DESIGN PRINCIPLES: MECHANICAL VENTILATORS

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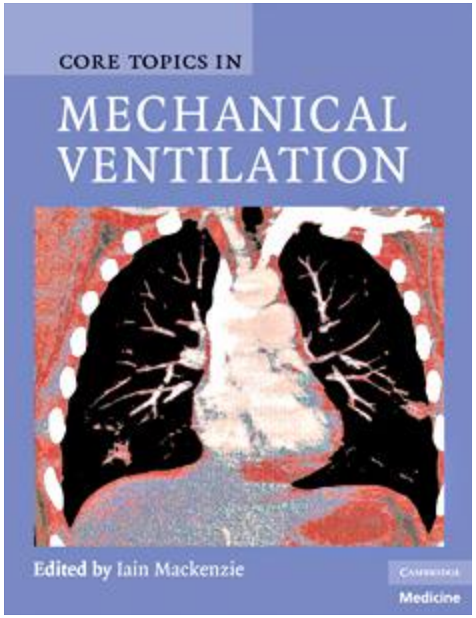
Recommended References

- Iain Mackenzie, *Core Topics in Mechanical Ventilation*, Cambridge University Press, Cambridge, 2008. (ISBN: 978-0521867818)
- Rüdiger Kramme, Klaus-Peter Hoffmann, Robert S. Pozos (Eds.), *Springer Handbook of Medical Technology*, Springer-Verlag, Berlin, 2011. (ISBN: 978-3-540-74657-7)

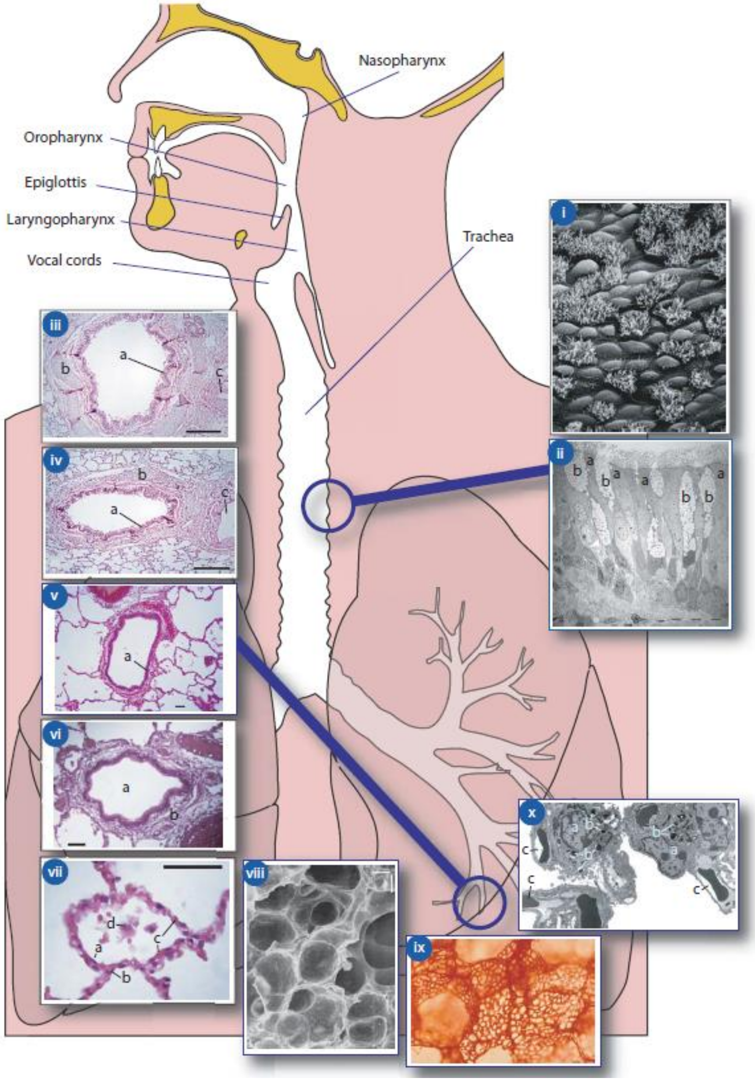


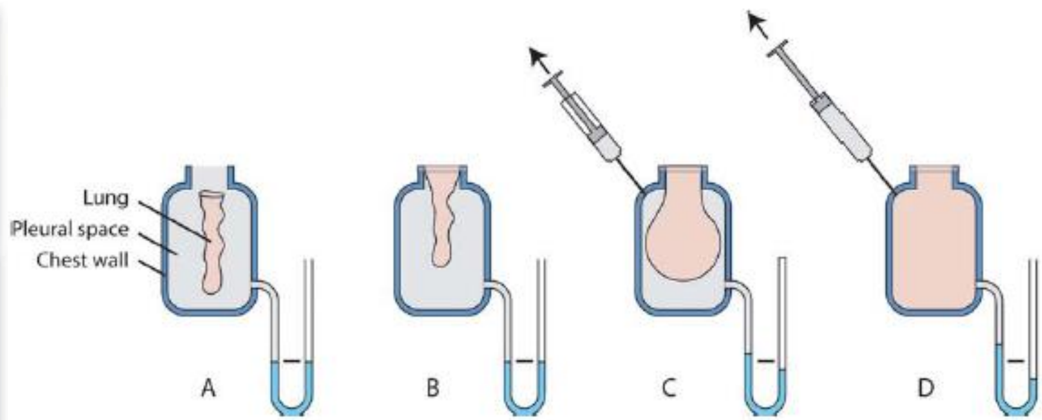
Mechanical Ventilator

- A ventilator is a life-sustaining device that supports or replaces spontaneous breathing of the patient

Reason for ventilation	Examples of possible causes
Functional limitations of the respiratory musculature	Due to a muscular injury or paralysis
Pathophysiological changes to the respiratory system and/or pulmonary tissue	Due to increased airway resistances or to a reduced lung compliance
Disruptions to respiratory mechanism	In case of thorax injuries
Disruptions to gas exchange/diffusion	Through the accumulation of pulmonary liquid or changes to the alveolar membrane
Disorders of the respiratory drive	Due to neurological disruption, cranial illness or injury

Anatomy of Respiratory Tract

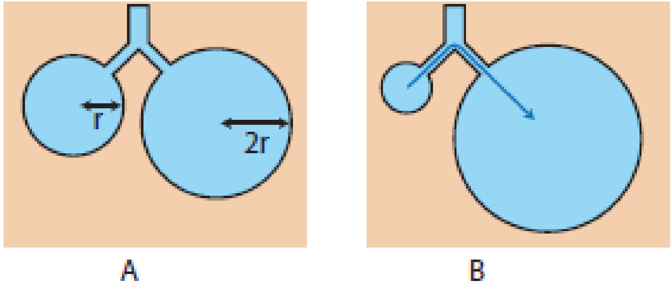




Surface Tension Forces within the Lung

- The pressure within a truly spherical alveolus (Pa) would normally be calculated as twice the surface tension (*Ts*) divided by the alveolar radius (r):

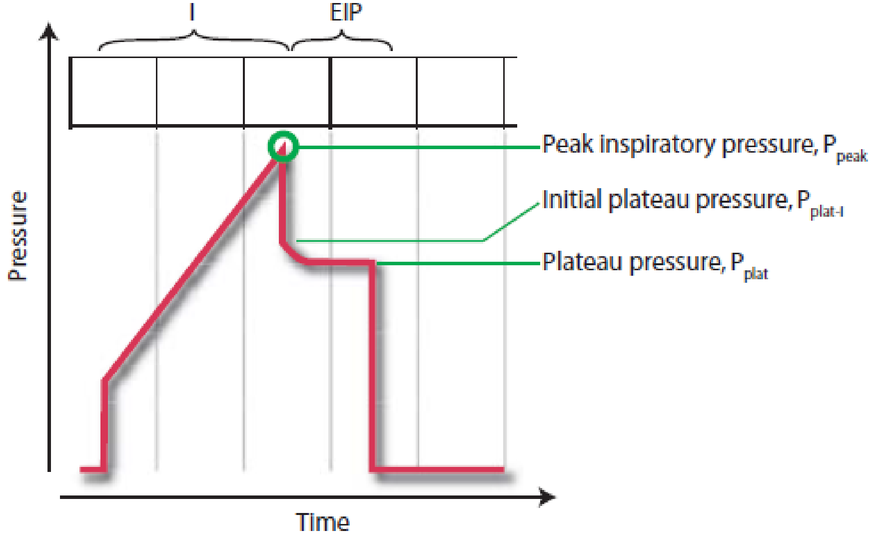
$$\boxed{P_A = \frac{2 \times T_s}{r}.}$$

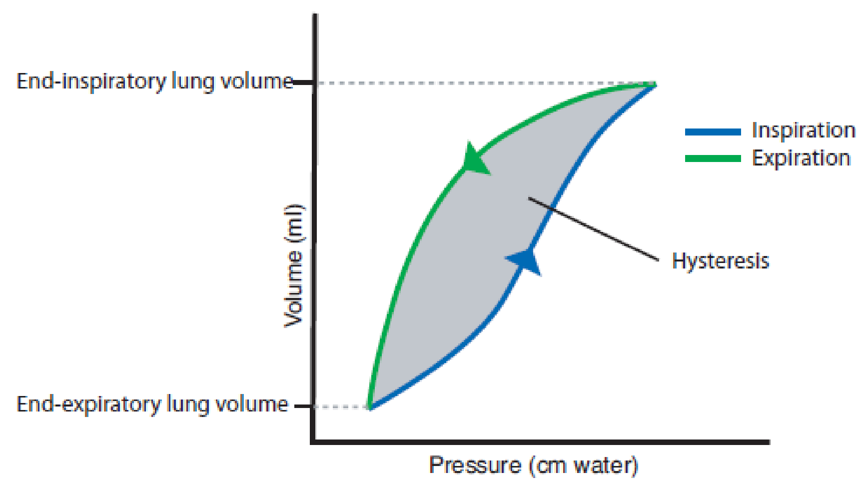


  - If *Ts* is constant, all of the alveoli in a lung would empty into one huge alveolus!
  - Fortunately, surface tension is *not* constant: surfactant reduces the surface tension in proportion to the change in the surface area
    - The smaller the surface area of the alveolus, the greater the reduction in surface tension
    - Gas flows from larger to smaller alveoli

