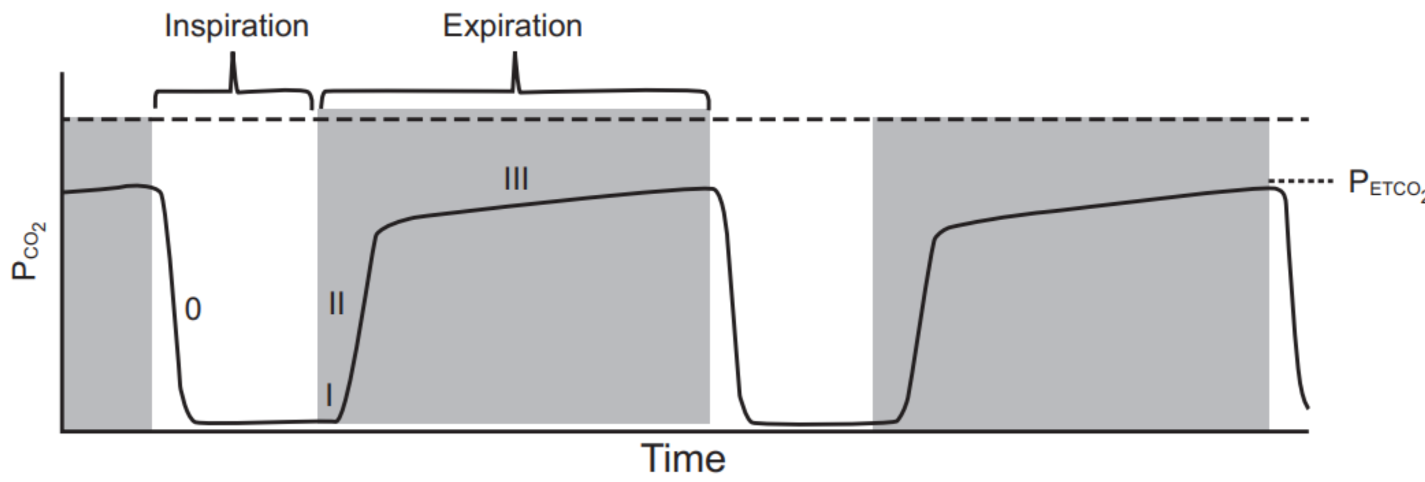
Fix: adjust the flow rate or inspiratory time

Others for clinical care

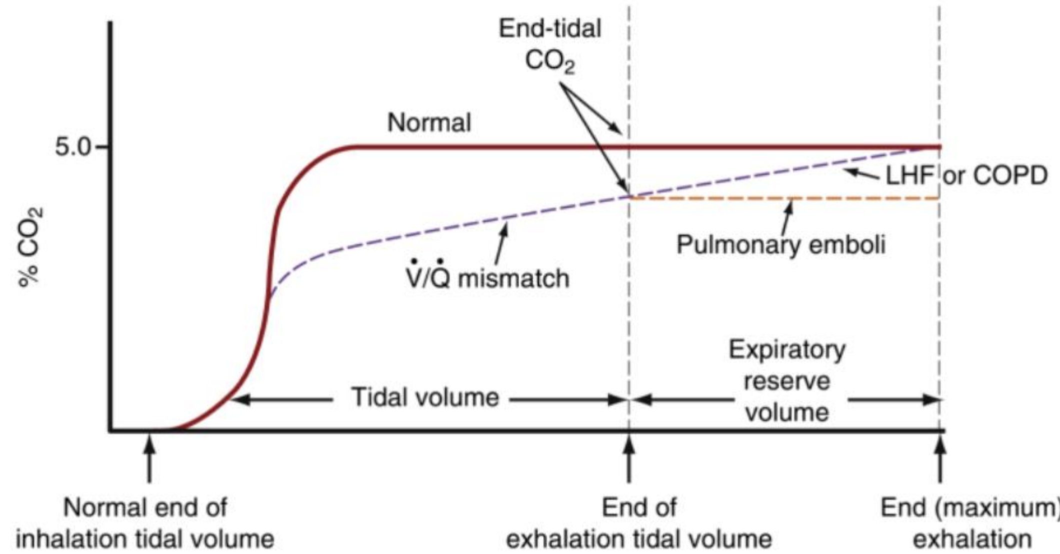
Capnometry

- Pulse oximetry: lack information about ventilation and CO_2 removal
- Disadvantage of hypercarbia
  - respiratory acidosis
  - cardiovascular collapse

