Respiratory Mechanics

Critical Care Medicine

Specialty Board Tutorial

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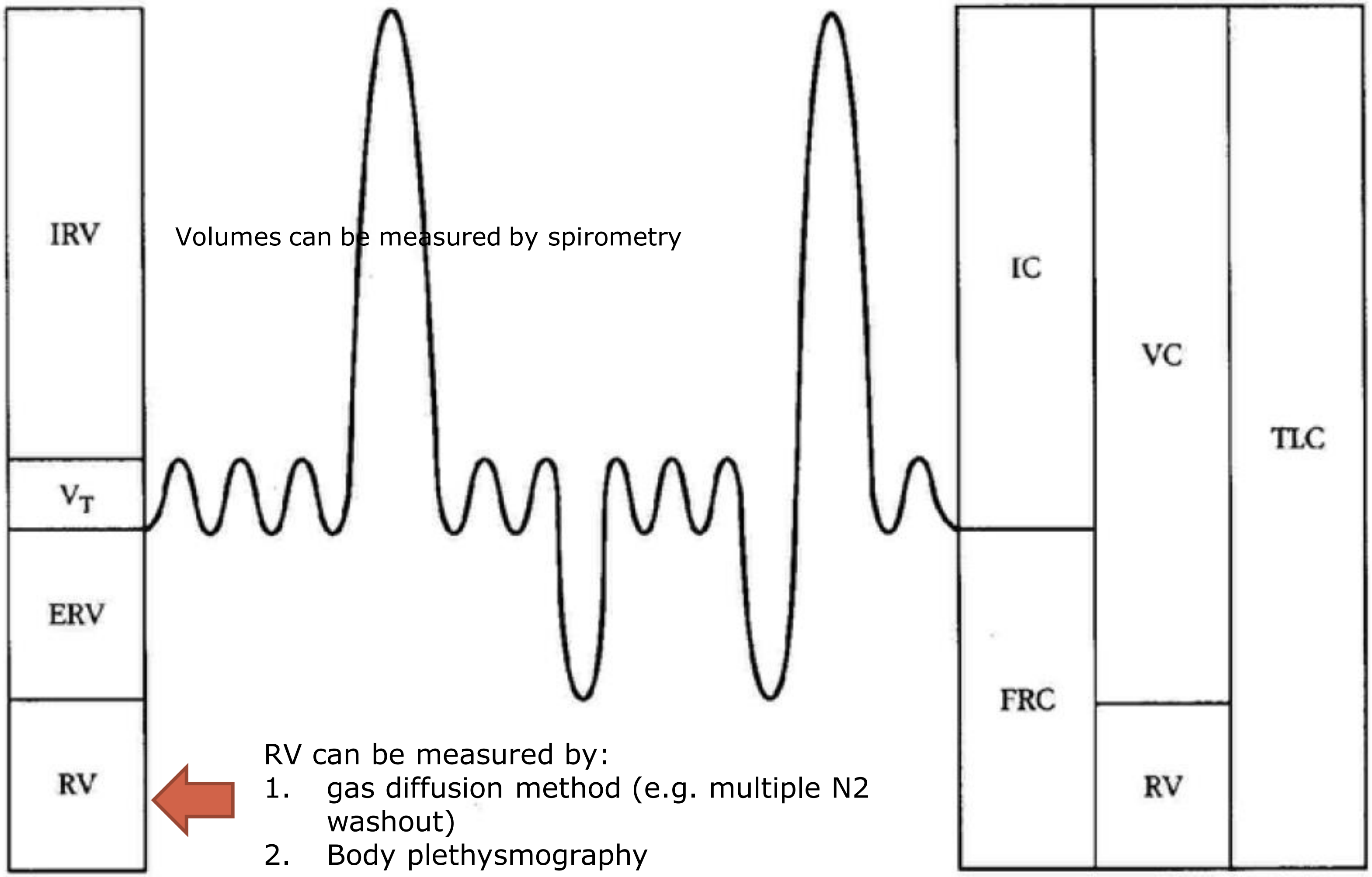
17th June 2014

This lecture covers:

1. Basic knowledge: volume, flow, pressure
2. Lung parenchymal condition: compliance
3. Airway condition: FEV1/FVC, Resistance, Flow pattern
4. Chest wall condition: Chest wall compliance
5. Interaction of all factors: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV
6. Work of breathing: Campbell diagram, Pressure-Time Product (PTP)
7. The force of breathing: SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1
8. Other application: Transpulmonary pressure

Basic knowledge: Volume, flow, pressure

Lung volumes



Volumes can be measured by spirometry

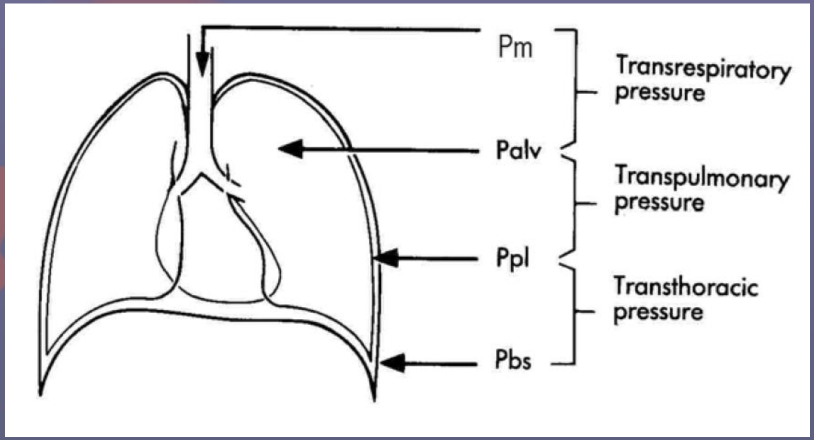
RV can be measured by:

1. gas diffusion method (e.g. multiple N2 washout)
2. Body plethysmography

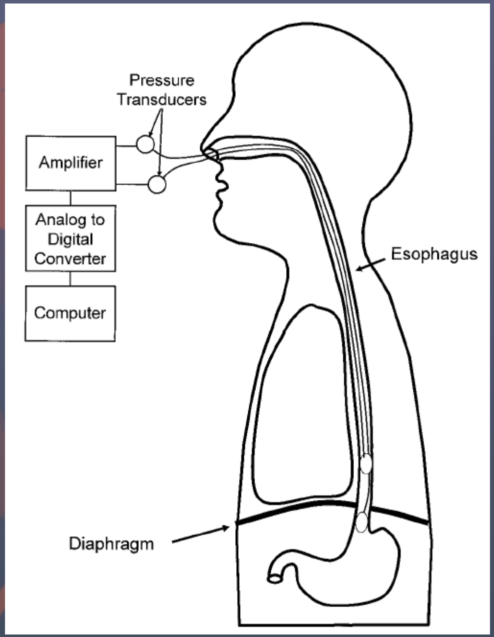
Airflow and Pressures

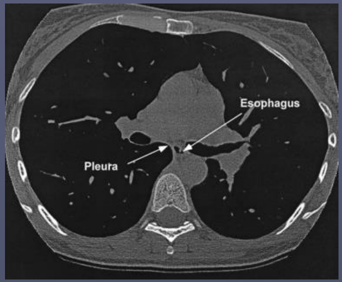
- Airflow is measured at the airway opening
  - With a pneumotach
  - Integration of flow witth time is volume
- Primary pressures
  - Pbs (body surface) = Patm = 0
  - Ppl = Pes
  - Pm (mouth) = Paw at Y-end (during MV)
  - Pgastric
- Derived pressures
  - Trans-resp system P = Paw – Patm
  - Palv = Paw during no flow
  - Transpulmonary P = Palv (or Paw during no flow) – Pes
  - Transthoracic P = Pes - Patm

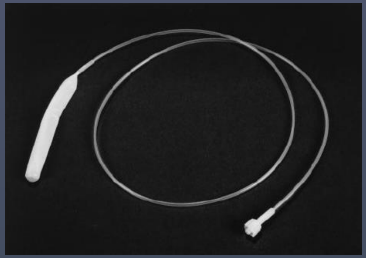
Basic primary and derived pressures



Others: Pes and Pgastric P

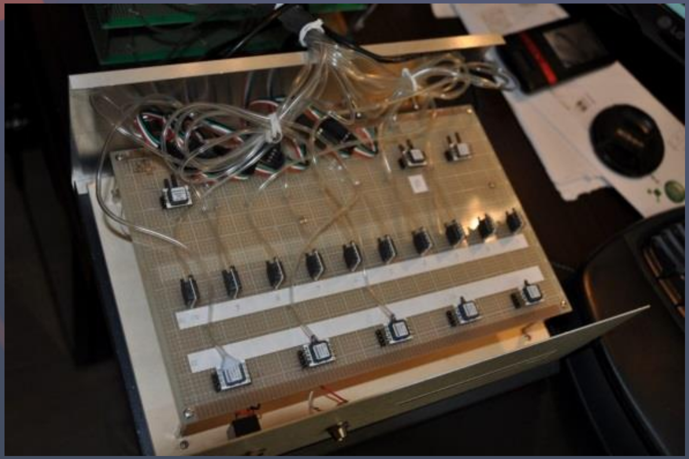






Actual measurement

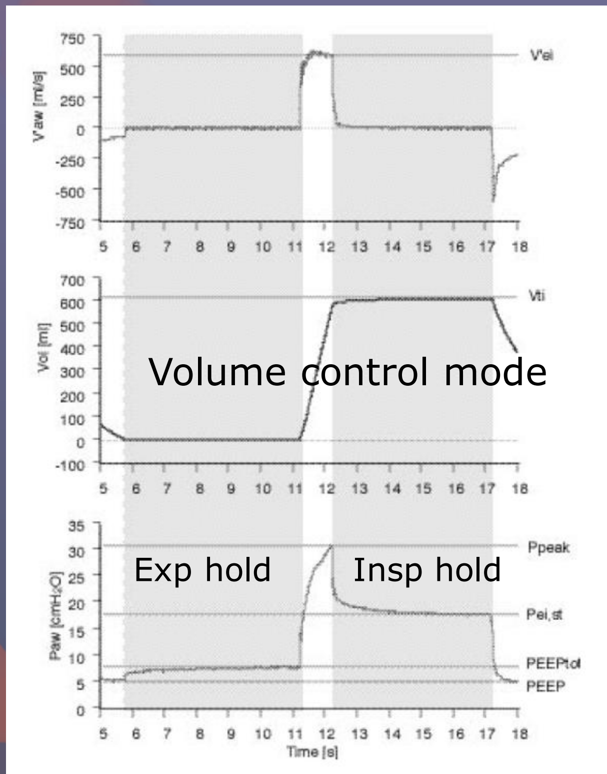
- Flow & pressures
  - Pneumotach & airway pressure transducer placed distal to Y-connector
  - Esophageal balloon catheter
  - Signals transformed by an analogue-to-digital converter, recorded by LabVIEW software
- Edi signal
  - Acquired from ventilator at 100 Hz via a RS232 interface to the ServoTracker software
- Time-aligned and analyzed off-line