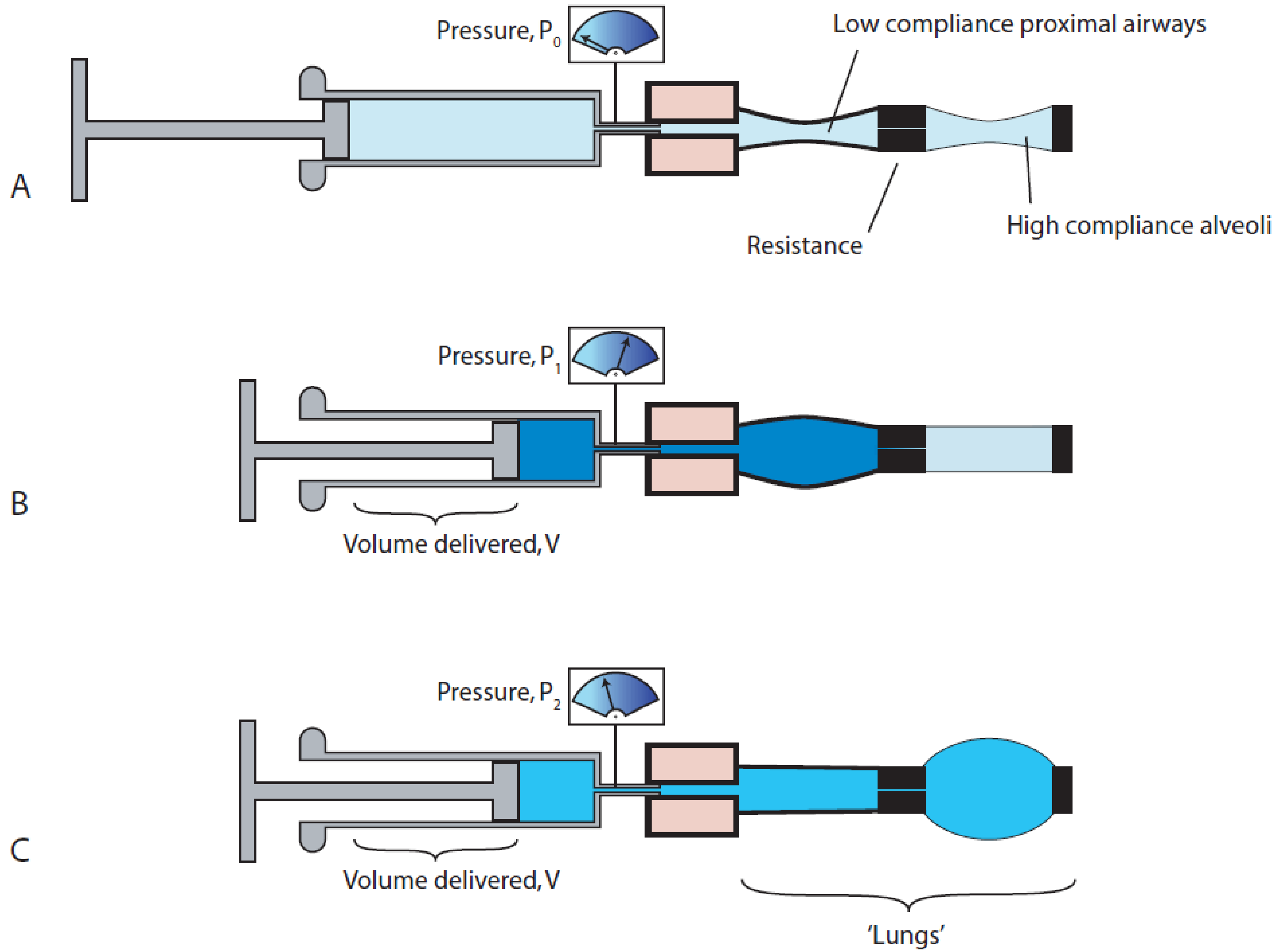
Lung Compliance

- The ‘expandability’ of the lung is known as its compliance.
  - A high compliance means that the lung expands easily
  - Compliance is generally given by Volume/Pressure
- For a delivered tidal volume of V mL:
  - Dynamic compliance is given by V/P_{peak}
  - Static compliance is given by V/P_{plat}



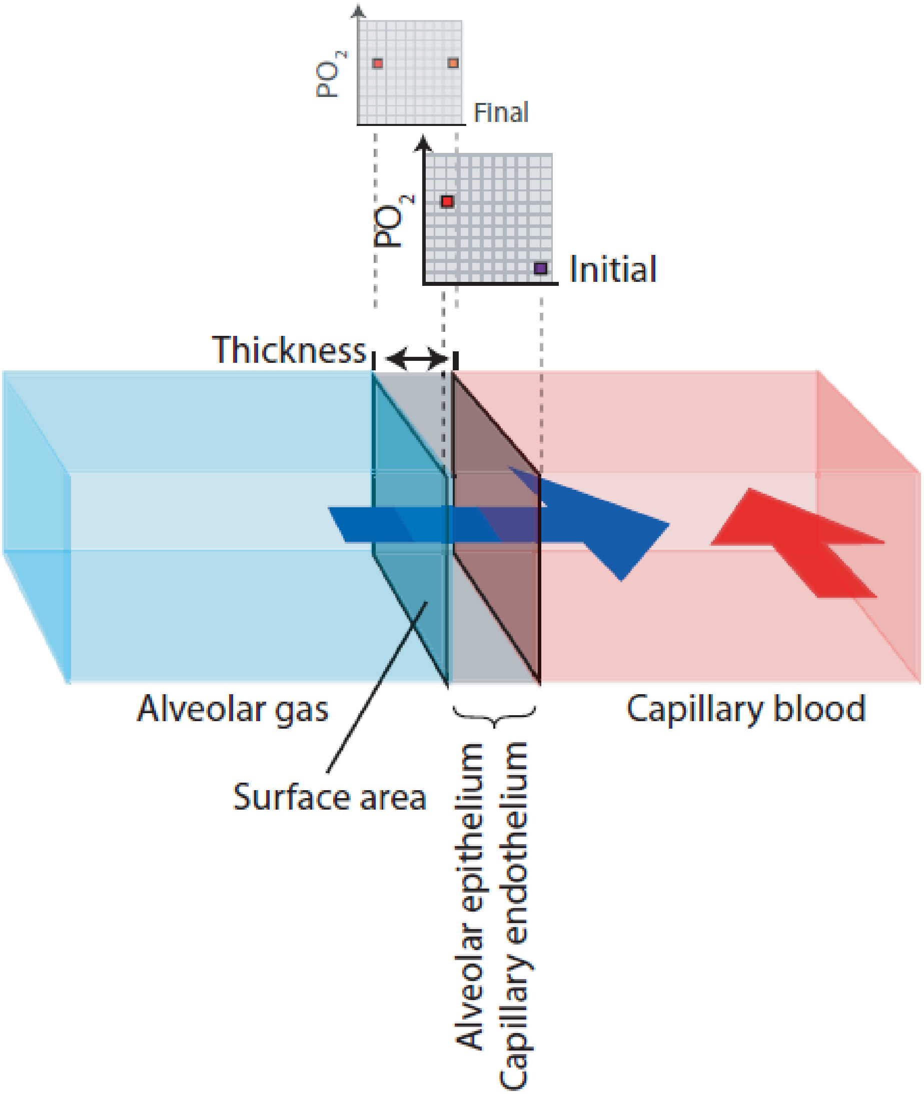


Two-Compartment Model of Static and Dynamic Compliance



Gas Exchange

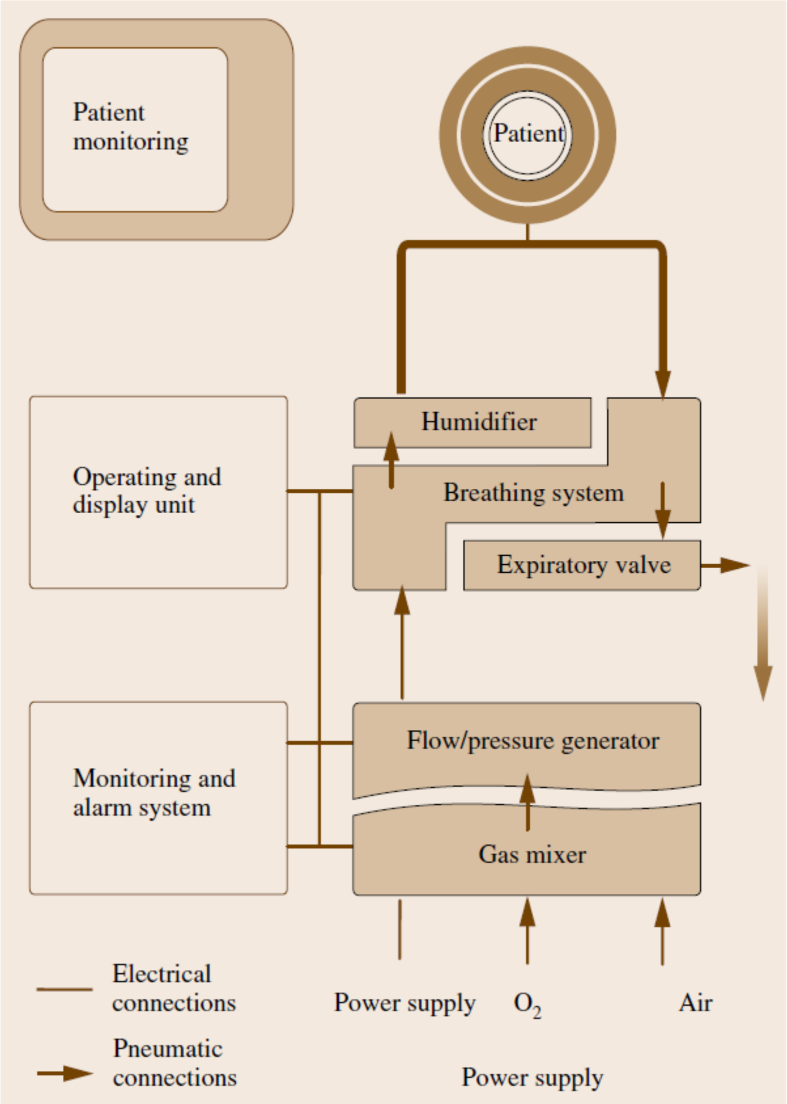
- Speed of diffusion is determined by:
  - partial pressure gradient
  - thickness of barrier
  - solubility of oxygen in barrier
- Contact time is inversely proportional to the cardiac output
  - At rest is normally 0.75 s
  - At sea level, only 0.25 s is needed



