

Respiratory mechanics in mechanical ventilation

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- Introduction
- Mechanics during ventilation
- PV curves
- Application in health & disease
- Difficulties & pitfalls
- The future....

Monitoring Mechanics

- Pressure, flow, and volume
- Time-based graphics (waveforms)
 - Pressure
 - Flow
 - Volume
- Derived measures
 - Compliance
 - Resistance
- Loops
 - Pressure volume
 - Flow volume

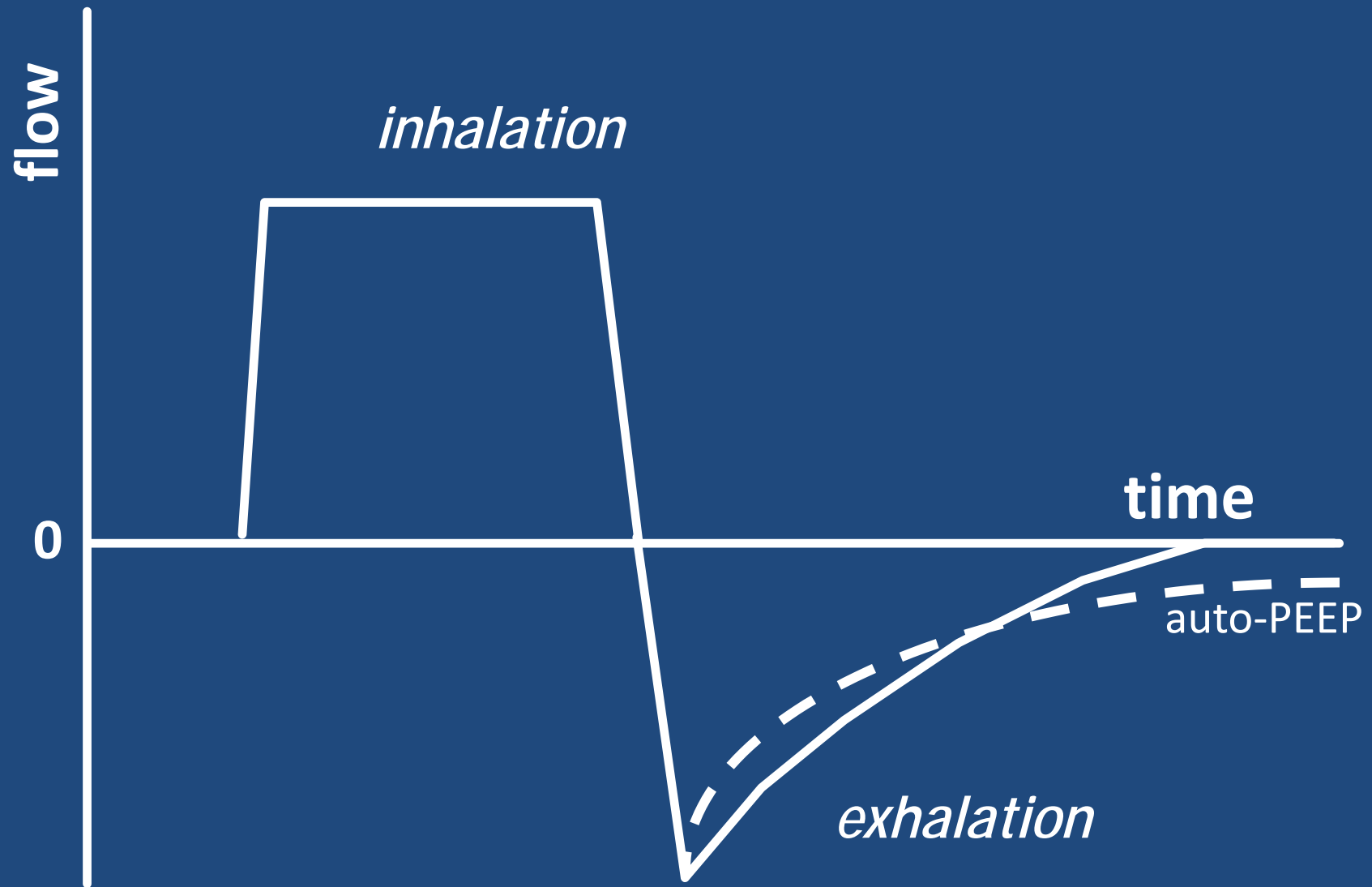
Pressures

- Peak inspiratory pressure (PIP)
 - Pressure generated to drive gas into the lungs to overcome resistance & elastic property of RS
 - Dependant on flow, resistance, TV, compliance & PEEP
 - Slope of the curve depends on flow pattern
- Plateau pressure(P_{plat})
 - Measured after E_{ins} pause of ~ 2 secs
 - Represents alveolar pressure
 - True inflation pressure

PEEP_i

- Presence of positive P_{aw} at E_{exp} in the absence of PEEP_E
- Measured by application of E_{exp} pause
- Etiology
 - Dynamic hyperinflation with airflow obstruction
 - Dynamic hyperinflation without airflow obstruction
 - Without either
- Leads to
 - Hyperinflation- volutrauma
 - Decreases trigger sensitivity- fatigue
 - Hemodynamic compromise