Lung and chest wall conditions: Compliance

- Two situations:
  - Dynamic compliance (actively breathing, e.g. at peak flow)
  - Static situation (during no flow condition, e.g. at plateau pressure obtained by inspiratory pause; or in a totally relaxed patient, P and V obtained point-by-point)
- Formulae
  - Compliance = delta volume / delta P *(P is across unit to be measured, unit of compliance is ml/cmH2O)*
    - Crs = Vt/(Trans-resp system P at end-insp – Trans-resp system P at end-exp)
    - Clung = Vt/ (Trans-pulmonary P at end-insp – Trans-pulmonary at end-exp)
    - Ccw = Vt/ (Trans-thoracic P at end-insp – Trans-thoracic P at end-exp)
  - Elastance = 1/Compliance

Compliance and Resistance measurement of the respiratory system (Double Occlusion Method, paralyzed patient)



Static compliance = TV / (Pplat – PEEP)

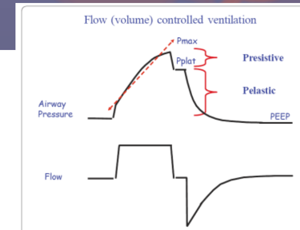


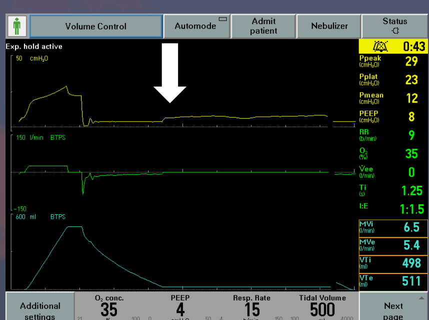
Figure 2. Analysis of airway pressures and flow during volume-controlled mechanical ventilation. The difference between peak or maximal pressure (P_{max}) and plateau pressure (P_{plat}) defines the resistive pressure, whereas the difference between P_{plat} and positive end-expiratory pressure (PEEP) defines the elastic pressure. Analysis of the airway pressure shape during the phase of constant flow inflation (removing initial and final parts) can be used to calculate the stress index (arrow).

The respective data are:

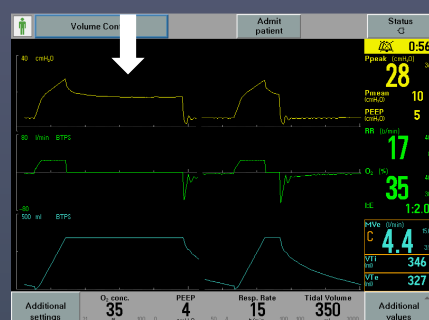
V'ei	0.6	l/s
Vti	610	ml
Ppeak	31	cmH2O
Pei,st	17.5	cmH2O
PEEPtot	7.5	cmH2O
PEEPe	5	cmH2O

Based on these data, we can calculate Rmax, Cstat, and PEEPi according to the formulas of § 4.2., as follows :

Cstat	610 / (17.5 - 7.5)	=	61	ml/cmH2O
Rmax	(31 - 17.5) / 0.6	=	22.5	cmH2O/l/s
PEEPi	7.5 - 5	=	2.5	cmH2O



Exp hold



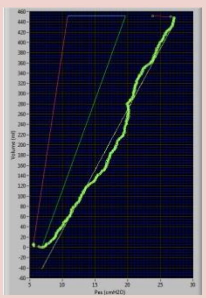
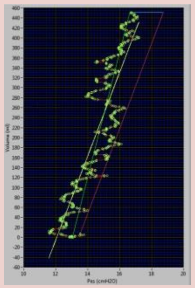
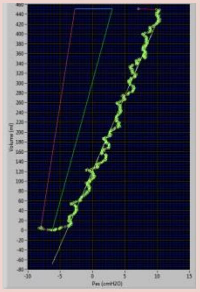
Insp hold

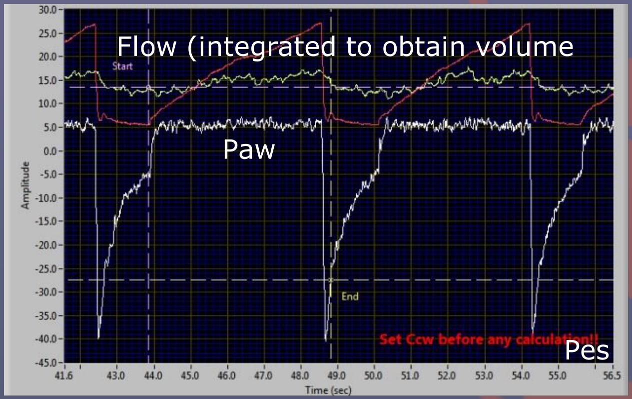
- Compliance if of:

1. The whole respiratory system (tubings, ETT, patient) if pressure port is in ventilator
2. The patient and ETT, if pressure port is at Y-end
3. The patient only, if pressure port is at carina (beyond ETT tip)

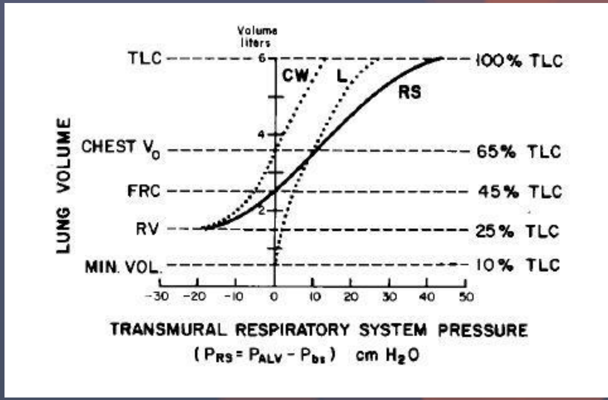
Full compliance study of respiratory system, lungs and chest wall in research setting (paralyzed patient)

Formula: 1/Clung = 1/Ctotal – 1/Ccw

Patient	Total compliance (ml/cmH2)	Chest wall compliance	Lung compliance	Lung (calculated as C_{total} - C_{cw})
CHF	23.6  Paw C_{total} = Delta (Paw – Patm) /TV	84  Pes C_{cw} = Delta (Pes – Patm)/TV	30.5  Transpul P = Paw - Pes C_{lung} = Delta (Paw-Pes)/TV	32.8 $1/C_{lung}$ = $1/C_{total}$ – $1/C_{cw}$
COPD	84.5	195	142	149

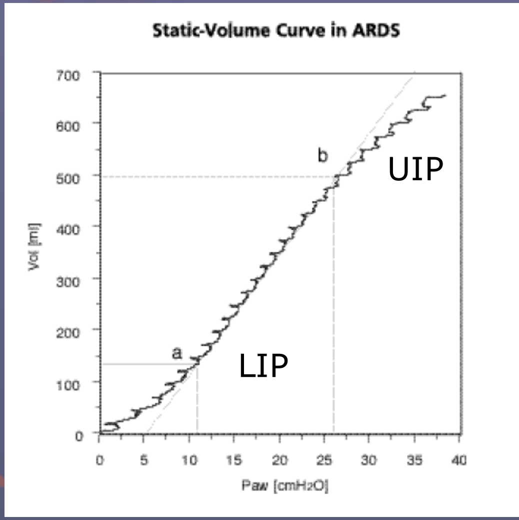


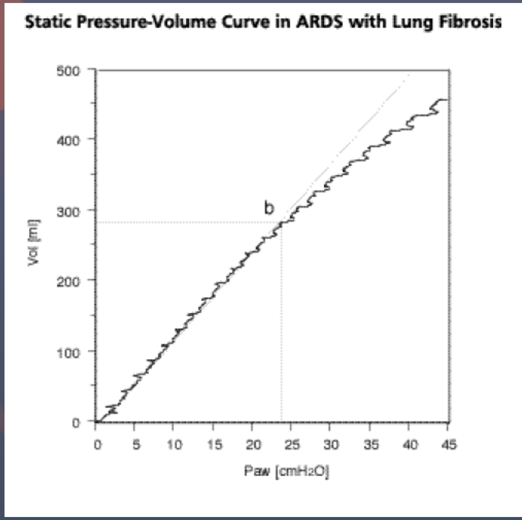
Time tracings of the paralyzed CHF patient