  } Late awareness
- Most common: end-tidal CO_2 pressure ($P_{ET}CO_2$)



Inspiration
Expiration
P_{CO_2}
0
I
II
III
P_{ETCO_2}
Time



End-tidal CO_2
Normal
5.0
% CO_2
LHF or COPD
Pulmonary emboli
$\dot{V}/\dot{Q}$ mismatch
Tidal volume
Expiratory reserve volume
Normal end of inhalation tidal volume
End of exhalation tidal volume
End (maximum) exhalation

Use of capnometry

- Ensure adequate ETT placement
- Detect return of spontaneous circulation
- Detect degree of ventilation/perfusion mismatch
- Measure dead space (V_D)
- Detect air-flow obstruction
- Diagnose pulmonary embolism
- Estimate changes in cardiac output

TABLE 19-7

Conditions Associated With Changes in $PETCO_2$

Change	High $PETCO_2$	Low $PETCO_2$
Sudden	Sudden increase in cardiac output	Sudden hyperventilation
	Sudden release of a tourniquet	Sudden decrease in cardiac output
	Injection of sodium bicarbonate	Massive pulmonary embolism
		Air embolism
		Disconnection of ventilator
		Obstruction of endotracheal tube
		Leakage in the circuit
Gradual	Hypoventilation	Hyperventilation
	Increase in CO_2 production	Decrease in oxygen consumption
		Decreased pulmonary perfusion

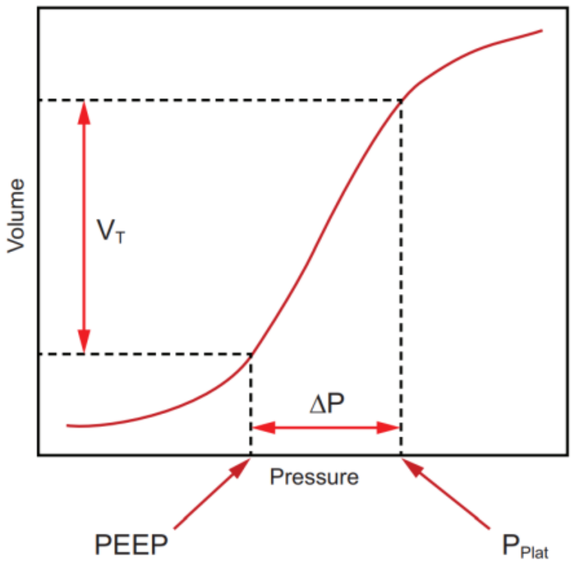
Note: An absent $PETCO_2$ means that a system leak, esophageal intubation, or cardiac arrest has occurred.

Clinical application

- Time capnography
  - detect respiratory insufficiency
    - during procedural sedation
    - postoperative period
  - In MV patients
    - ensure adequate ETT placement and provide an approximation of V_D
- Volumetric capnography
    - further research is needed to define its diagnostic value and its potential utility for guiding therapy

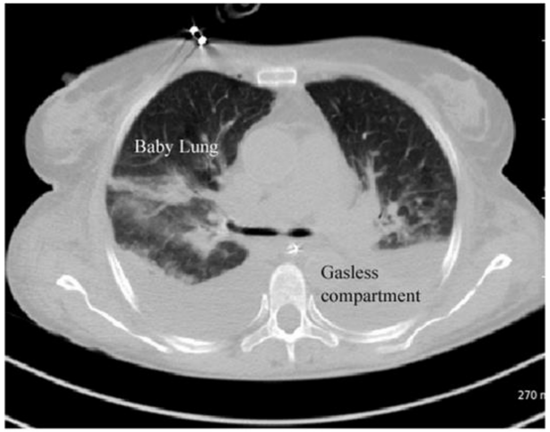
Driving Pressure

- Driving pressure: stress applied to the lungs
- Driving pressure: $\triangle P = V_T/C_{RS}$
- Difference between plateau pressure (P_{plat}) and PEEP