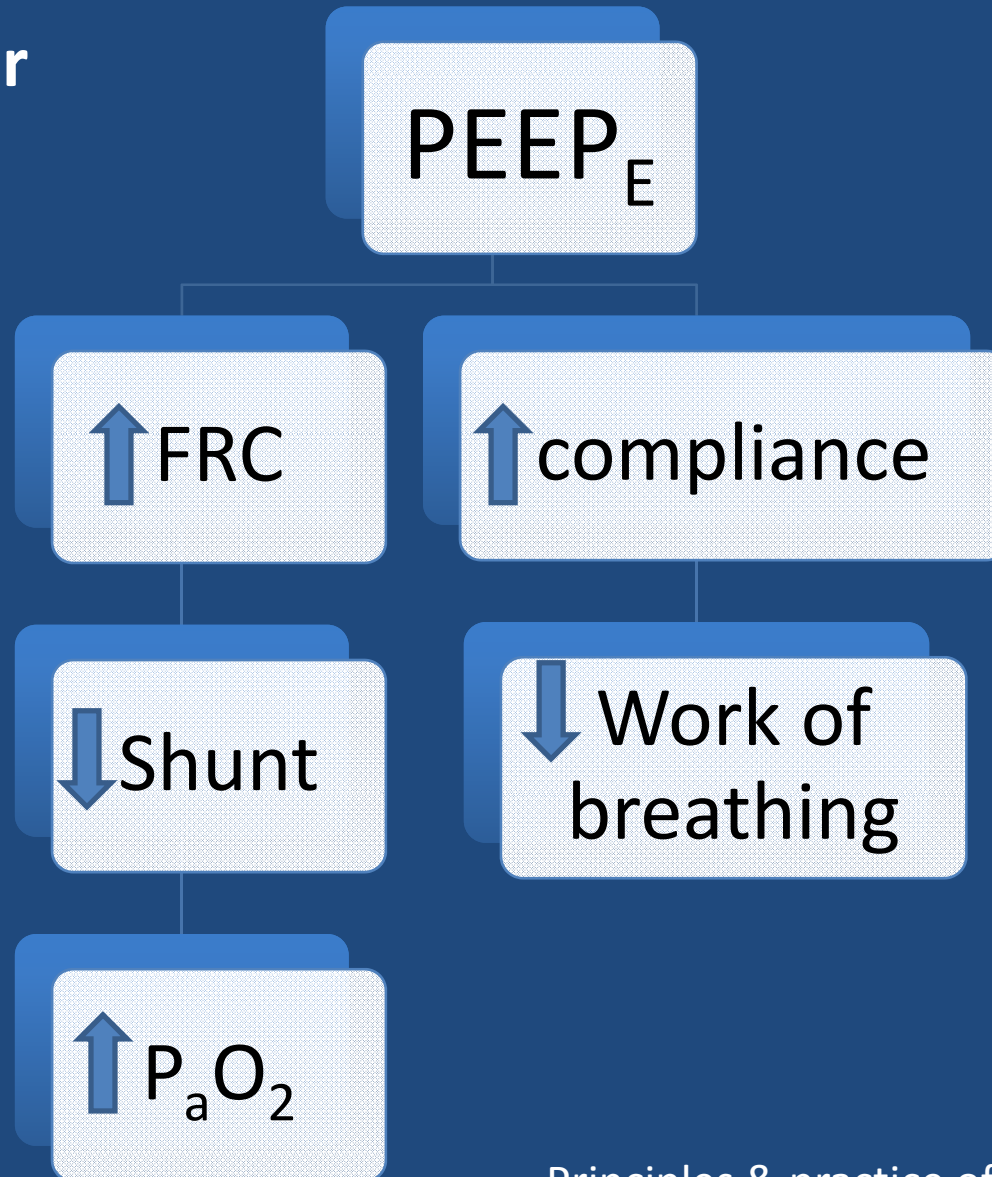
Flow with PEEP_i



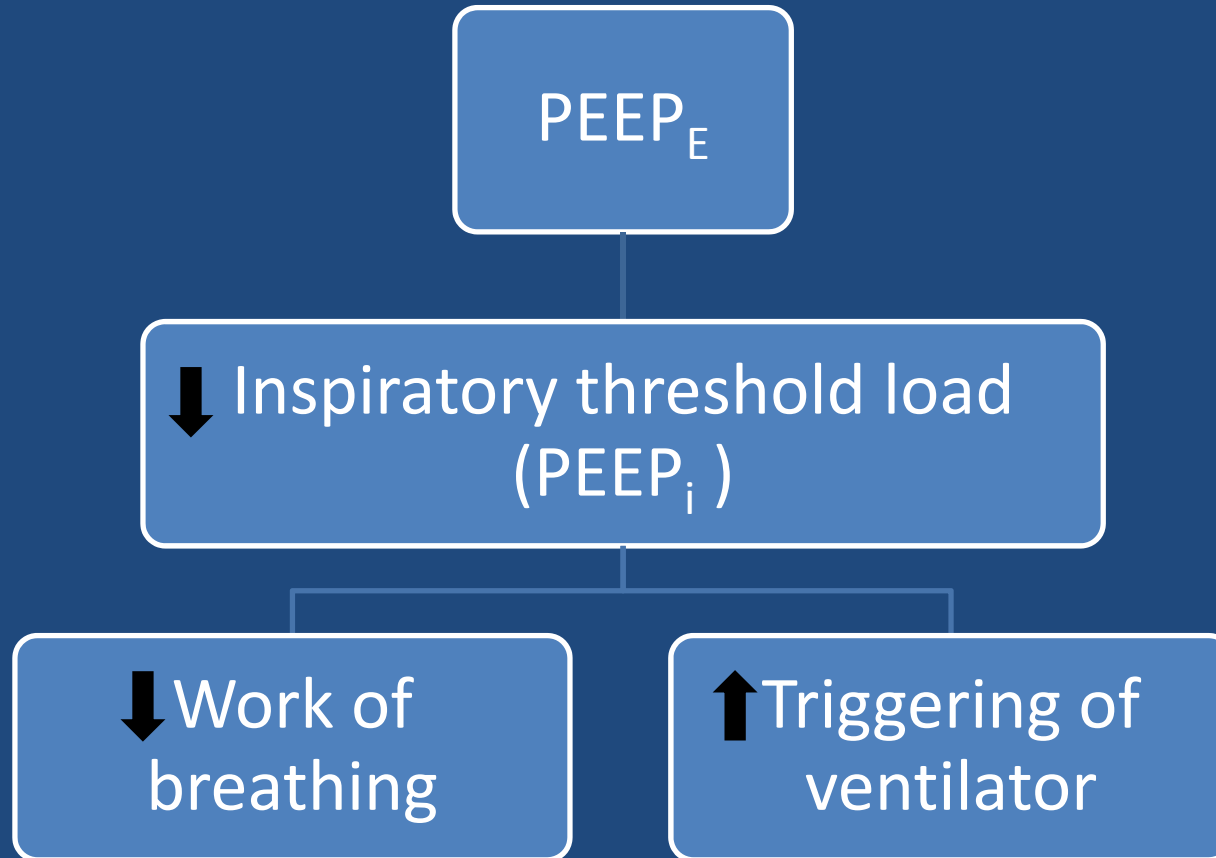
PEEP_E

- Positive end expiratory pressure set by the clinician
- Ashbaugh & Petty in 1967 as useful tool in Mx of ARDS
- Our understanding continues to evolve
- Is being applied in wide variety of pulmonary disorders
- So how does it work?

Edema & /or
atelectasis



Obstructive airway disease



Lung inflation & mechanics

- $P_{rs} = P_{AO} + P_{mus} = \dot{V} \times R + V/C$

- $\dot{V} = \text{flow}$

- $R = \text{resistance}$

- $V = \text{volume}$

- $C = \text{compliance of sytem}$

- *During mechanical ventilation*