Static relaxation pressure-volume curve

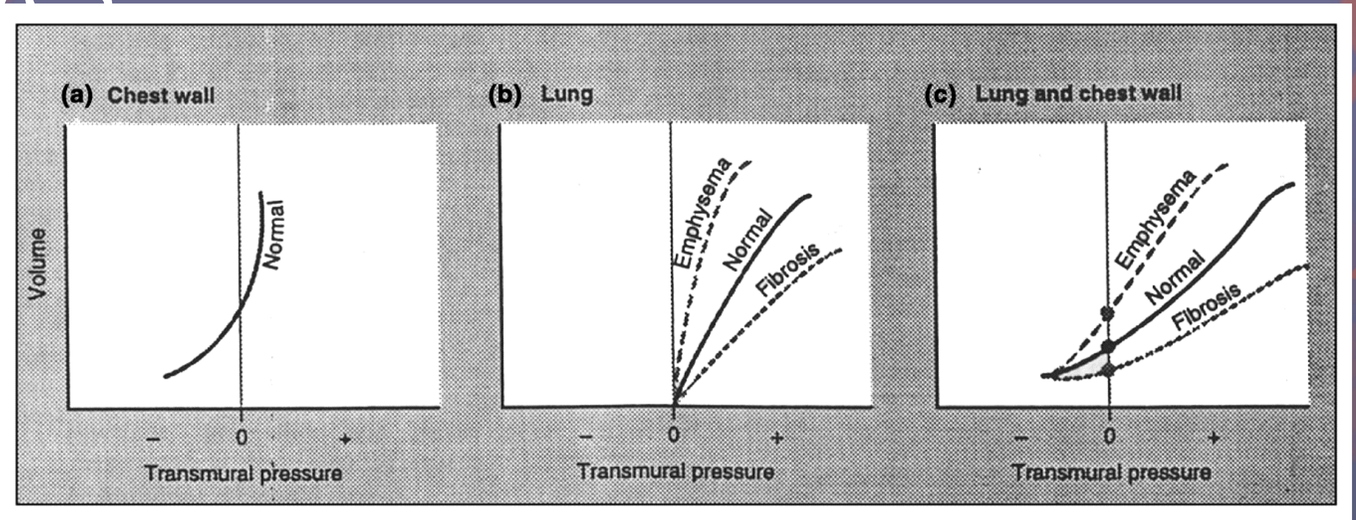
Compliance measurement of the respiratory system in research situation: Static PV curve by the Low Constant Flow method

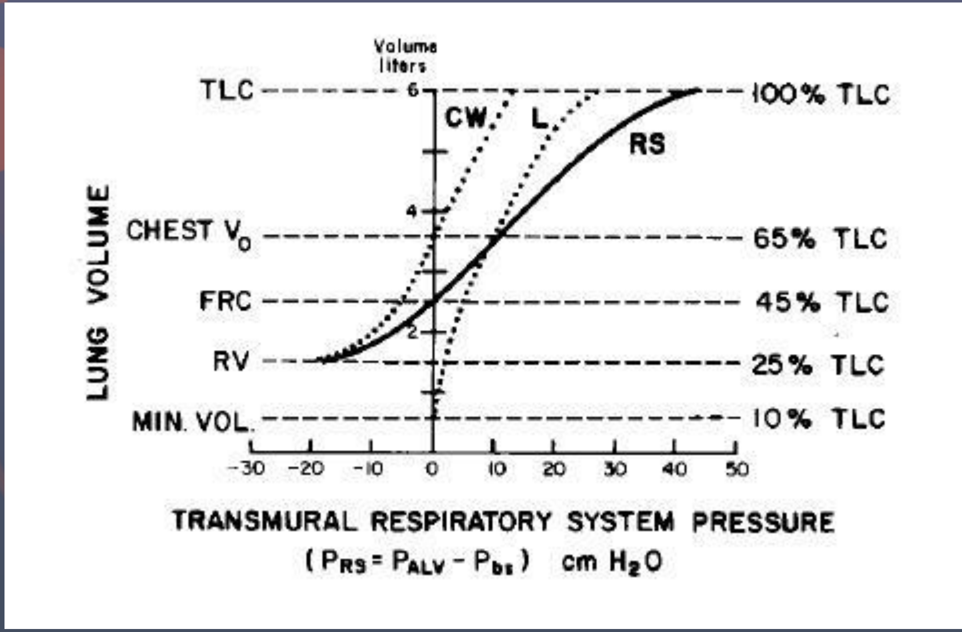




- Compliance is of the whole respiratory system if Paw is used
- Tiny irregularities correspond to cardiac oscillations
- Slope of straight portion = best compliance of the resp system
- ARDS: Lower (LIP) and upper inflection points (UIP) in ARDS
- Lung fibrosis: No lower inflection point implies no recruitable alveoli, B represents start of upper inflection zone and implies overdistension

Static Relaxtion Pressure-Volume Curves





Grinnan and Truwit Critical Care 2005 9:472-484
doi:10.1186/cc3516

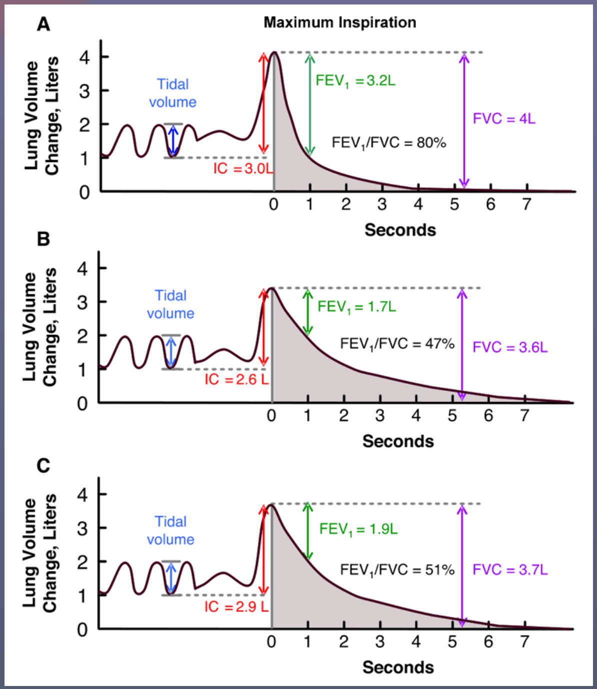
- At lung volumes above ~70% of the vital capacity, the chest wall no longer tends to spring out but instead to spring in.
- relaxation pressure of the lung plus chest wall is simply the sum of the relaxation pressures of the two components.

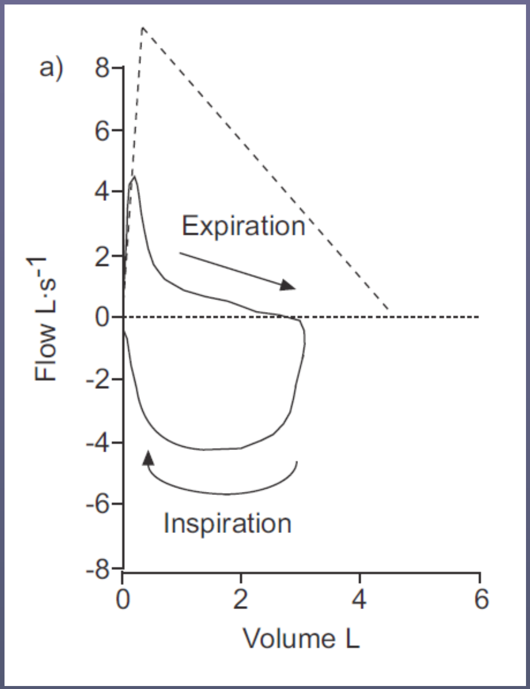
Application: Open lung tool to look for the best dynamic compliance for PEEP setting

Airway condition

- Awake patient: FEV1/FVC by forced spirometry
- Intubated patient: Resistance by inspiratory hold

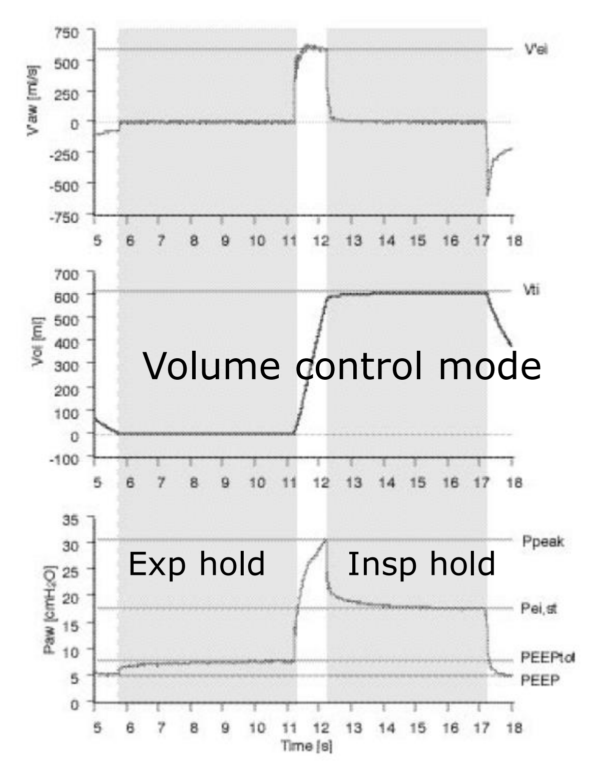
Forced spirometry: in non-intubated patients





1. FEV1/FVC ratio
   - If <70%, means there if airflow obstruction (GOLD Guideline criteria)
   - If <lower 5th percentile, means there is airflow obstruction (more stringent statistical critieria, HK local reference equation: *Ip MS et al. Updated spirometric reference values for adult Chinese in Hong Kong and implications on clinical utilization. Chest. 2006 Feb;129(2):384-92.*)
2. FEV1
   - The predicted percentage reflects the severity of the airflow obstruction, if present
   - Severity of obstruction is based on FEV1
     - < 35% predicted: severe
     - 35 – 50% predicted: moderate
     - 50 – 80% predicted: mild

Compliance and Resistance measurement of the respiratory system (Double Occlusion Method, paralyzed patient)