Ventilator Tasks

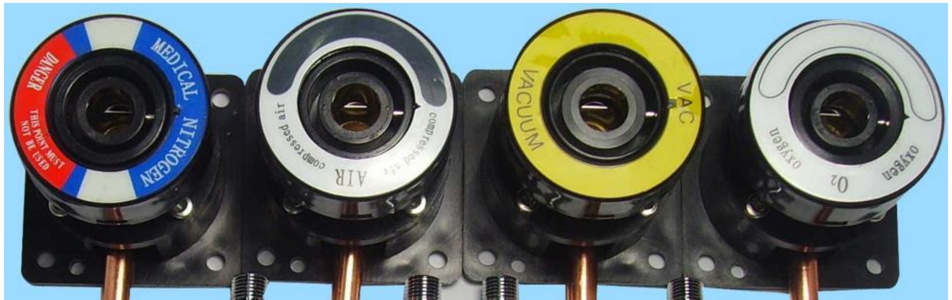
- Oxygenation of the patient
  - Provide and supply the patient with a mixture of oxygen and air
- Partial or total assumption of respiratory work
  - Generate and dose defined gas flow and respiratory pressure
- Monitoring of the device and patient
  - Generate alarms and visualize changes

Functional Block Diagram



Power Supply

- Ventilators require electric power, oxygen, and compressed air
  - Usually supplied via external power source as well as via hospital's central gas supply (with supply pressure of approximately 3–6 bar)
- In areas without central gas supply or during transportation of patients within the hospital, it is necessary to ensure the functioning of the device by other means
  - Potential solutions include the use of separate compressors, compressed gas cylinder packs, and accumulators
- Increasingly, ventilators not dependent on compressed air are used
  - Provide ventilation by filtering and using ambient air
  - Only oxygen source and electric power supply are needed to operate



Gas Mixer

- Gas mixer allows the user to vary the oxygen concentration of inspiratory gas between 21% and 100% by volume
  - Mechanical gas mixers (old technology)
  - Electronically-controlled gas mixer integrated in ventilator (standard now)
- Gas mixers usually responsible for ensuring that breathing gas to be supplied is prepared and delivered in required quantity and rate
- It is often the threshold ranges which pose the greatest challenges to these metering systems
  - For volume of 20 ml with an oxygen concentration of 30% by volume, 17.7ml of gas must be delivered via compressed air valve and 2.3ml via oxygen valve

Pressure/Flow Generator

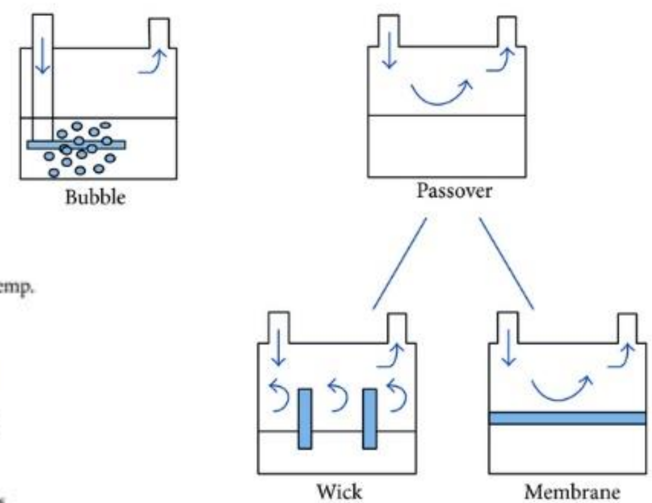
- The pressure or flow generator is responsible for delivering mixed gas prepared by the gas mixer according to selected ventilation parameters
- Flow generator is a controlled valve whose output provides defined gas flow with output pressure is not specified
- Pressure generator behaves similar to compressor, whose output provides defined pressure with unspecified gas flow
  - Often used to drive ventilators not dependent on compressed air that use ambient air for ventilation

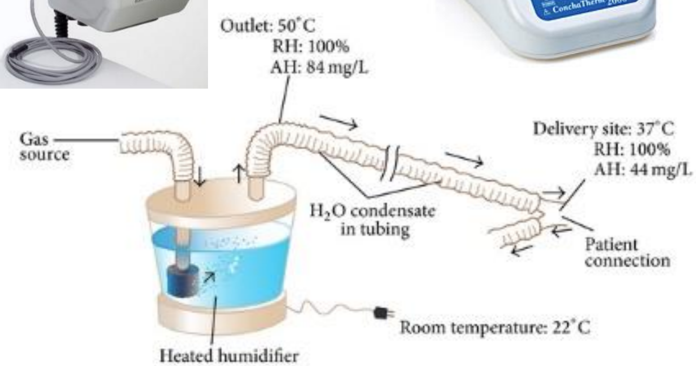
Breathing System

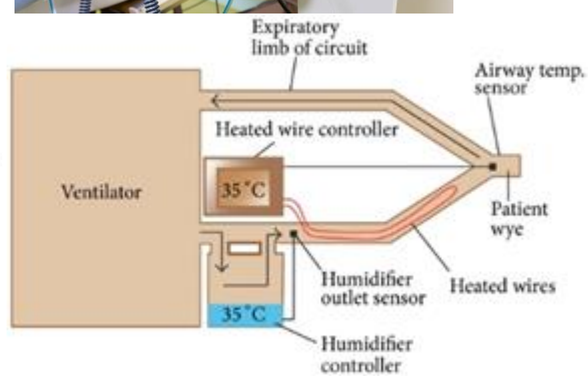
- Breathing system forms interface between patient and the ventilator
- Clinical ventilators are usually connected to patient via inspiratory and expiratory hose (dual-hose circuit).
  - Expiratory valve is closed during the inspiratory phase.
- Gas flow delivered through inspiratory port passes through breathing gas humidifier before entering patient's lungs
  - To make it adapted to climatic conditions in patient's lungs
- After inspiratory phase, patient exhales when expiratory valve is opened
  - Expiratory gas passes through ventilator again, but not reused for following inspiration
- Based on this characteristic, the breathing systems of ventilators are also referred to as non-rebreathing circuits

Gas Humidifier

- Humidifiers are used to warm and humidify inspiratory gas.
  - Dry and relatively cool supply gas would dry out the patient's airways with risk of causing irreversible damage to the ciliated epithelium
- Active gas humidifiers are located in the inspiratory limb and use electrical energy to heat a water bath. When the cold, dry gas passes over the water surface it absorbs water molecules and is thus warmed and humidified
  - Example: Pass-over humidifiers and Bubble-through humidifiers

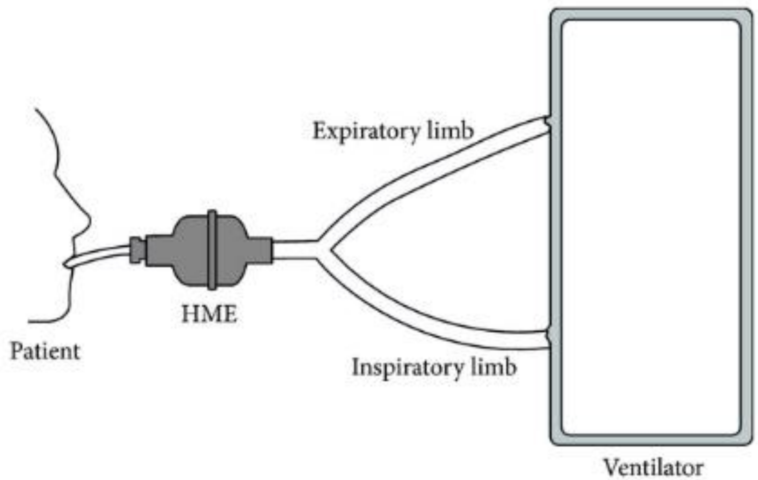


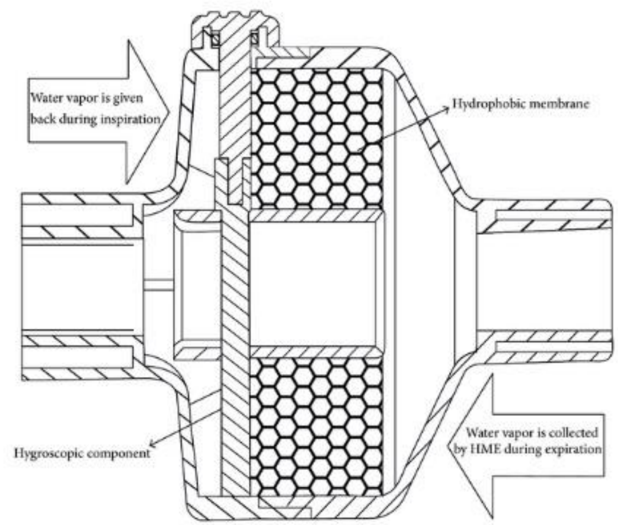




Gas Humidifier

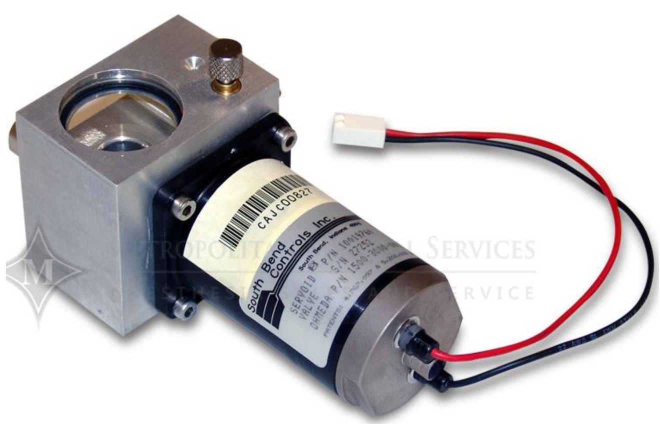
- Passive breathing gas humidifiers, termed heat and moisture exchangers (HMEs), are placed close to patient and designed to buffer significant fraction of moisture and heat expired by patient.
  - Retained moisture is then used to condition inspired gas passing through HME during next inspiration
- Using HME together with active breathing gas humidifier in single breathing circuit is not permitted as it would significantly impair resistance of HME