- $P_{rs} = P_{AO} = \dot{V} \times R + V/C$

- Dynamic mechanics
 - Relation between Pressure, flow & volume without flow interruption
 - Ventilators use linear regression analysis to compute C & R from constantly changing variables from 100 or more equations per breath
- Static mechanics
 - Done with flow interruption (zero flow)

- Compliance (C)

- Change in lung volume per unit change in pressure gradient.

- $\Delta V / \Delta P$

- $C_{rs} = C_l + C_{cw}$

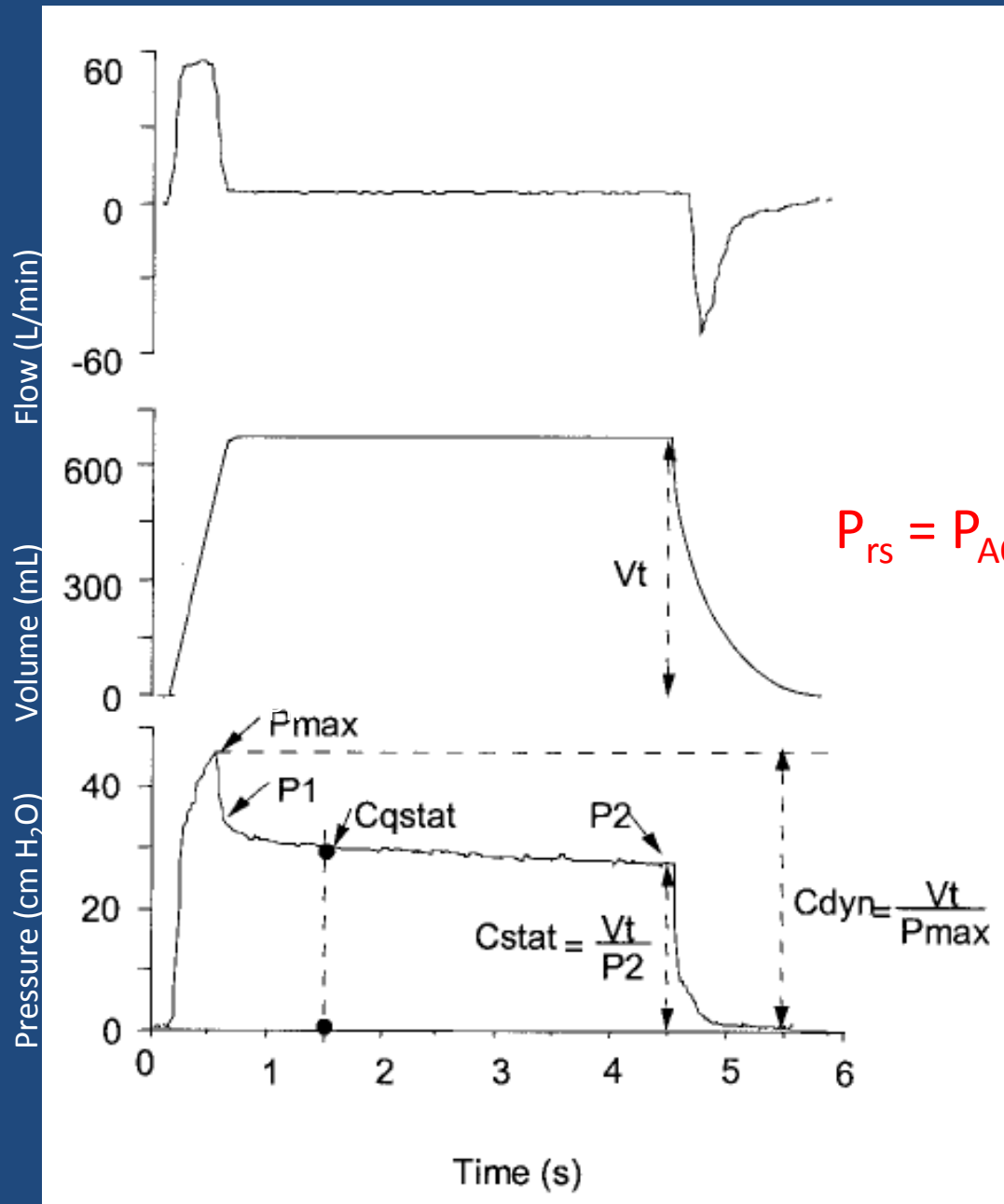
$$\frac{1}{C_{\text{Total}}} = \frac{1}{C_{\text{Chestwall}}} + \frac{1}{C_{\text{Lung}}}$$