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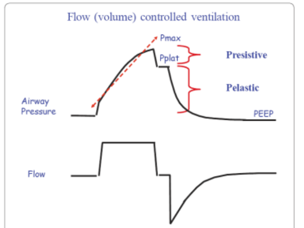

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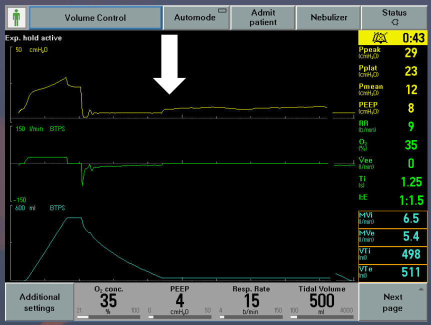

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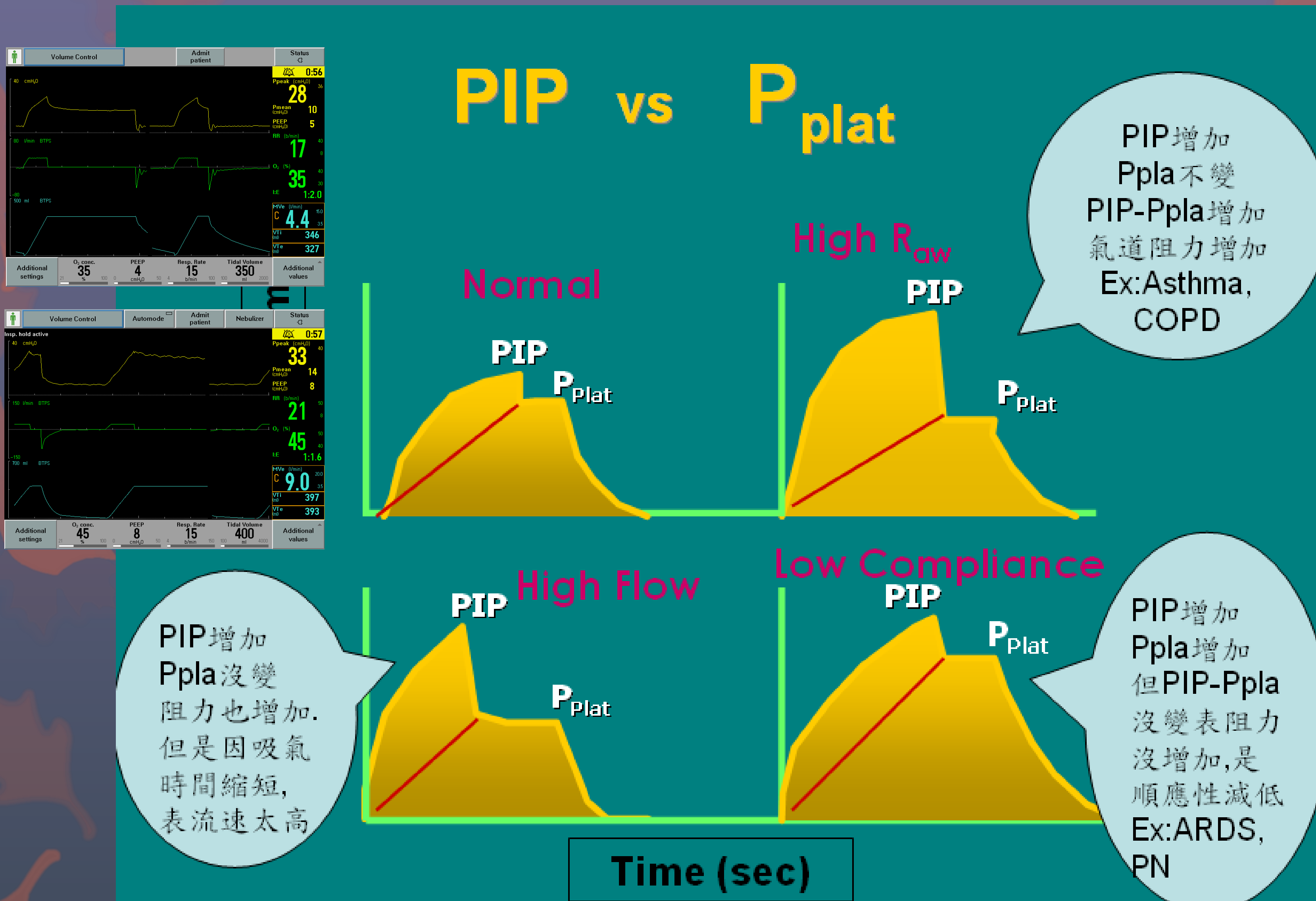
Inspiratory hold, volume control mode: Distinguish among resistance, compliance and flow problem

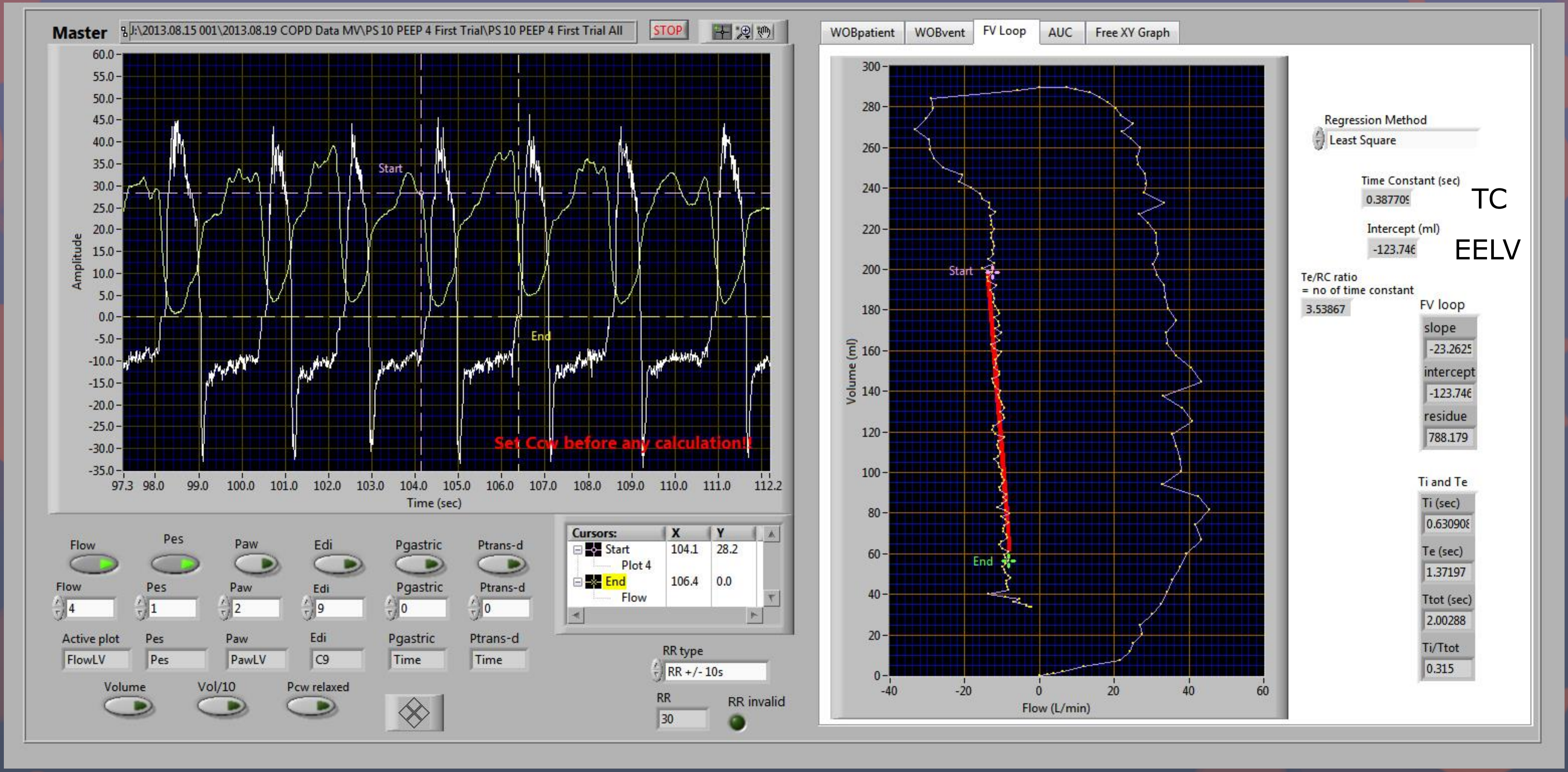


Interaction of all factors

Interaction of of lung, airway and chest wall: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV

Time Constant

- = Resistance x Compliance = (delta P/Flow) x (delta vol / delta P)
- = delta Volume/Flow (can be read at expiration of passive flow-volume loop)



Flow-Volume Loop in an actively breathing COPD Patient: Shows Time Constant and End-Exp Lung Volume (EELV)

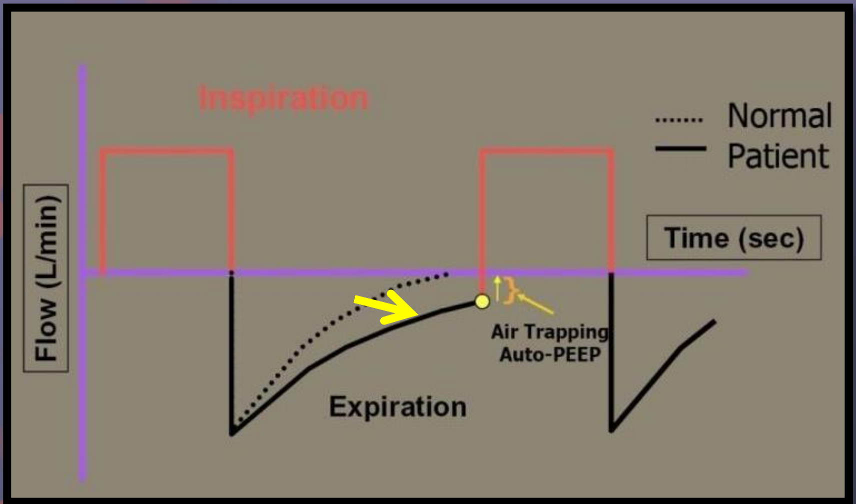
Clinical implications

Duration of step change in pressure (s)	Resulting change in volume (% of ΔVol,max)
1 x Time Constant	63
2 x Time Constant	86.5
3 x Time Constant	95
4 x Time Constant	98
5 x Time Constant	99
Infinite x Time Constant	100