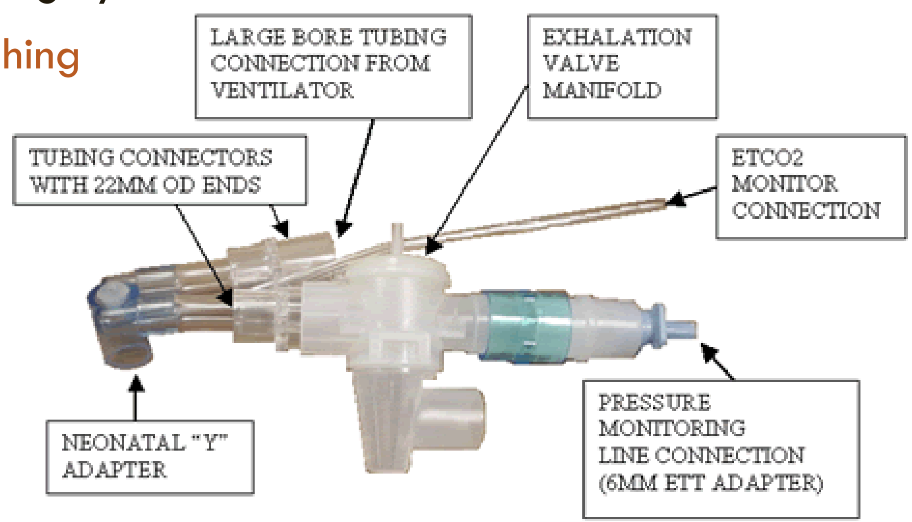




Expiratory (Exhalation) Valve

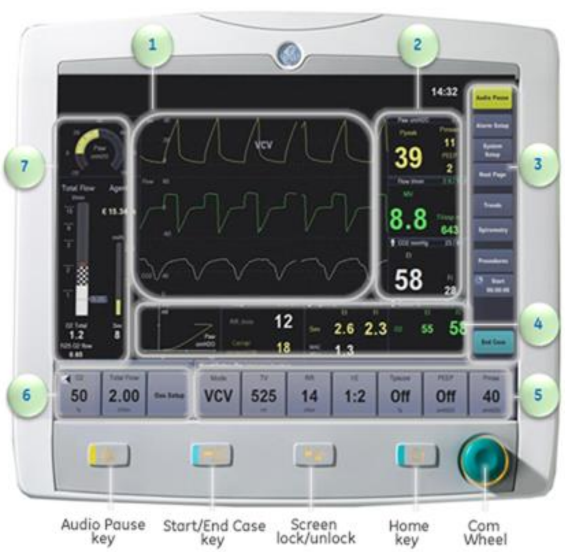
- Expiratory valve switches between inspiration and expiration phases of ventilation
- If valve is not opened completely during expiration, positive end-expiratory pressure (PEEP) is created in lungs
  - PEEP is therapeutically important as it increases gas exchange surface of lungs
  - Adequate PEEP can also prevent collapse of individual alveolar areas
- If expiratory valve is controlled during inspiratory phase, it can compensate for undesired pressure rises in breathing system
  - Caused, for example, by patient coughing





Operating and Display Unit

- Operating and display unit is the interface between ventilator and user.
  - Often touchscreens designed to display pressure and flow curves as well as multiple menus for setting different ventilation modes, adjusting alarm limits or measured value overviews, etc.
  - Parameter settings entered in operating unit control device components and therefore determine ventilation pattern applied to the patient



Alarm System

- Ensures that ventilation parameters set in operating and display unit are actually applied
- Issues audible and visual alarms to alert staff to critical changes in the patient’s condition or technical malfunctions
- Monitors the following:
  - Inspiratory oxygen concentration (controlled by the gas mixer)
  - Ventilation Pressure and Volume (to monitor the pressure/flow generator)
  - Inspiratory breathing gas temperature (when using active gas humidifier)

Patient Monitoring

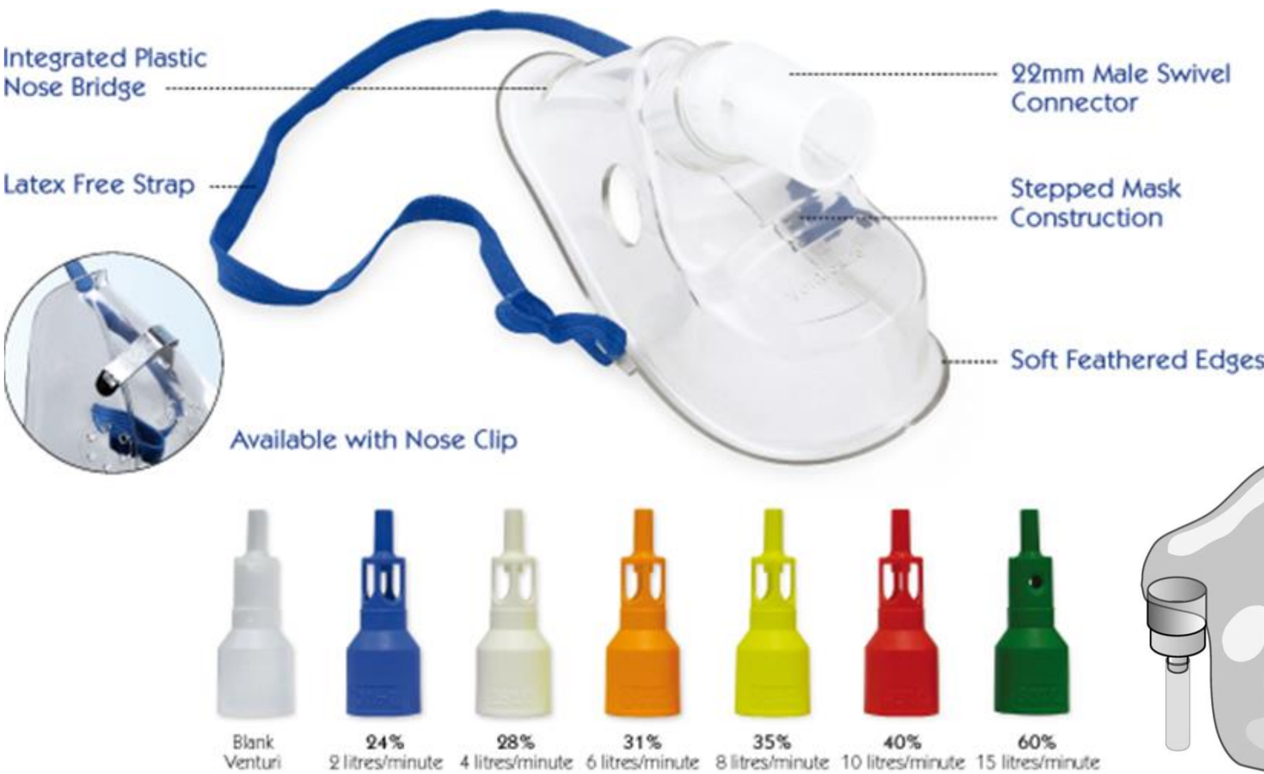
- Patient monitoring is used to monitor the patient's vital functions
  - Electrocardiogram (ECG)
  - Blood pressure (noninvasive and/or invasive)
  - Oxygen saturation
  - Carbon dioxide concentration in the breathing gas
- Although patient monitors do sometimes display ventilation data, these devices are to be seen as an independent display unit with an alarm facility
  - Not considered part of the ventilator

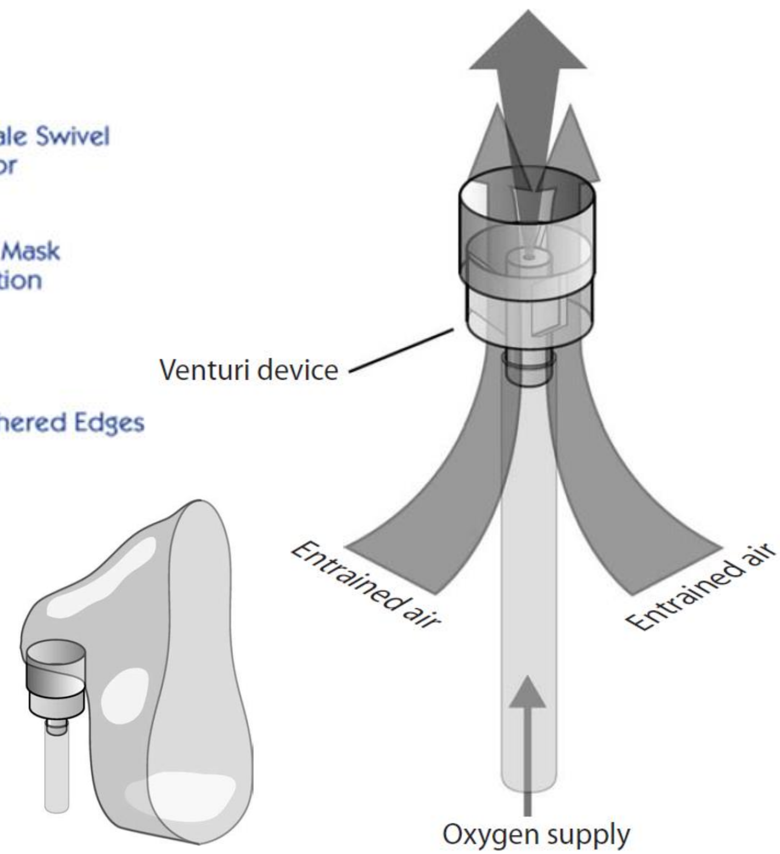
Devices for Administration of Oxygen

- A: Nasal cannulae
- B: Variable performance mask
- C: Variable performance mask with reservoir
- D: Fixed performance mask