- Static compliance

- Measured after an end inspiratory pause of few seconds (to attain $P_2 = P_{plat}$)
- Pause ensures $P_{aw} = P_{avl}$
- Is not influenced by R_{aw}

- Dynamic compliance

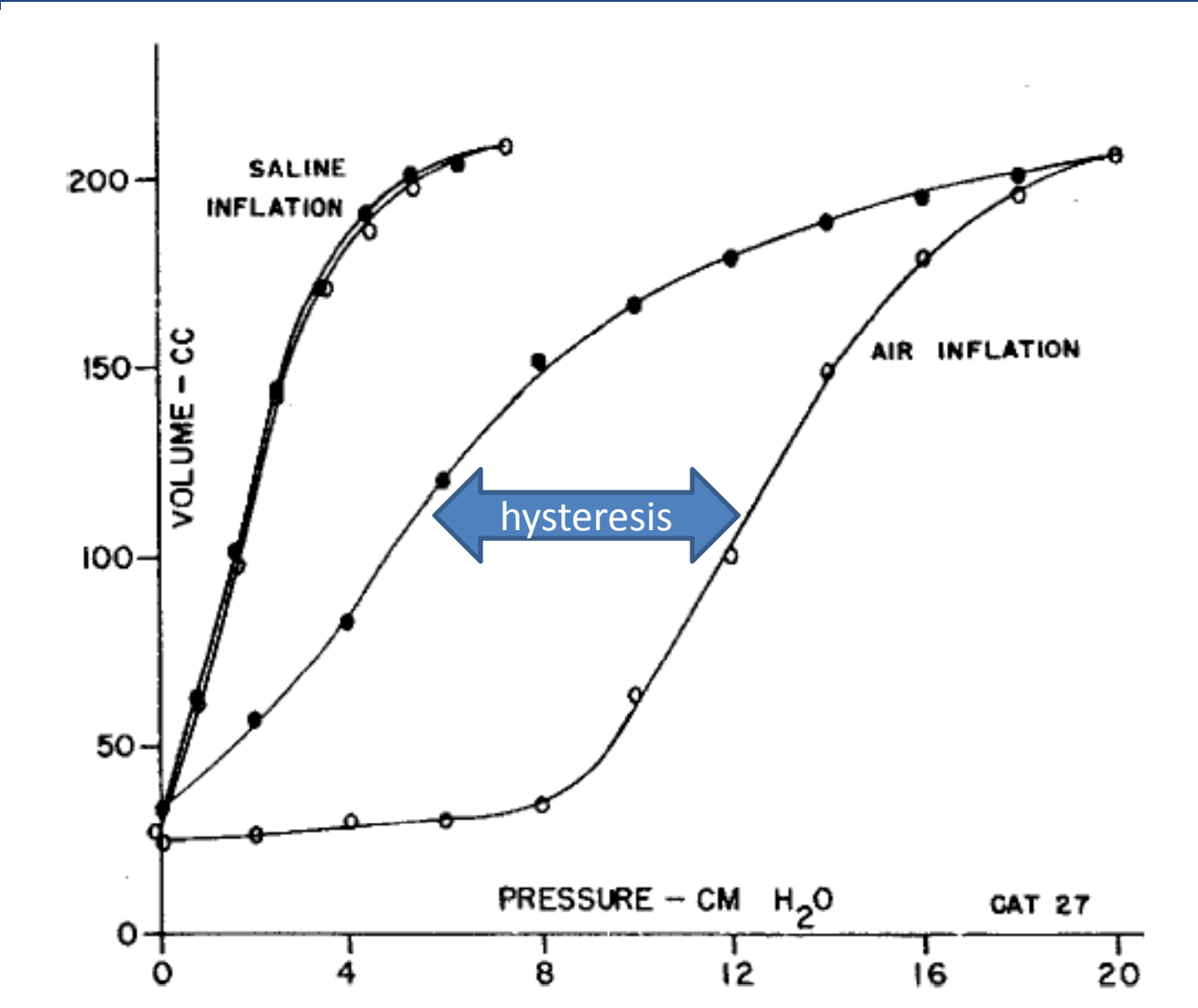
- Measured between E_{exp} and E_{ins} without pause (PIP)
- Affected by R_{aw}



$$P_{rs} = P_{AO} = \dot{V} \times R + V/C$$

Need to know about compliance..