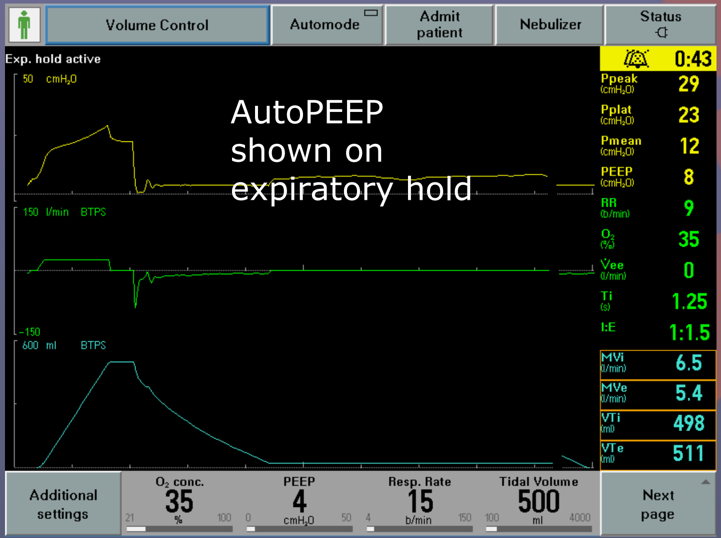
- To avoid hyperinflation, we must allow an expiratory time of 4, or at least 3, time constants.

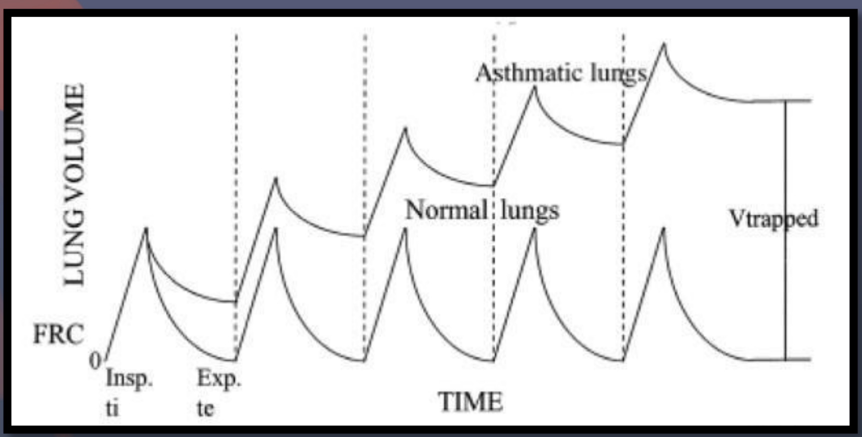
	Resistance	Compliance	RC	Te required
ARDS	Low	Low	Low	Low
Acute Asthma	High	Normal	High	High
Emphysema	High (exp)	High	High	High

Ventilator tracing of incomplete emptying due to AFO



Flow vs time curve





Actually what happens is: Volume vs time curve (without zero resetting before each breath)

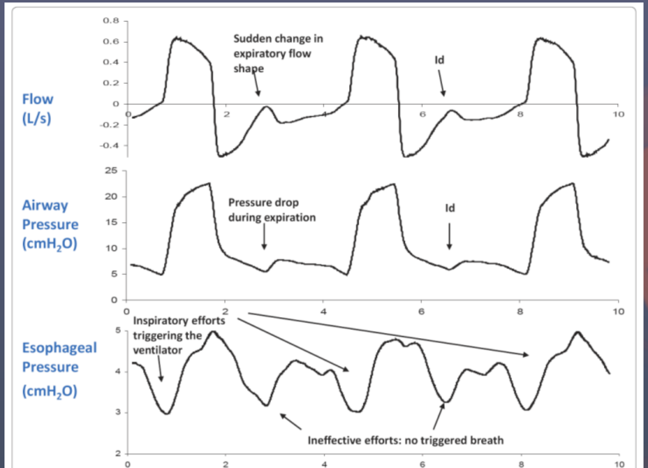
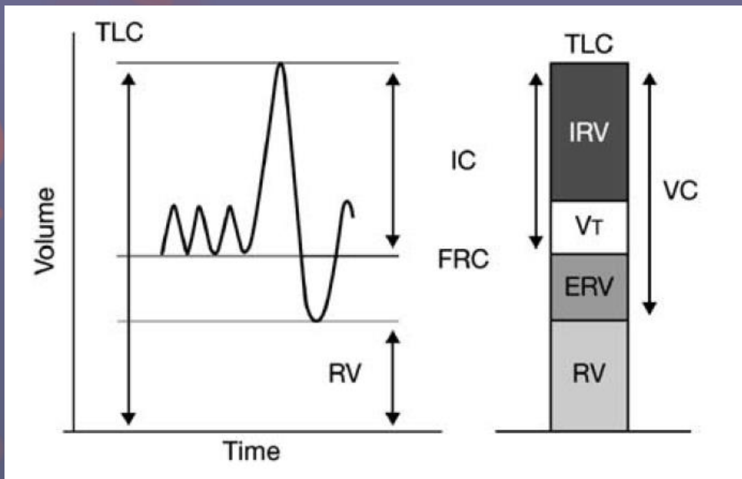
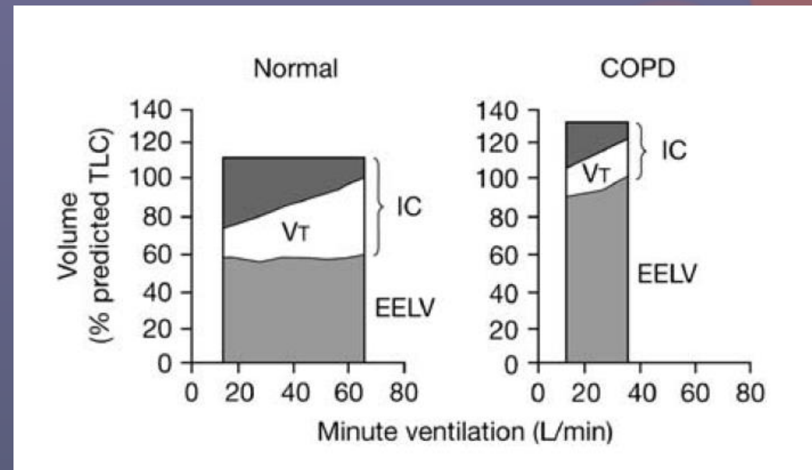


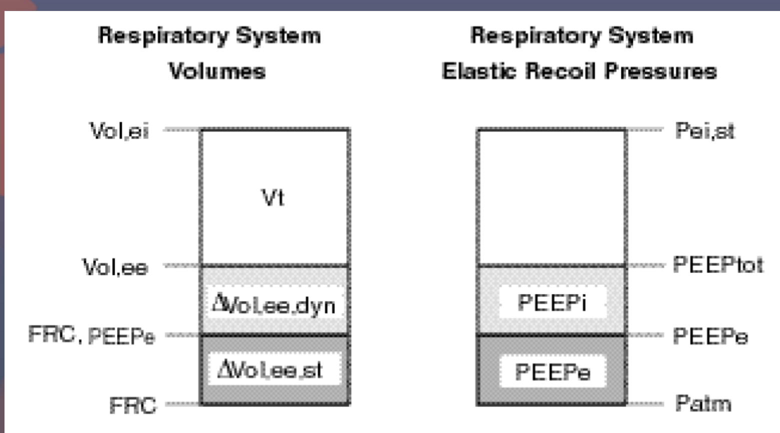
Figure 5. Example of ineffective efforts demonstrated on the esophageal pressure analysis. These missing efforts can be easily recognized on the airway pressure trace and the flow trace as indicated by the arrows. Id, idem.

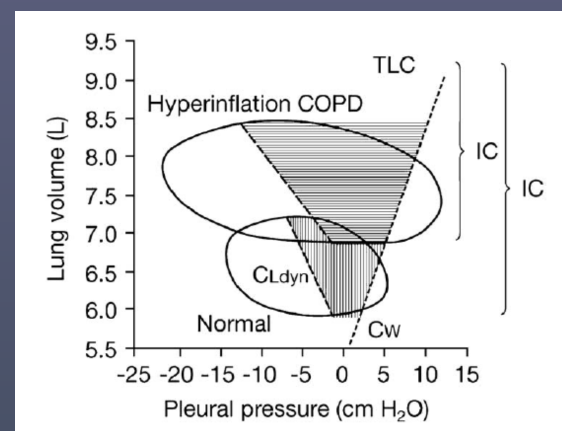
O'Donnell DE, et al. Eur Res Rev 2006

Terminology







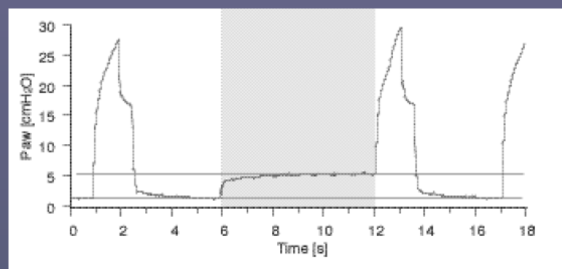


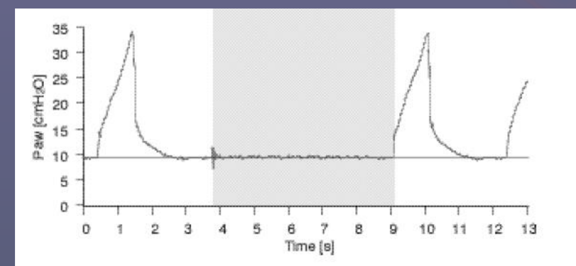
PEEPtot = PEEPe + PEEPi; i.e. PEEPi = PEEPtot – PEEPe