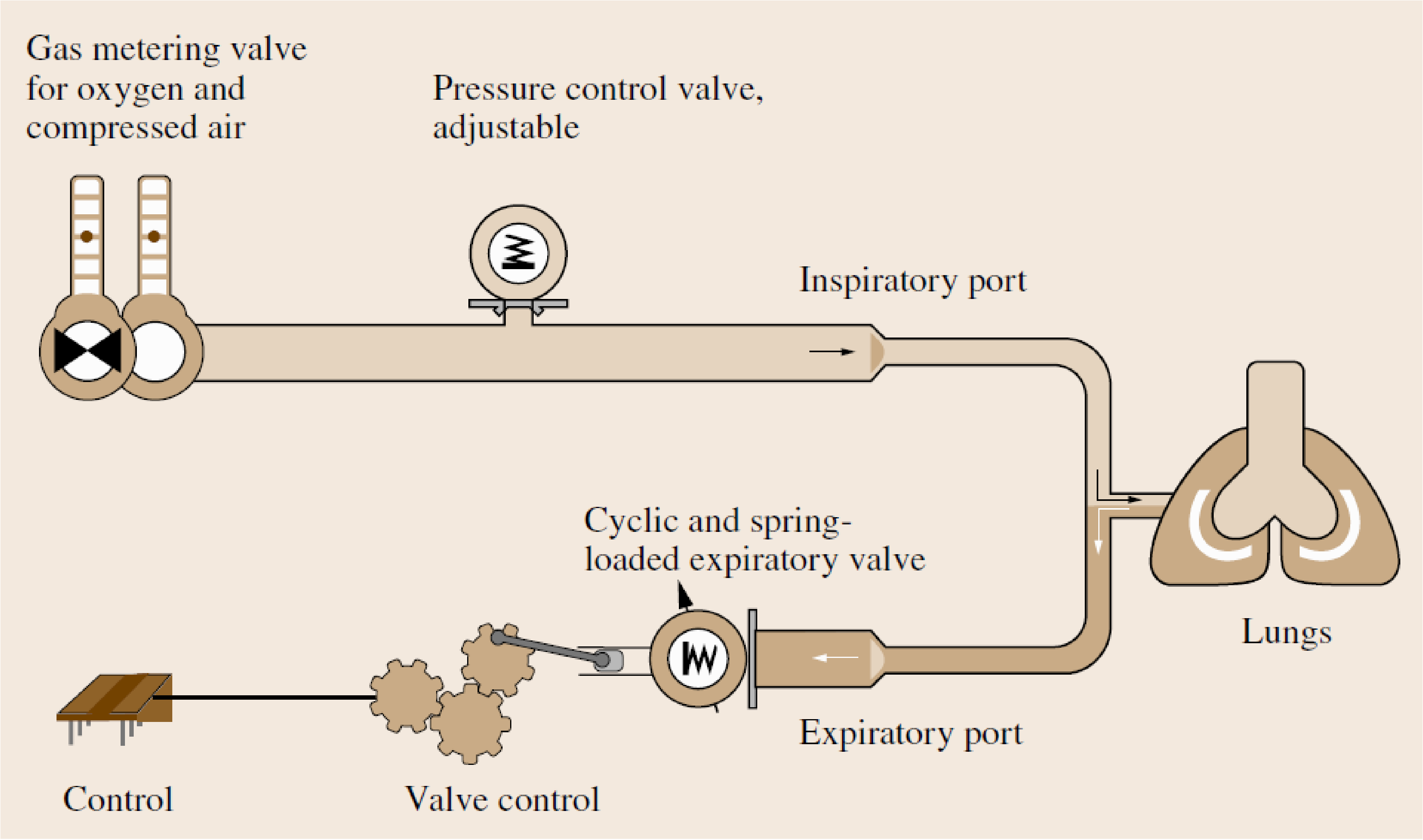
Venturi Mechanism

- If oxygen is supplied to the venturi device at the correct flow rate, air will be entrained through the vents to provide an air/ oxygen mixture with a specific oxygen concentration