- Volume dependent
 - Its relation with volume is non linear (sigmoid)
 - Specific compliance is useful in overcoming this problem(C/TLC)
- Hysteresis
 - Unrecoverable energy, or delayed recovery of energy, that is applied to a system
 - Attributed mainly to air fluid interface
 - Intrinsic property also contribute



- Regional variation

- Compliance measured is a function of many different regional compliances
- In health, the difference is not significant
- In disease, its may contribute significantly to distribution of ventilation

Resistance

- Airflow & lung visco-elastic property
 - Natural & artificial airways contribute
 - IPPV flow is considered to be laminar

- $R_{rs} = R_{aw} + R_l$

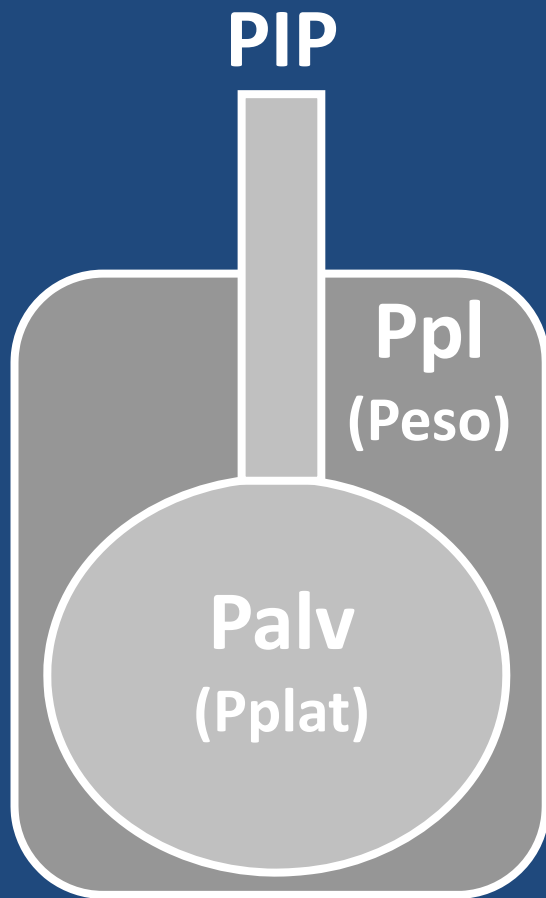
- $R_{aw} = PIP - P_1 / \dot{V}$

- $R_l = P_1 - P_2 / \dot{V}$

- $R_{rs} = PIP - P_2 / \dot{V}$

Resistance affected by...

- Volume
 - Larger the volume, lower the resistance
- Changes with inspiration & expiration
- Regional differences in health & disease
- Natural & artificial airway in series



$$C_{rs} = \frac{\text{tidal volume}}{P_{plat} - PEEP}$$

$$C_{cw} = \frac{\text{tidal volume}}{\Delta P_{eso}}$$

$$C_L = \frac{\text{tidal volume}}{(P_{plat} - PEEP) - \Delta P_{eso}}$$

$$R_i = \frac{PIP - P_{plat}}{\text{flow}}$$

Work of breathing (Wob)

- Performed by the ventilator on a paralyzed patient on full support
- Calculated during passive constant flow

$$W = (PIP - 0.5 \times P_{plat}) / 100 \times V_T$$

- Increases with increase in R , V_T or decrease in C
- $PEEP_i$ increases Wob
- Increase – fatigue & weaning failure

PV curves

- The quasi-static (P-V) relationship
 - Lungs deform during breathing in health and disease
 - Devised to diagnose & stage ARDS half a century back
- Plotted with the hope of
 - Diagnosing lung disease
 - Customize ventilator setting
 - Prognostication
 - Improve standard of care

How to measure ?

- Static methods
 - Supersyringe method
 - Multiple occlusion method (gold standard)
- Dynamic method
 - Constant low flow technique(< 10 L/min) (easy & fast)

Normal PV curve

- Sigmoid in shape
 - upward concavity at low pressures & downward concavity at higher pressures
 - Balance of forces between chest wall (diaphragm and rib cage) and lung
 - Forces are equal & opposite at FRC
 - Below FRC, chest wall contributes to curvature
 - Lung contributes to curvature above FRC

Classics concepts

- Zone 1
 - Low compliance
 - Due to collapsed alveoli
- LIP
 - Proposed magic point of recruitment
- Zone 2
 - Area of linear compliance

- Lower & upper pflex
 - Tangent from slope
- UIP
 - Start of over distension
- Zone 3
 - Decreased compliance due to over-distension

Practical difficulties, trials, controversies & changing concepts

- Identification of LIP
 - Inter observer variation
 - O'Keefe et al - 5 to 9cm variability
 - Harris et al -13cms variability
- Inflation vs. deflation limb
- Optimal PEEP?
- How does recruitment take place?

A pubmed search revealed over 600 articles

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Inspiratory vs. expiratory pressure-volume curves to set end-expiratory pressure in acute lung injury

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Abstract Objective: To study the effects of two levels of positive end-expiratory pressure (PEEP), 2 cmH₂O above the lower inflection point of the inspiratory limb and equal to the point of maximum curvature on the expiratory limb of the pressure-volume curve, in gas exchange, respiratory mechanics, and lung aeration. **Design and setting:** Prospective clinical study in the intensive care unit and computed tomography ward of a university hospital. **Patients:** Eight patients with early acute lung injury. **Interventions:** Both limbs of the static pressure-volume curve were traced and inflection points calculated using a sigmoid model. During ventilation with a tidal volume of 6 ml/kg we sequentially applied a PEEP 2 cmH₂O above the inspiratory lower inflection point (15.5±3.1 cmH₂O) and a PEEP equal to the expiratory point of maximum curvature (23.5±4.1 cmH₂O). **Mea-**

surements and results: Arterial blood gases, respiratory system compliance and resistance and changes in lung aeration (measured on three computed tomography slices during end-expiratory and end-inspiratory pauses) were measured at each PEEP level. PEEP according to the expiratory point of maximum curvature was related to an improvement in oxygenation, increase in normally aerated, decrease in nonaerated lung volumes, and greater alveolar stability. There was also an increase in PaCO₂, airway pressures, and hyperaerated lung volume. **Conclusions:** High PEEP levels according to the point of maximum curvature of the deflation limb of the pressure-volume curve have both benefits and drawbacks.