Static and dynamic intrinsic PEEP: Static and dynamic refers to the method of measurement, not whether the patient is actively breathing or paralyzed

Static intrinsic PEEP

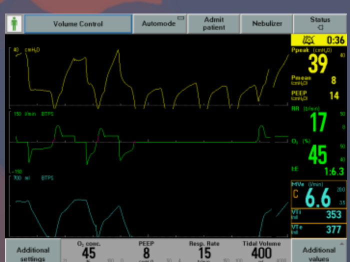
- In a paralyzed patient
  - End-exp occulsion manoevre (i.e. Based on PEEPi, st = PEEPtot – PEEPe)



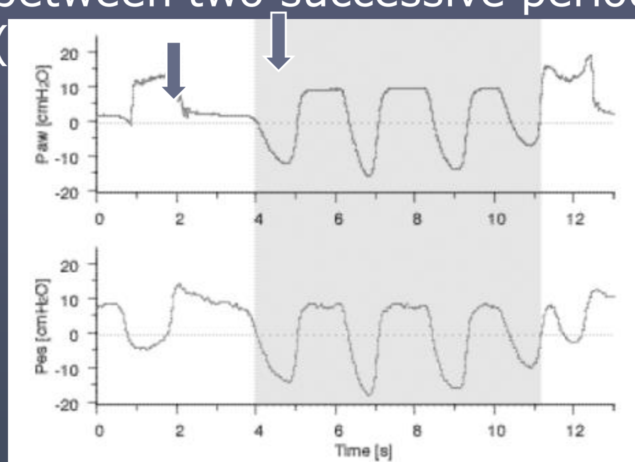


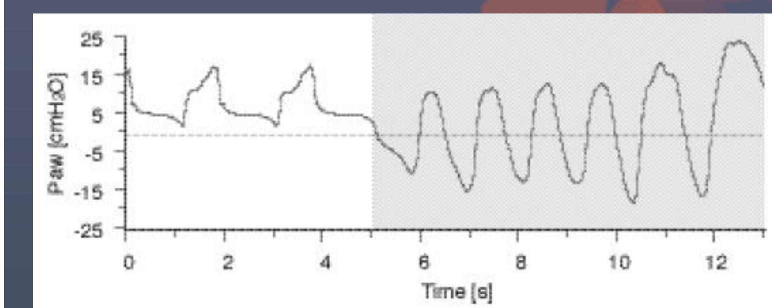
Zero PEEPi

- In actively breathing patient
  - 7-sec end exp occlusion manoevre, PEEPtot is the Paw between two successive periods of muscular activation (



Real-life tracing





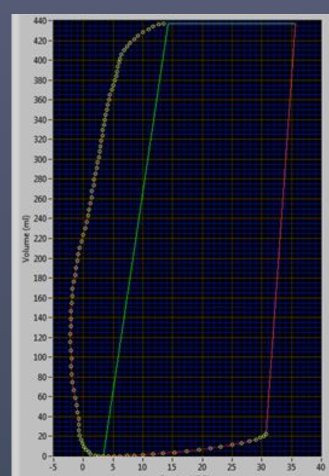
Pseudo-relaxation period too short and not flat: Not fit for analysis

Dynamic PEEPi

- Based on Pes drop to initiate flow, therefore refers to actively breathing patients only
- = Negative deflection of Pes from the onset of inspiratory effort to onset of flow from zero

TV

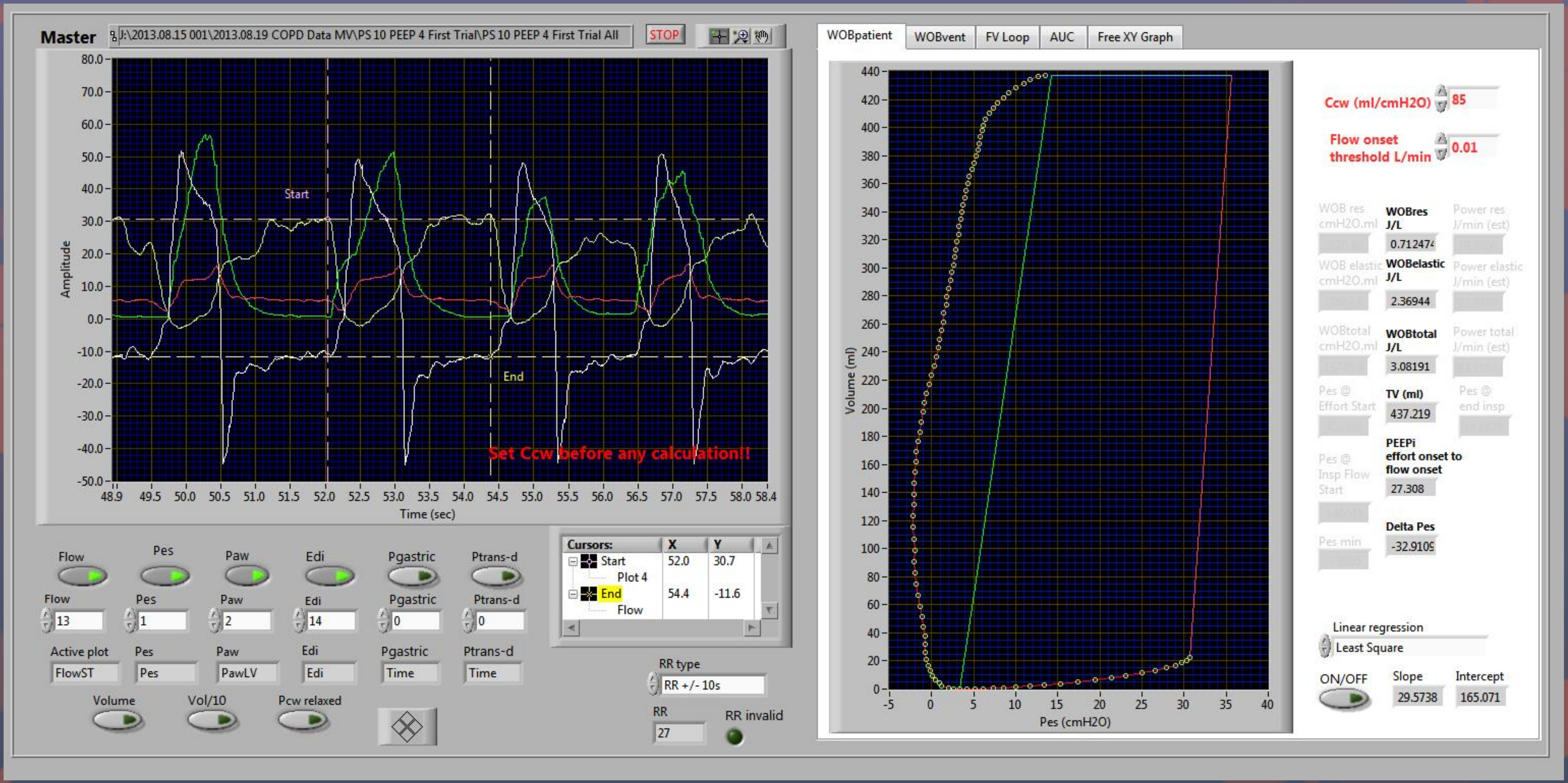
When displayed in a Pes-Vol loop:



Pes generated to initiate flow

Dynamic PEEPi

Based on the Pes drop to initiate flow, in a spontaneously breathing patient



Work of breathing

Campbell’s Diagram, Pressure-Time Product

Campbell's Diagram

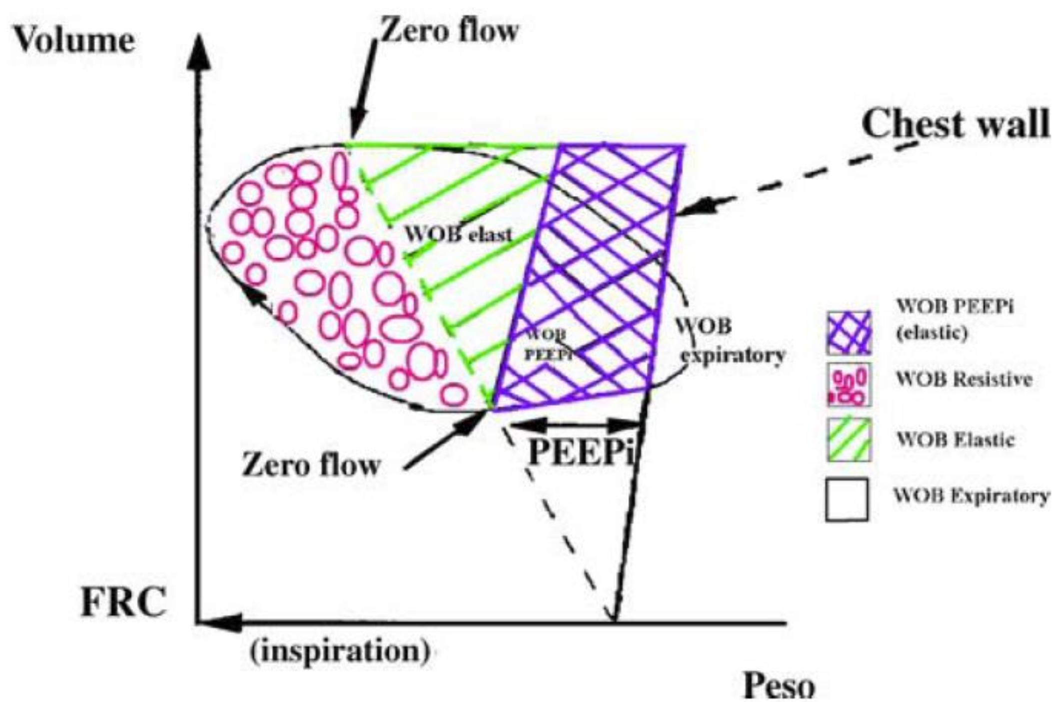
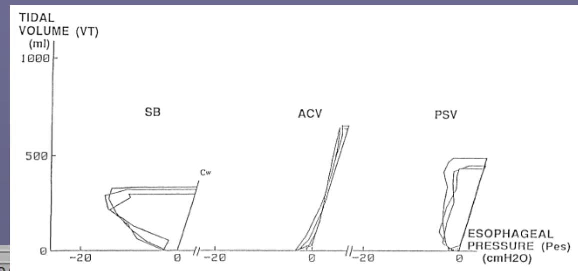