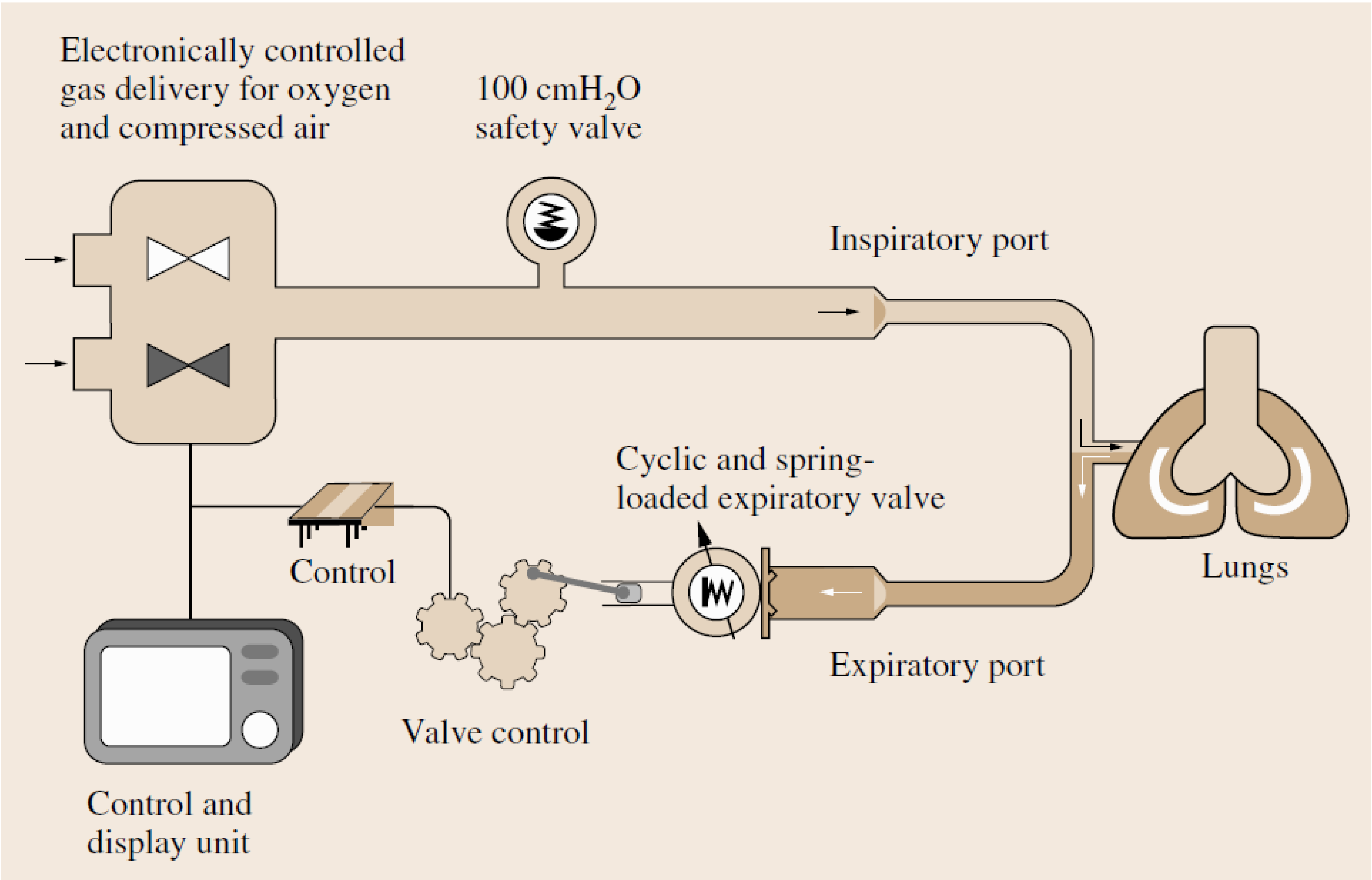




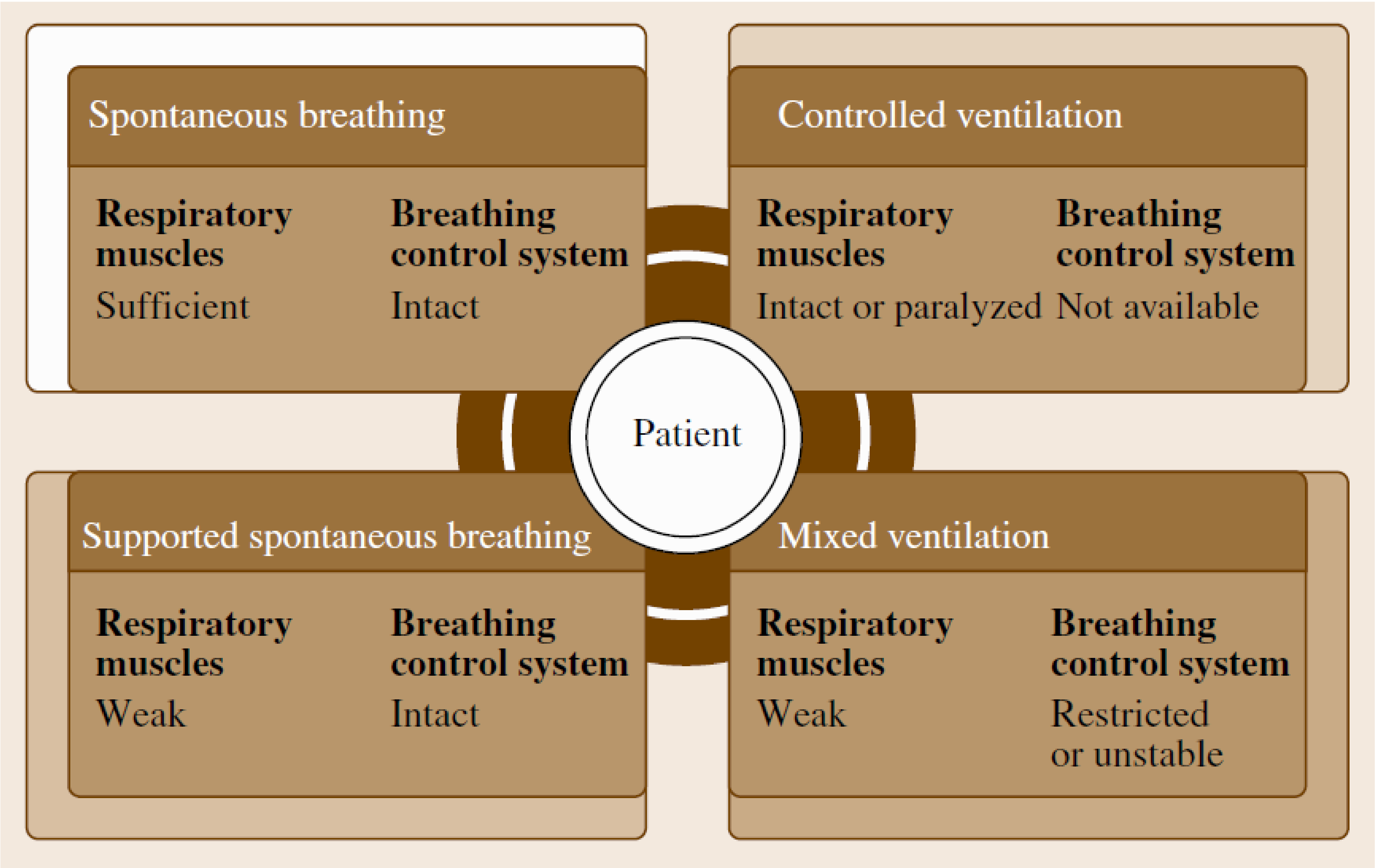
Continuous Flow Systems



Demand Flow Systems



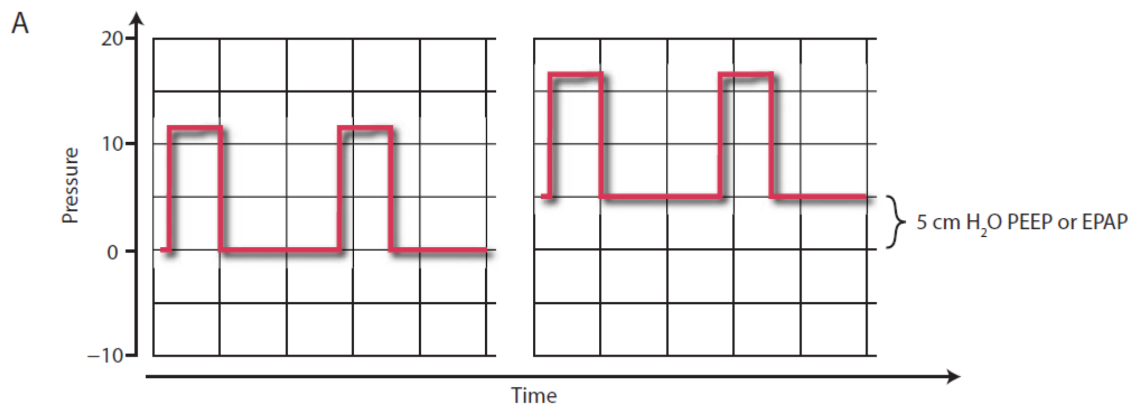
Forms of Mechanical Ventilation



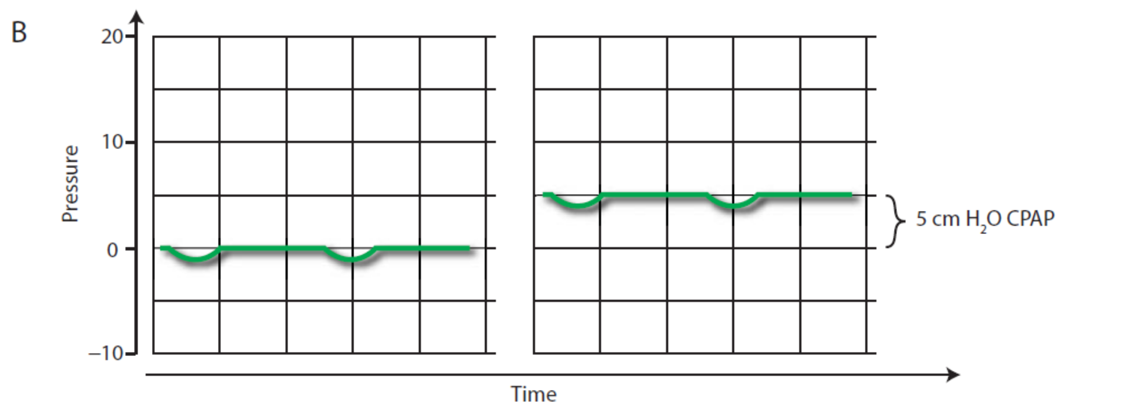
Non-Invasive Ventilation (NIV) vs. Continuous Positive Airway Pressure (CPAP)

- NIV: PEEP or EPAP
  - Positive end-expiratory pressure (PEEP)
  - Expiratory positive airway pressure (EPAP)

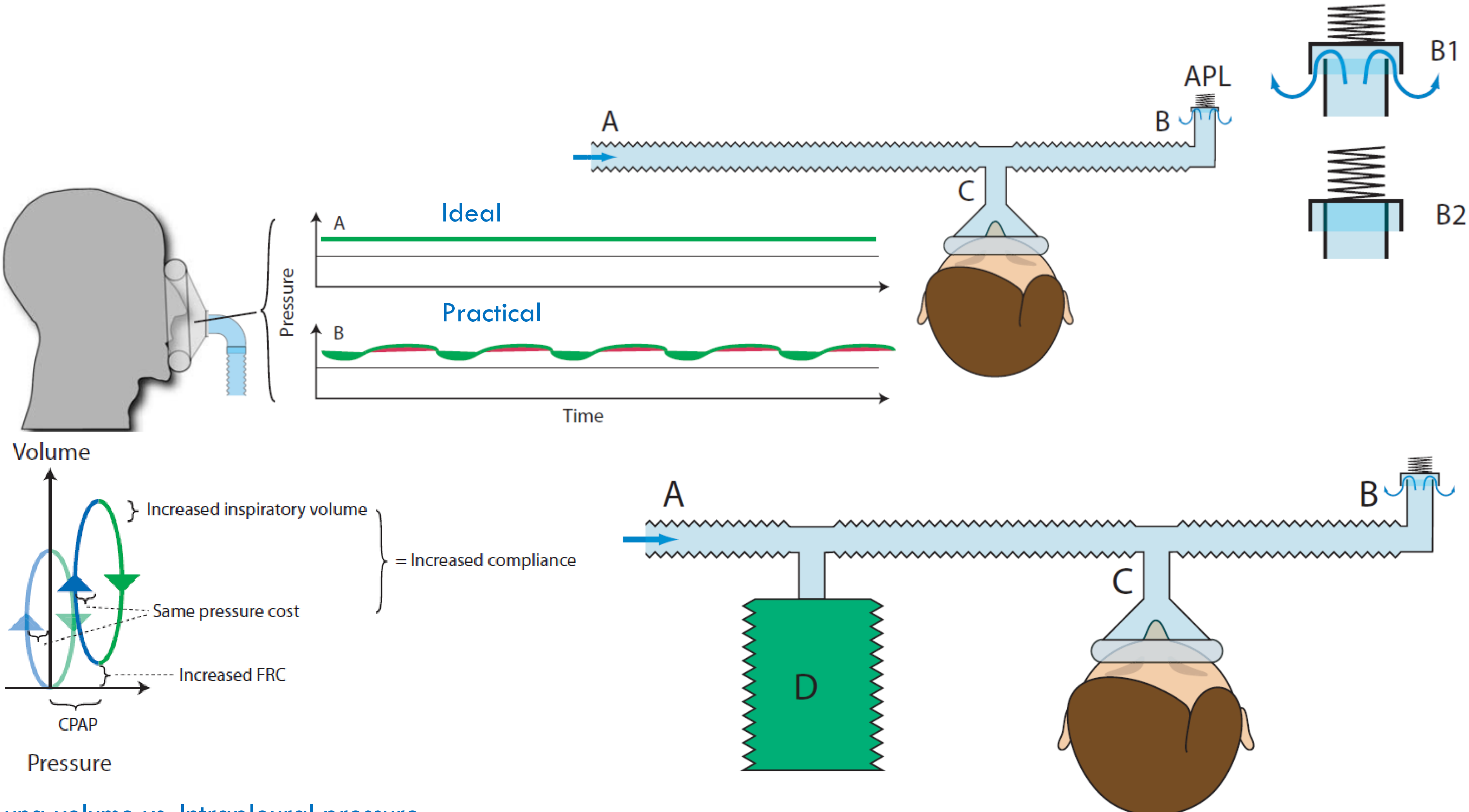
Pressure profile measured in the upper airway



Pressure profile measured just above the larynx



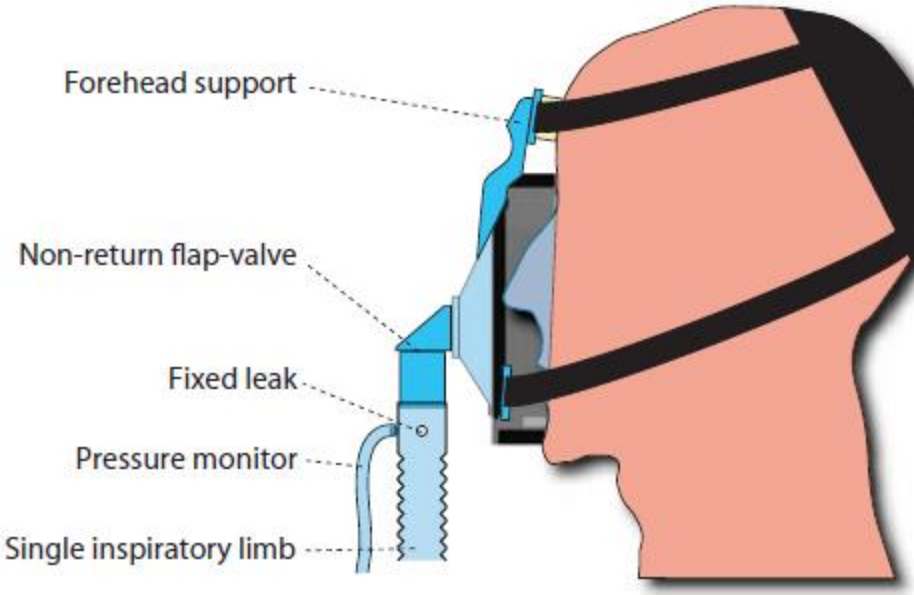
CPAP Circuit



Lung volume vs. Intrapleural pressure

NIV Circuit

- Unlike ventilator circuits used for anesthesia or critical care which have two limbs, one taking fresh gas to the patient and a second returning expired gas to the ventilator, breathing circuits for non-invasive ventilation (NIV) only have one limb for taking fresh gas to the patient