Respiratory Care 2020

- In ARDS, lungs damage is heterogeneous
  - baby lung
  - delivered positive-pressure breath prefer to healthier regions
  - normal V_T may produce excessive regional dynamic and static strain

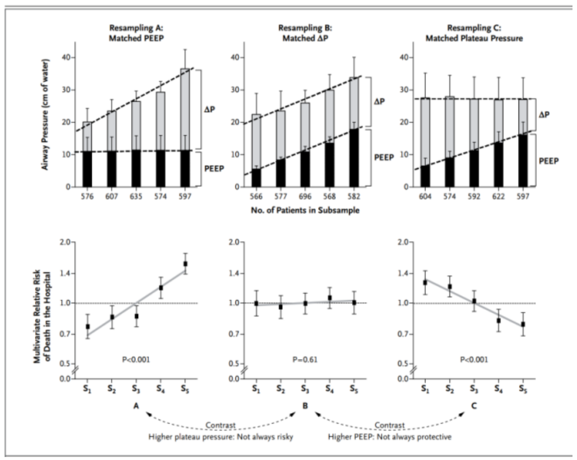


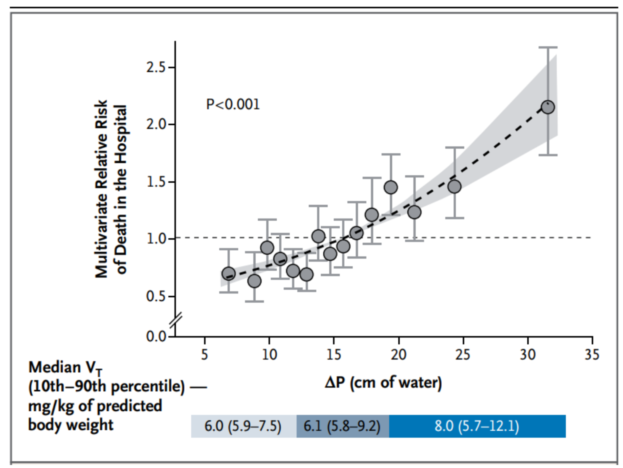
SPECIAL ARTICLE

Driving Pressure and Survival in the Acute Respiratory Distress Syndrome

Marcelo B.P. Amato, M.D., Maureen O. Meade, M.D., Arthur S. Slutsky, M.D.,

retrospective re-analysis





Driving pressure was more strongly associated with survival than V_T, Pplat, or PEEP

Barotrauma and mortality increased at driving pressures > 15 cm H_2O

N Engl J Med 2015;372:747-55

Clinical application

- Driving pressure means the stress of lungs
- Monitor driving pressure ensure patients not be excessively ventilated
- No prospective clinical trials performed

Conclusions

Conclusions (1)

- Recognize ventilator graphics can be useful in
  - improve patient–ventilator synchrony
  - reduce WOB
  - improve patient comfort
  - decrease mortality；improve outcomes

Conclusions (2)

Table 1. Factors Contributing to Asynchrony

Patient-related/ physiological	**Disease-related**	**Ventilator-related**
• Anxiety • Pain • Fever • Delirium	• High resistance (e.g., COPD) • Low compliance (e.g., ARDS) • Auto-PEEP (e.g., COPD) • Decreased/ Increased respiratory drive due to central and neuromuscular problems	Inappropriate ventilator settings of trigger, rise time, level of pressure support, cycling, inspiratory flow, respiratory rate, tidal volume, inspiratory time, etc.

Thanks for your attention!!