Fig. 1 Campbell's diagram. Work of breathing measured by the esophageal pressure: resistive WOB (W_{resist}), elastic WOB (W_{elast}), WOB related to active expiration (*WOB expiratory*) and WOB related to intrinsic PEEP (W_{PEEPi}). *Chest wall*: this *thick line* (the chest wall compliance) represents the pleural (esophageal) pressure obtained when muscles are totally relaxed and lung volume increases above functional residual capacity, measured in static conditions

Cabello B, et al. ICM 2006

Campbell's Diagram in practice



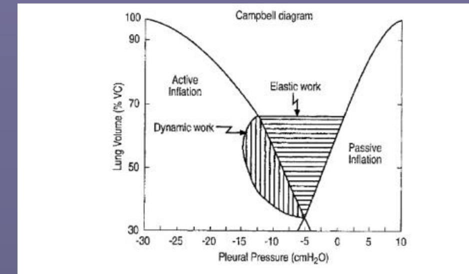
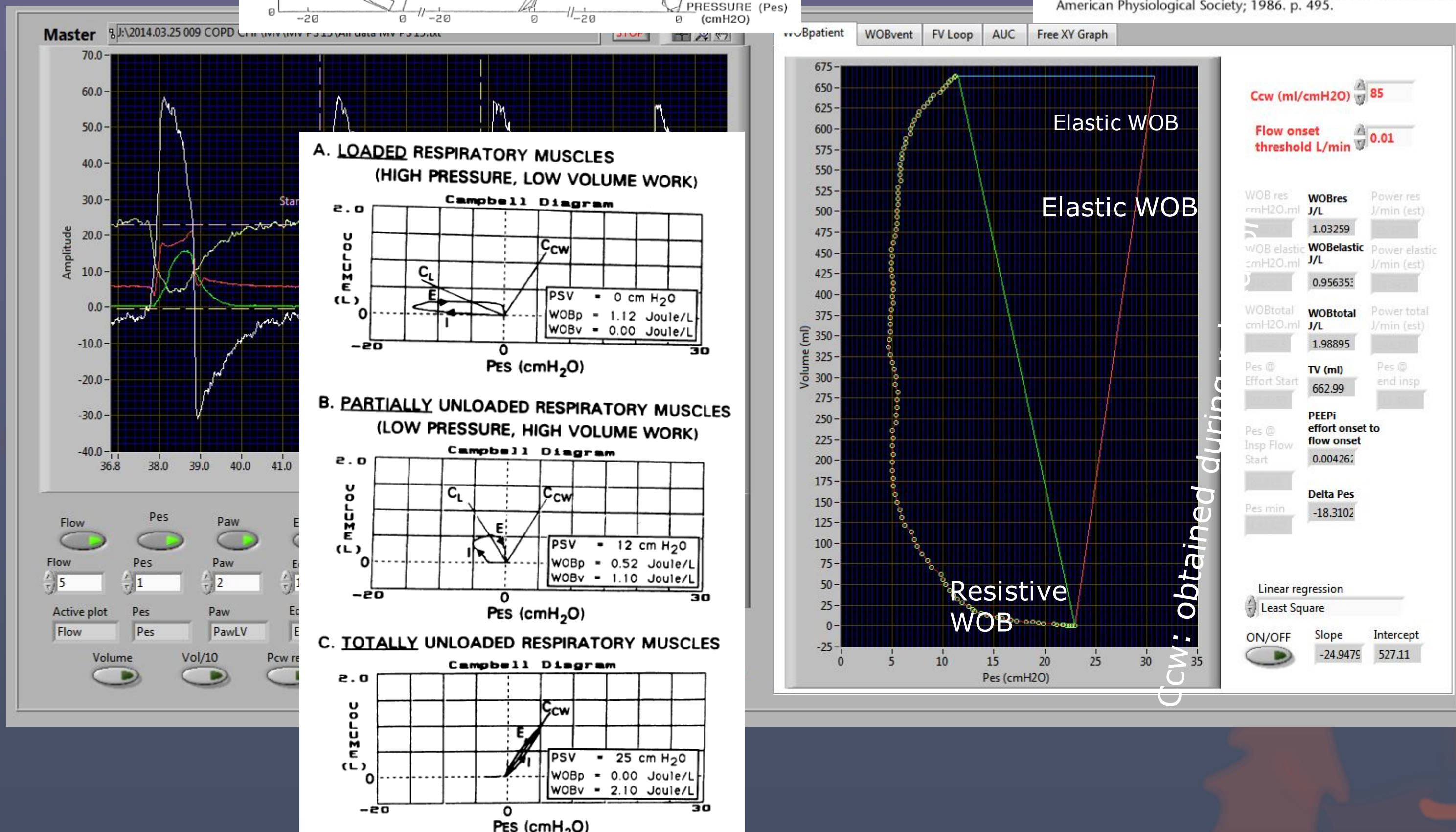
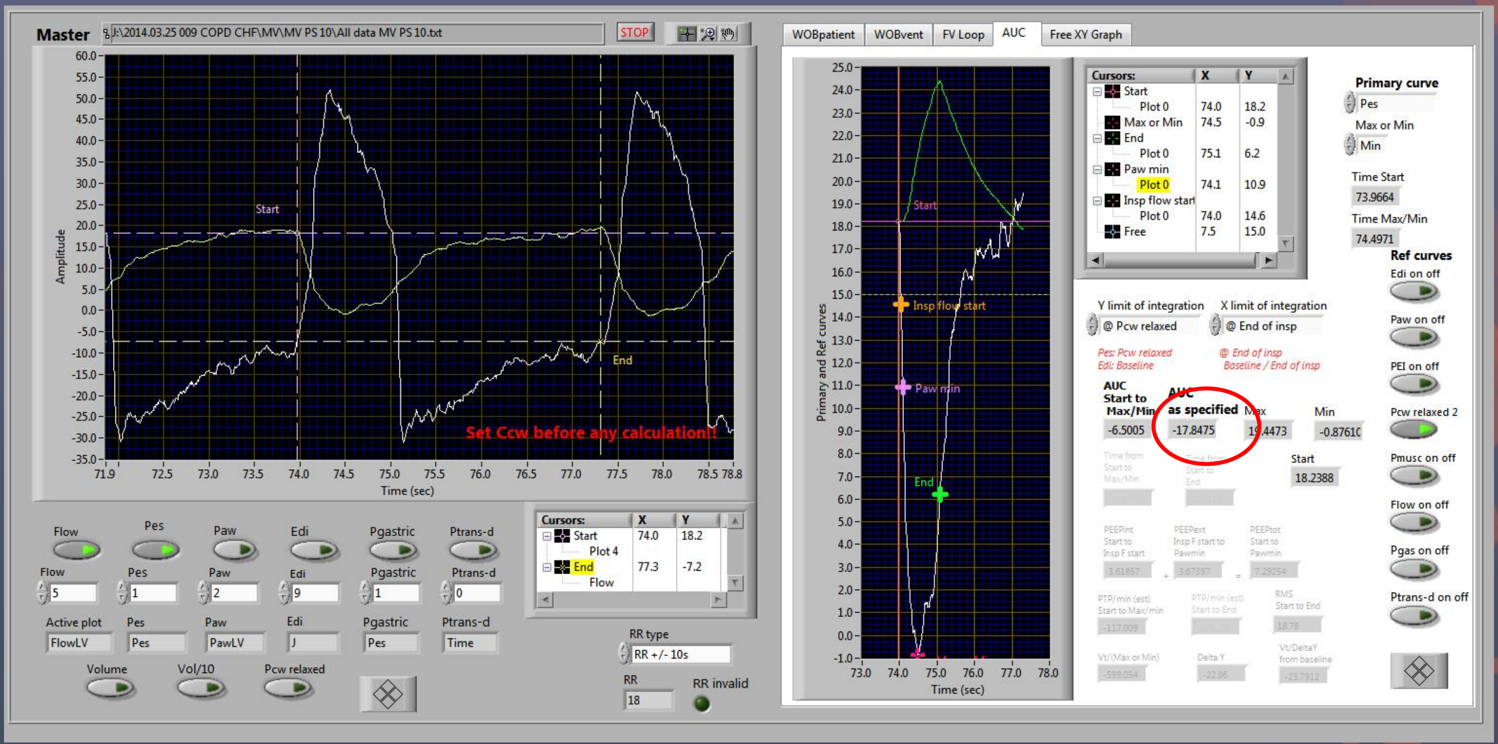


Figure 2. Campbell diagram. Graphical analysis of the work done during a breathing cycle by the inspiratory muscles. *Vertical hatching*: Work done to overcome flow resistance of the lungs. *Horizontal hatching*: Work done to overcome elastance of the lungs and chest wall. Modified by permission from Macklem PT, Mead J, editors. Handbook of physiology. Vol. 3: The respiratory system, Part 3. Bethesda, MD: American Physiological Society; 1986. p. 495.