Respiratory Cycle

$$T_I + T_E = T_C.$$

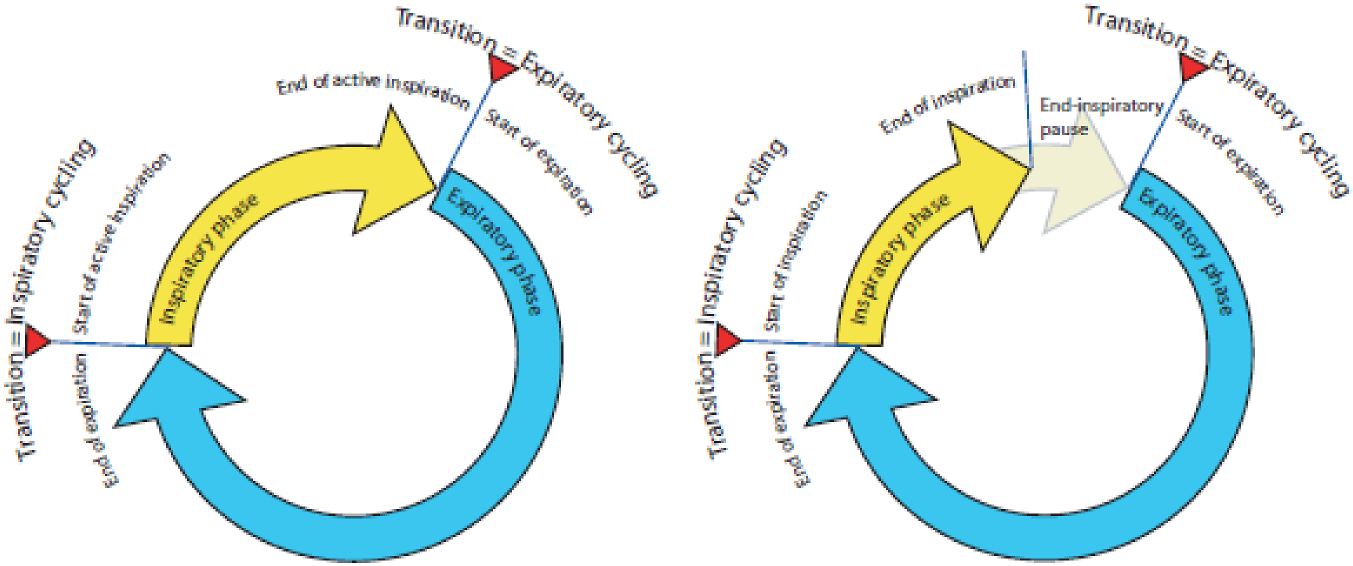
$$T_I = T_{I\,flow} + T_{I\,pause}$$

$$f = \frac{60}{T_C}.$$

$$\frac{T_I}{T_I + T_E} \times 100 = \frac{T_I}{T_C} \times 100 = \text{Duty cycle (\%)}.$$

$$f = \frac{\dot{V}}{V_T}.$$

$$\dot{V}_I = \frac{V_T}{T_I}.$$



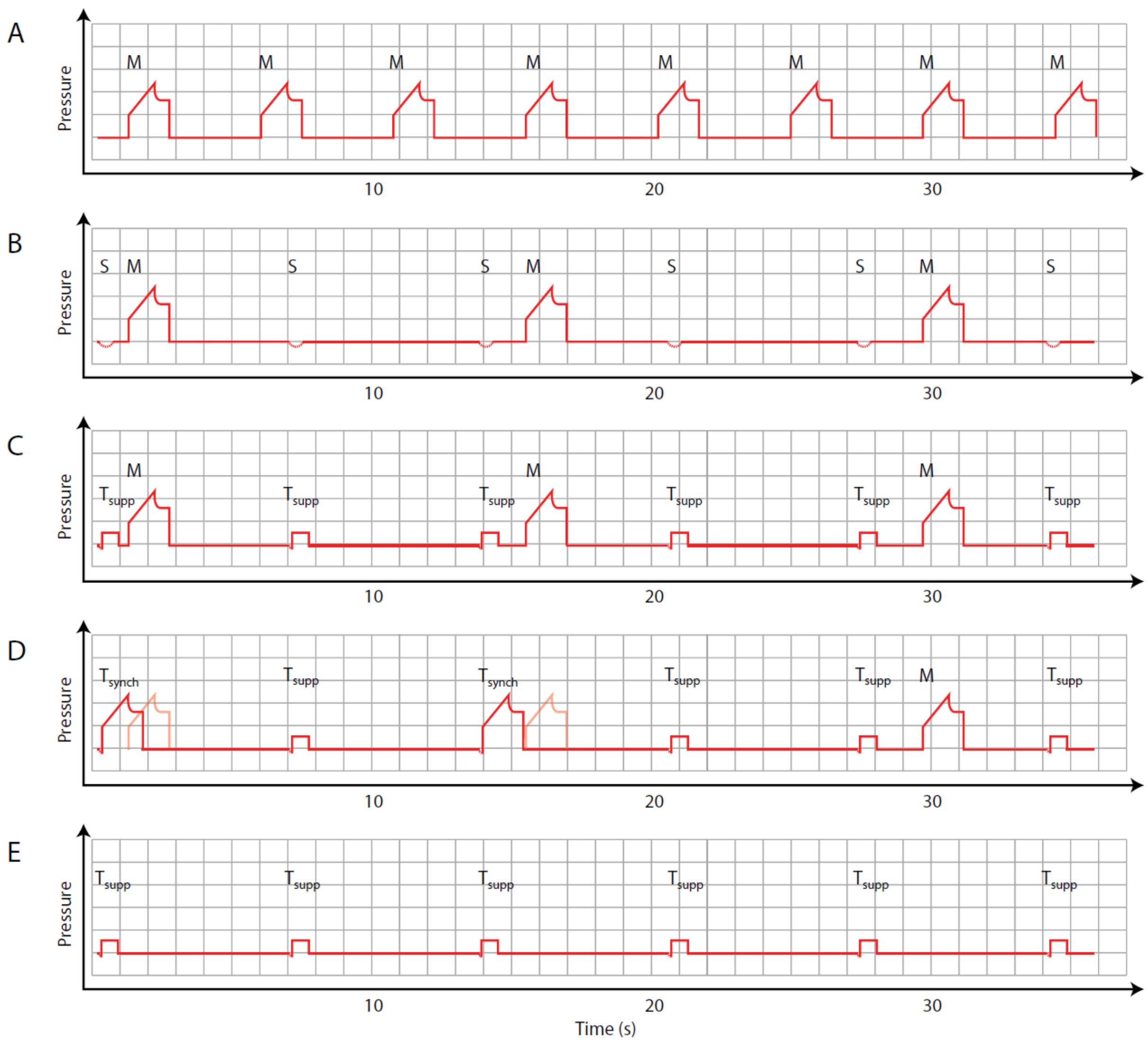
Trigger, Limit, Cycle, and Baseline Variables

- Trigger variable is one that is measured and used to start inspiration
- Limit variable is one that can reach and maintain a preset value before inspiration ends (i.e., does not end respiration)
- Cycle variable is one that is measured and used to end respiration
- Baseline variable is the parameter controlled during expiration
  - Pressure control is most practical and used in all modern ventilators

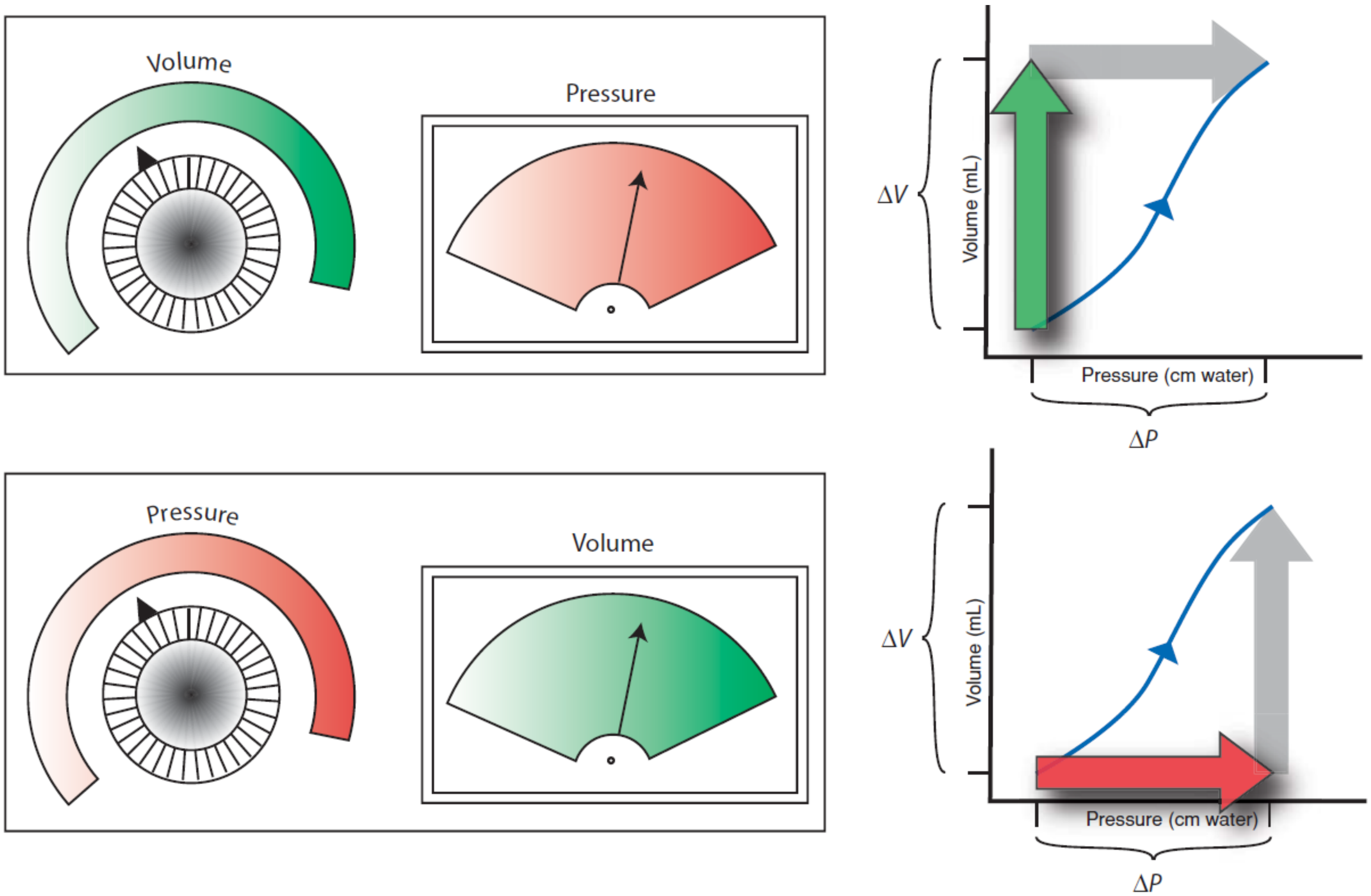
Inspiratory vs. Expiratory Cycling

- Exactly when a phase transition occurs can either be determined by the ventilator or by the patient.
- Inspiratory cycling: time or spontaneous (patient)
- Expiratory cycling: time or flow
- Inspiratory triggering
  - Volume
  - Pressure

Mandatory, Spontaneous and Triggered Inspiratory Cycling



Volume- or Pressure-Driven Inspiration



Classifying Modes of Mechanical Ventilation

- A “mode” of mechanical ventilation can be generally defined as a predetermined pattern of interaction between a ventilator and a patient.
  - There are over 100 names for modes of ventilation on commercially available mechanical ventilators.
  - Neither the manufacturing community nor the medical community has developed a standard taxonomy for modes

Classification of Modes

- In mandatory breaths (if present)
  - What determines inspiratory cycling?
  - What drives inflation and what is the breath targeted to or limited by?
  - Is feedback intra-breath or inter-breath?
  - What determines expiratory cycling?
- In triggered breaths (if present)
  - What breath types are present? Mandatory-pattern, supported or both?
  - In supported breaths (if present), what drives inflation (control parameter) and what is the breath targeted to or limited by?
  - Is feedback intra-breath or inter-breath?
  - What determines expiratory cycling?
- Are spontaneous breaths accommodated and if so, when?