Keywords Acute lung injury · Positive end-expiratory pressure · Pressure-volume curves · Computed tomography · Mechanical ventilation

Deflation Limb of the PV Curve

Recently, a growing interest has emerged from the literature as regards the deflation part of the PV curve. This is mainly due to the fact that PEEP remains exclusively an expiratory maneuver, suggesting that the deflation curve that immediately precedes PEEP may play an important role in the rules governing recruitment and derecruitment. **Since PEEP is mainly devoted to preventing alveolar derecruitment, it seems logical that the deflexion point read on the deflation curve may be more relevant than the LIP read on the inflation curve.** This interesting point of view was recently elegantly developed via a mathematical model recently reported by **Hickling.**²⁹ Nevertheless, **several flaws** render this theory difficult to transpose in clinical practice. To record the deflation part of the PV curve, expiratory flow should be dramatically limited, thus generating artificial hysteresis. This expiration obtained by an artificial increase of the time constant of the respiratory system likely affects the dynamic behavior of the system. It is therefore extremely difficult to extend information done by the low flow deflation with regard to what occurs during a normal breath. Moreover, by definition the

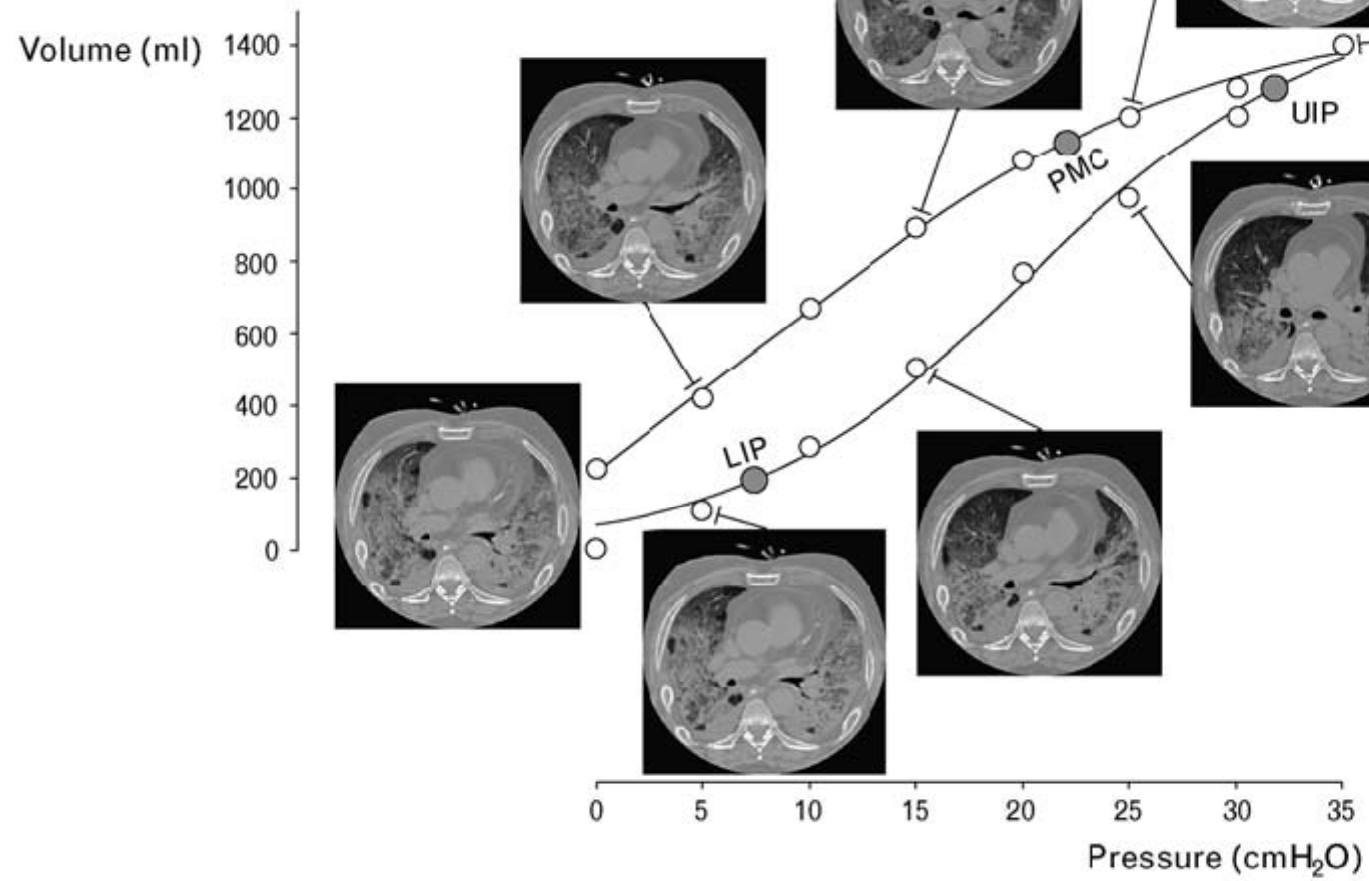
Pressure-Volume Curves and Compliance in Acute Lung Injury

Evidence of Recruitment Above the Lower Inflection Point

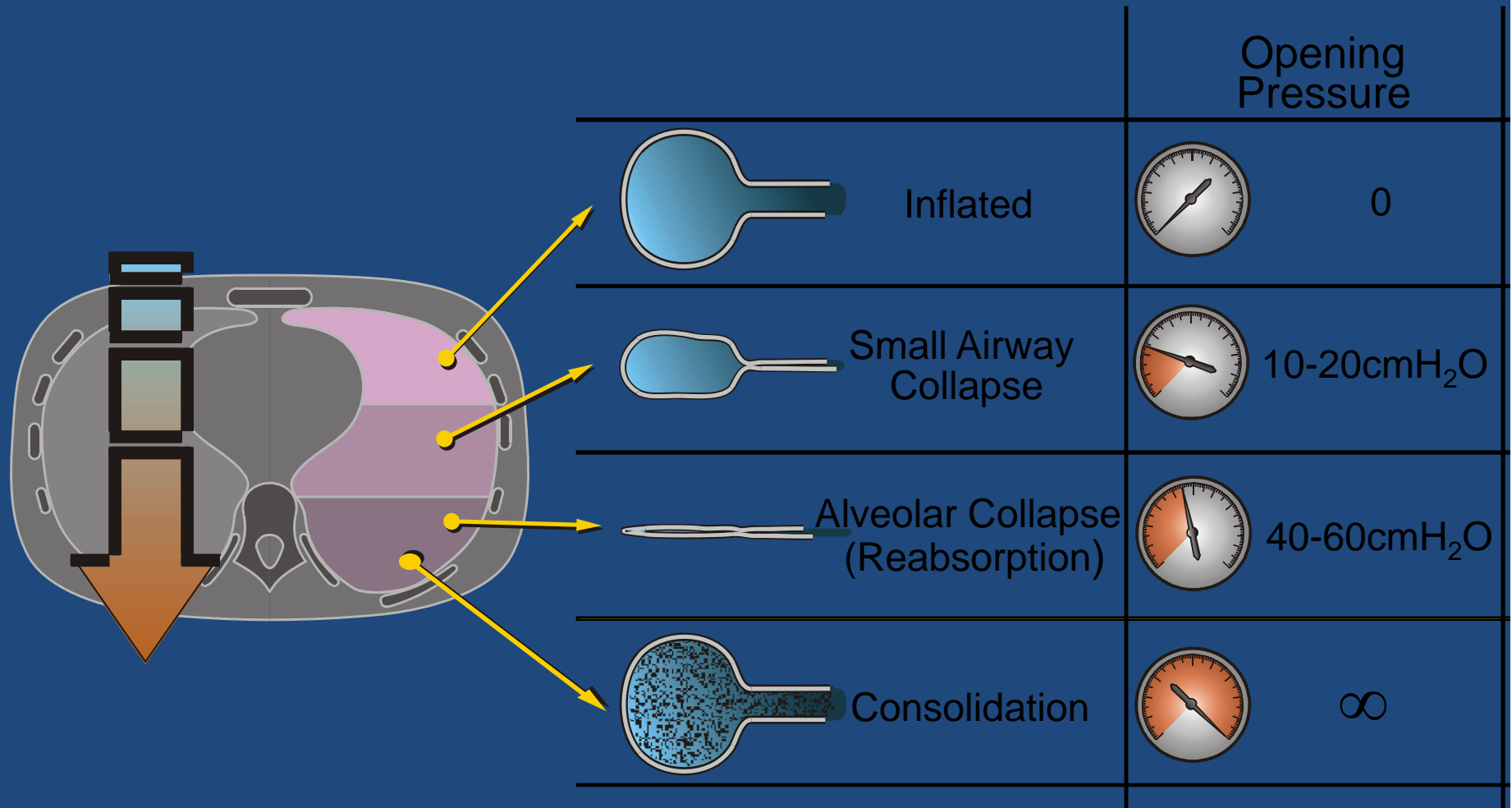
BJÖRN JONSON, JEAN-CHRISTOPHE RICHARD, CHRISTIAN STRAUS, JORDI MANCEBO, FRANÇOIS LEMAIRE, and LAURENT BROCHARD

Medical Intensive Care Unit, INSERM U492, Hôpital Henri Mondor, AP-HP Paris XII University, Créteil, France; Department of Clinical Physiology, University Hospital of Lund, Lund, Sweden; and Hospital of Sant Pau, Barcelona, Spain

Measuring elastic pressure-volume (P_{el}-V) curves of the respiratory system and the volume recruited by a positive end-expiratory pressure (PEEP) allows one to study the pressure range over which recruitment occurs in acute lung injury (ALI), and to explain how recruitment affects the compliance. P_{el}-V curves were measured with the low flow inflation technique in 11 patients mechanically ventilated for ALI. Curve I was recorded during inflation from the volume attained after a prolonged expiration (6 s) at PEEP (9.0 ± 2.2 cm H₂O), and Curve II after expiration to the elastic equilibrium volume at zero end-expiratory pressure (ZEEP). By using the end-expiratory volume of the breaths, the curves were aligned on a common volume axis to determine the effect of a single complete expiration. In each patient, Curve II (from ZEEP) was shifted toward lower volumes than Curve I. The volume shift, probably due to derecruitment, was 205 ± 100 ml at 15 cm H₂O ($p < 0.01$) and 78 ± 93 ml at 30 cm H₂O ($p < 0.01$); thus, during inflation from ZEEP, the volume deficit was successively regained over a pressure range up to at least 30 cm H₂O. At any pressure, compliance was higher on the curve from ZEEP than from PEEP, by 10.0 ± 8.7 ml/cm H₂O at 15 cm H₂O ($p < 0.01$), and by 5.4 ± 5.5 at 30 cm H₂O ($p < 0.01$). It is concluded that in ALI, a single expiration to ZEEP leads to lung collapse. High compliance during insufflation from ZEEP indicates that lung recruitment happens far above the lower inflection point of the P_{el}-V curve. **Jonson B, Richard J-C, Straus C, Mancebo J, Lemaire F, Brochard L. Pressure-volume curves and compliance in acute lung injury: evidence of recruitment above the lower inflection point.** AM J RESPIR CRIT CARE MED 1999;159:1172-1178.