Mandatory Modes of Ventilation

Mandatory breaths				
Inspiratory cycling	Time	Time	Time	Time
Control	Volume[a]	Volume	Volume	(Pressure)
Target/Limit	–	–	Pressure-limited	Volume-targeted
Feedback	–	–	Intra-breath	Inter-breath
Expiratory cycling	Time	Time	Time	Time[b]
Triggered breaths				
Types	None	None	None	None
Supported breaths				
Control	–	–	–	–
Target	–	–	–	–
Feedback	–	–	–	–
Expiratory cycling	–	–	–	–
Spontaneous breaths				
During mandatory inspiration	Not accommodated[c]	Not accommodated	Not accommodated	Accommodated
Otherwise	Not accommodated	Accommodated	Not accommodated	Accommodated
Synonyms	IPPV (Draeger[d]), Controlled Mandatory Ventilation or (historically) Control Mode Ventilation	Intermittent Mandatory Ventilation	IPPV (Draeger[e])	IPPV (Draeger[f])

Triggered Modes of Ventilation

Mandatory breaths			
Inspiratory cycling	–	–	–
Control	–	–	–
Target	–	–	–
Feedback	–	–	–
Expiratory cycling	–	–	–
Triggered breaths			
Types	Supported breaths only	Supported breaths only	Supported breaths only
Supported breaths			
Control	Pressure[a]	(Pressure[b])	(Pressure[b])
Target/Limit	–	Volume-targeted	Flow and volume
Feedback	–	Inter-breath	Intra-breath
Expiratory cycling	Flow[c]	Flow[c]	Flow[c]
Spontaneous breaths			
During mandatory inspiration	–	–	–
Otherwise	–	–	–
Synonyms	Assisted Spontaneous Breathing (Draeger), Spontaneous mode (Hamilton, Puritan-Bennett), Pressure support (Maquet), CPAP (Respironic), Pressure Support Ventilation (Viasys)	Volume Support (Maquet, Puritan-Bennett)	Proportional assist ventilation, Proportional Pressure Support (Draeger), Proportional Assist Ventilation Plus (Puritan-Bennet)

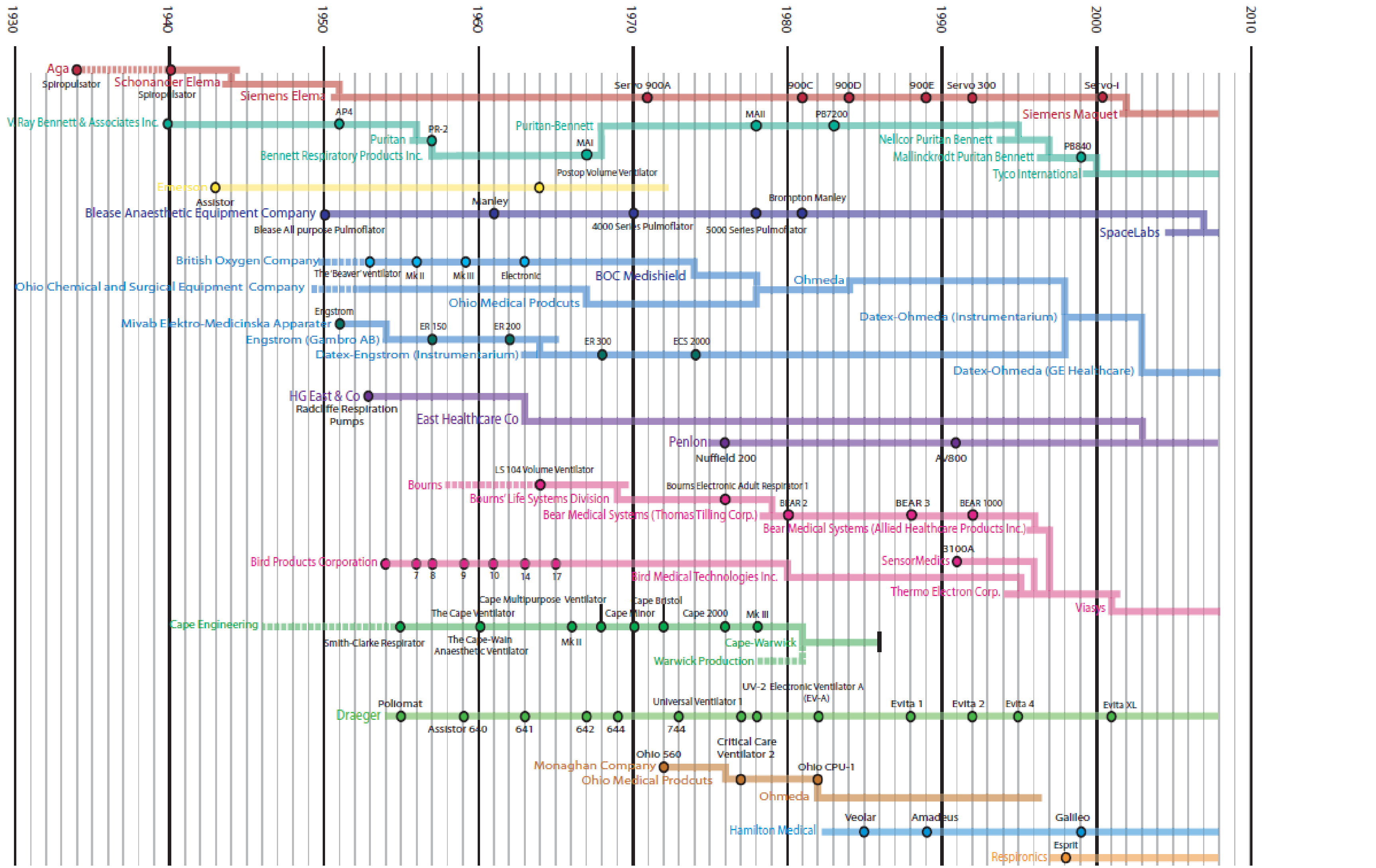
Hybrid Mode: Assist Control

Mandatory breaths			
Inspiratory cycling	Time or trigger	Time or trigger	Time or trigger
Control	Volume	Pressure[a]	(Pressure[b])
Target	–	–	Volume-targeted
Feedback	–	–	Inter-breath
Expiratory cycling	Time	Time	Time
Triggered breaths			
Types	Mandatory-pattern only	Mandatory-pattern only	Mandatory-pattern only
Supported breaths			
Control	–	–	–
Target	–	–	–
Feedback	–	–	–
Expiratory cycling	–	–	–
Spontaneous breaths			
During mandatory inspiration: Otherwise	Not accommodated[c]	Accommodated	Accommodated
Synonyms	$IPPV_{Assist}$ (Draeger[d]), Synchronized Controlled Mandatory Ventilation (Hamilton), Volume Control (Maquet), VCV-A/C (Puritan-Bennett, Respironics), Volume A/C (Viasys)	$BIPAP_{Assist}$ (Draeger), P-CMV (Hamilton), Pressure Control (Maquet), PCV-A/C (Puritan-Bennett, Respironics), Pressure A/C (Viasys)	Adaptive Pressure Ventilation CMV (Hamilton), Pressure Regulated Volume Control (Maquet), VC+ A/C (Puritan-Bennett), Pressure Regulated Volume Control A/C (Viasys), IPPV Assist Autoflow (Draeger)

Hybrid Mode: Synchronized Intermittent Mandatory Ventilation (SIMV)

Mandatory breaths			
Inspiratory cycling	Time or trigger	Time or trigger	Time or trigger
Control	Volume	Pressure[a]	(Pressure[b])
Target/Limit	–	–	Volume-targeted
Feedback	–	–	Inter-breath
Expiratory cycling	Time	Time	Time
Triggered breaths			
Types	Mandatory-pattern[c] and supported	Mandatory-pattern and supported	Mandatory-pattern and supported
Supported breaths			
Control	Pressure[d]	Pressure[d]	Pressure[d]
Target	–	–	–
Feedback	–	–	–
Expiratory cycling	Flow[e]	Flow[e]	Flow[e]
Spontaneous breaths			
During mandatory inspiration	Not accommodated	Accommodated	Accommodated
Otherwise	Only if support is OFF.	Only if support is OFF.	Only if support is OFF.
Synonyms	SIMV (Draeger, Hamilton), SIMV (VC) + PS (Maquet), VCV-SIMV (Puritan-Bennett, Respironics), Volume SIMV (Viasys)	P-SIMV (Hamilton), SIMV(PC) + PS (Maquet), PCV-SIMV (Puritan-Bennett, Respironics), Pressure SIMV (Viasys)	SIMV + Autoflow (Draeger), Adaptive Pressure Ventilation SIMV (Hamilton), SIMV (PRVC) + PS (Maquet), VC+ SIMV (Puritan-Bennett), PRVC SIMV (Viasys)

Commercial Development of Ventilator Technology



Suggested Readings and Assignments

- Chapters 1, 3 & 5 of Recommended Reference #1
- Chapter 27 of Recommended Reference #2

- Problem set posted on web site