Concept of “baby lung”



(modified from Gattinoni)

Current understanding

- Heterogeneity of lung injury – wide range of recruitment pressures
- Injury evolves over time – so does the curve
- LIP- beginning of significant recruitment
- UIP- end of significant recruitment vs. beginning of significant overdistension
- PEEP is definitely helpful but what is the optimum PEEP ?

Emphysema

- Early studies of P-V relationship in COPD hoped to diagnose and establish the severity of emphysema
- CT has supplanted the P-V curve for diagnosis of emphysema
- Done on spontaneously breathing patients
- Increased concavity towards pressure axis irrespective of volume (increased compliance)

Asthma

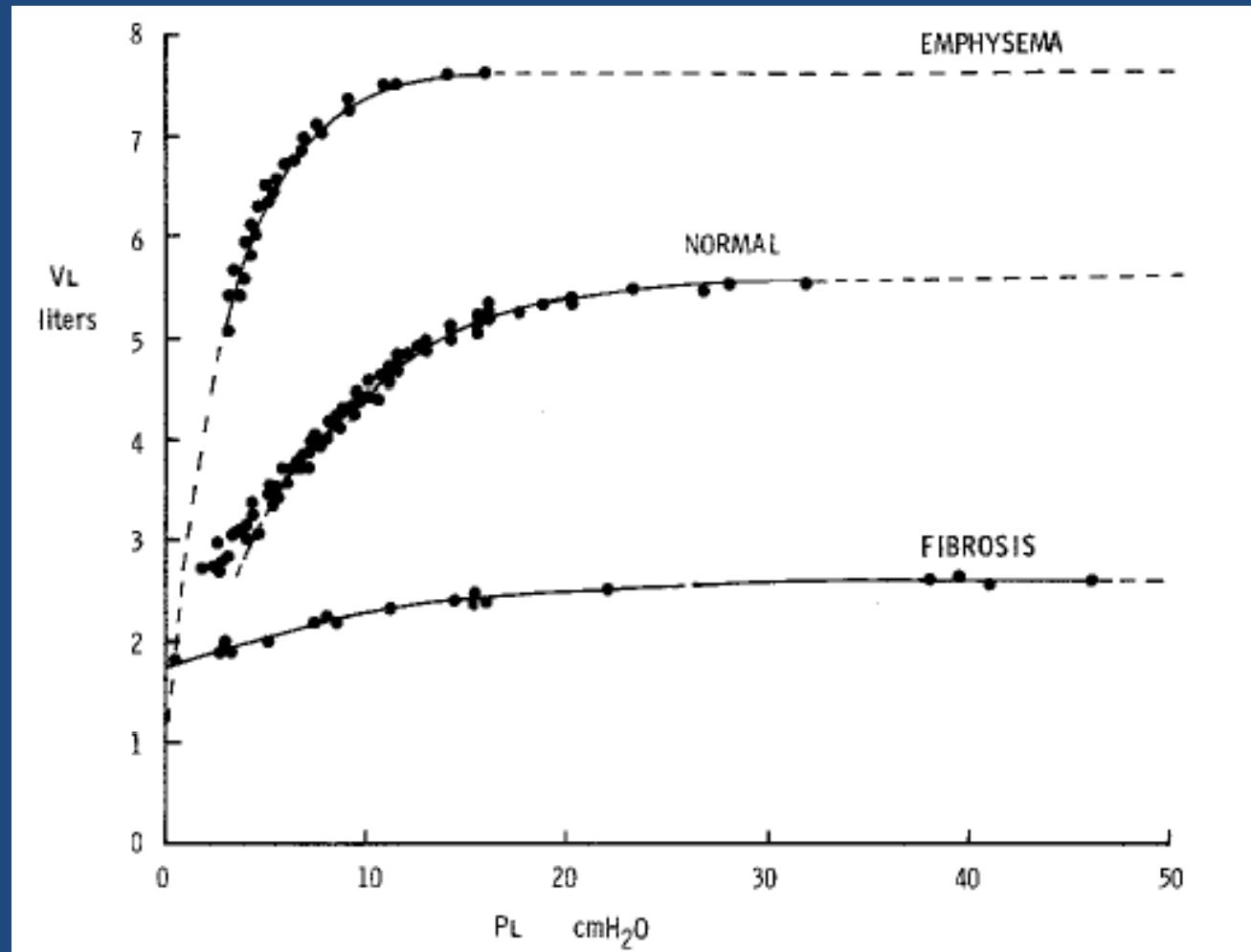
- Again in spontaneously breathing patients
- In one study, P-V curves (via plethysmography) during exacerbations showed a reduction in lung volume and an increase in elasticity with salbutamol
- It was due measurement error
- No data describing changes in the P-V curve during status asthmaticus

Thorax1978;33(3):394-400

ILD

- Alveoli become fibrotic, reducing lung gas volume, which shifts the P-V curve downward on the volume axis
- Concavity towards pressure axis is reduced
- Shape of the P-V curve may not be a sensitive means of assessing alveolar fibrosis

PV curves in emphysema & ILD



Pride NB, Macklem PT. Lung mechanics in disease. 1986:659-692.

In CCF

- Alveoli progressively fill with fluid, which impairs surfactant function and reduces gas volume
- Pathophysiology similar to early ARDS
- Marked increase in hysteresis due to surfactant loss
- Paucity of data depicting PV curves in CCF

Obesity

- Markedly reduced FRC
- Decreased compliance
 - Lung
 - Chest wall