Pressure-time product

- PTP that reflects the exertion of the respiratory muscles for inspiration (PTPinsp,pat) = time interval between the inspiratory effort start and the end of the inspiratory phase of a cycle
    - PTP/breath x RR = PTP per minute (cmH2O.s/min)



The Force of Breathing

SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1

Monitoring

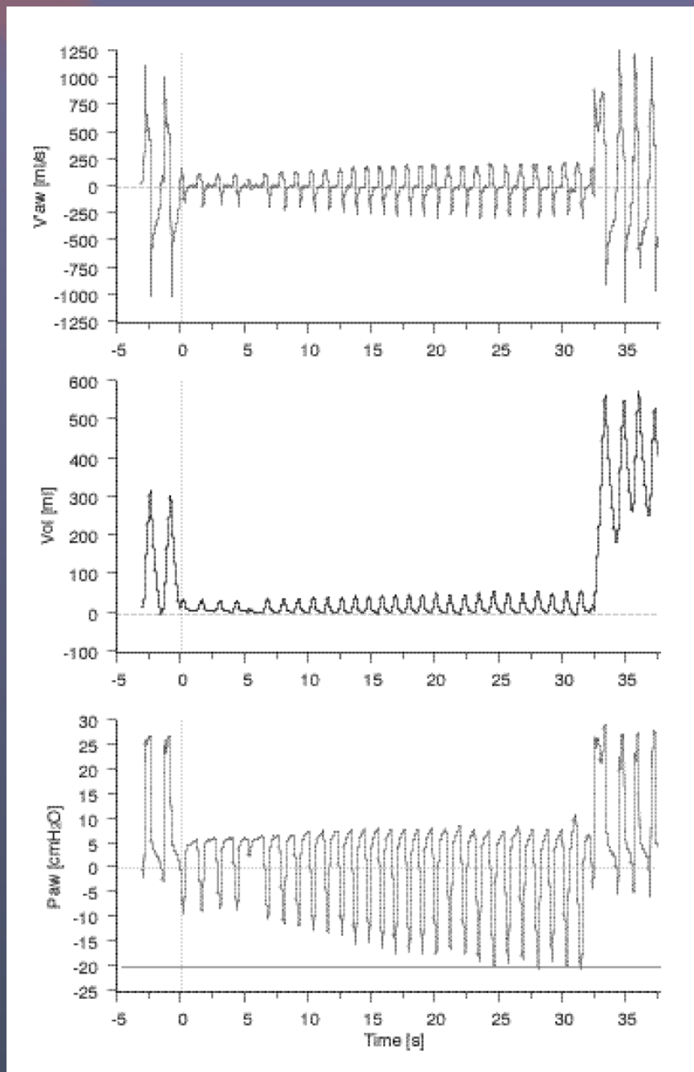
SVC, MIP, MEP in spontaneously breathing patient

	Normal	Predictive of respiratory failure
Slow Vital Capacity (SVC)	50 ml/kg	< 20 ml/kg
Maximal Inspiratory Pressure (MIP) – from RV	- 70 cm H2O	Less neg than – 30 H2O
Maximal Expiratory Pressure (MEP) -from TLC	150 cm H2O	< 40 cm H2O

MIP in intubated patient

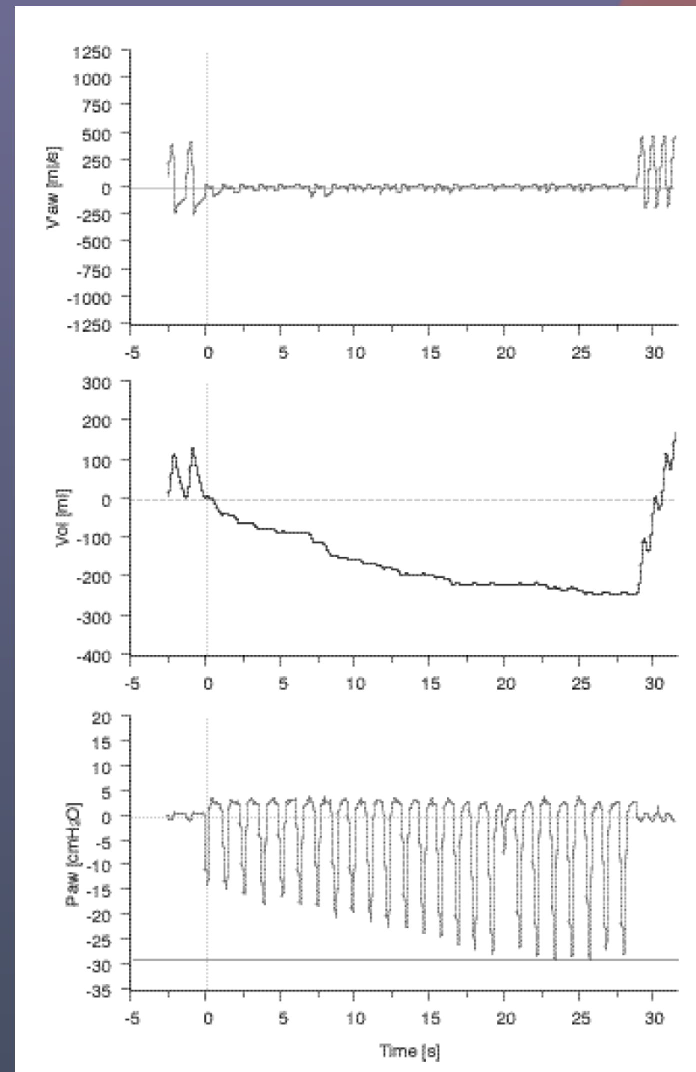
- Negative pressure generated by the inspiratory muscles during a maximal inspiratory effort, performed during temporary occlusion of the airway opening
- = PIMax, = NIP, expressed as a positive number
- Unit is cmH2O
- Two methods (after removal of any PEEPe applied by the ventilator):
  1. at the end-expiratory volume
  2. below the end-expiratory volume

Method 1



End-expiratory occlusion

Method 2



Requires a one-way valve that limit occlusion to inspiration only, but free to exhale

Transdiaphragmatic pressure

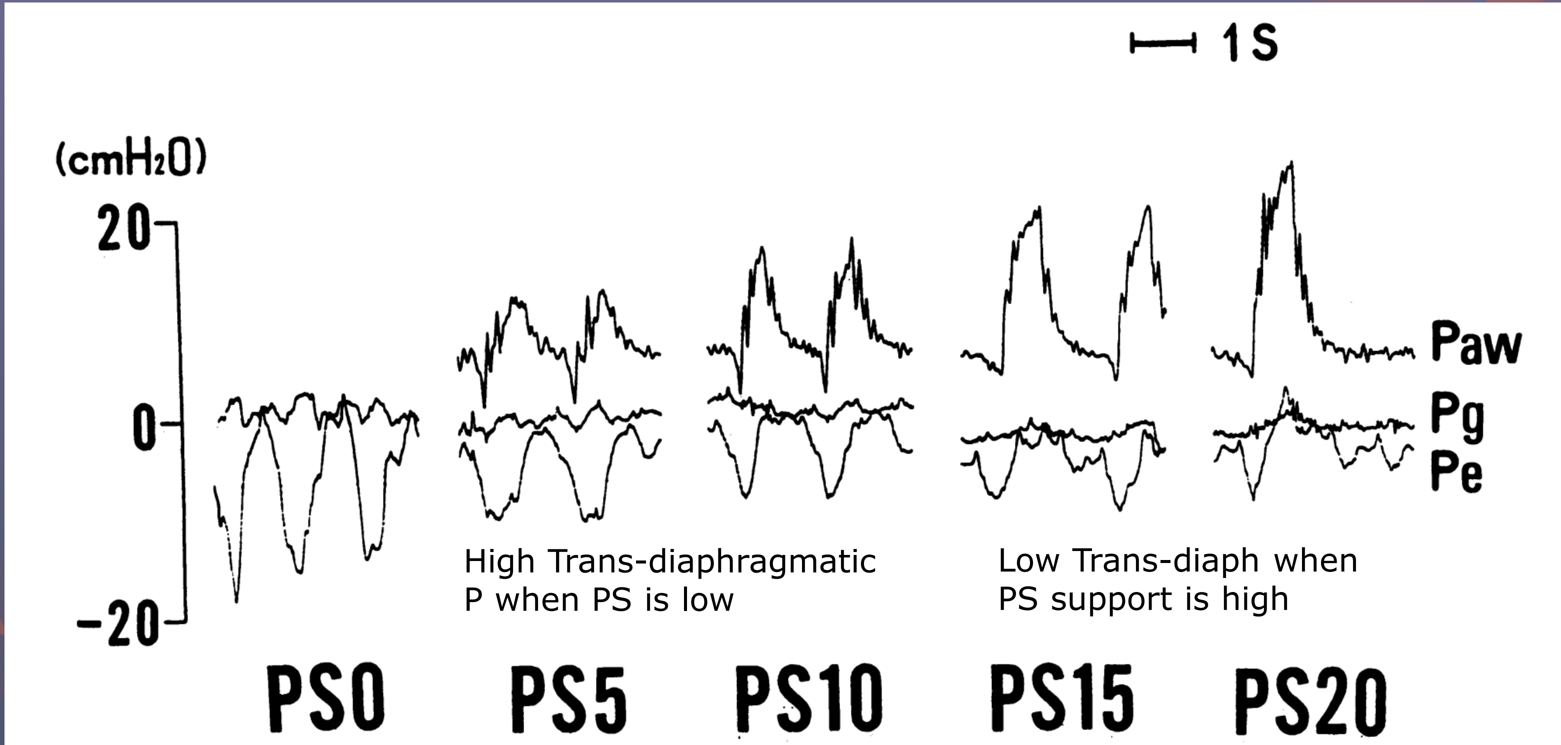
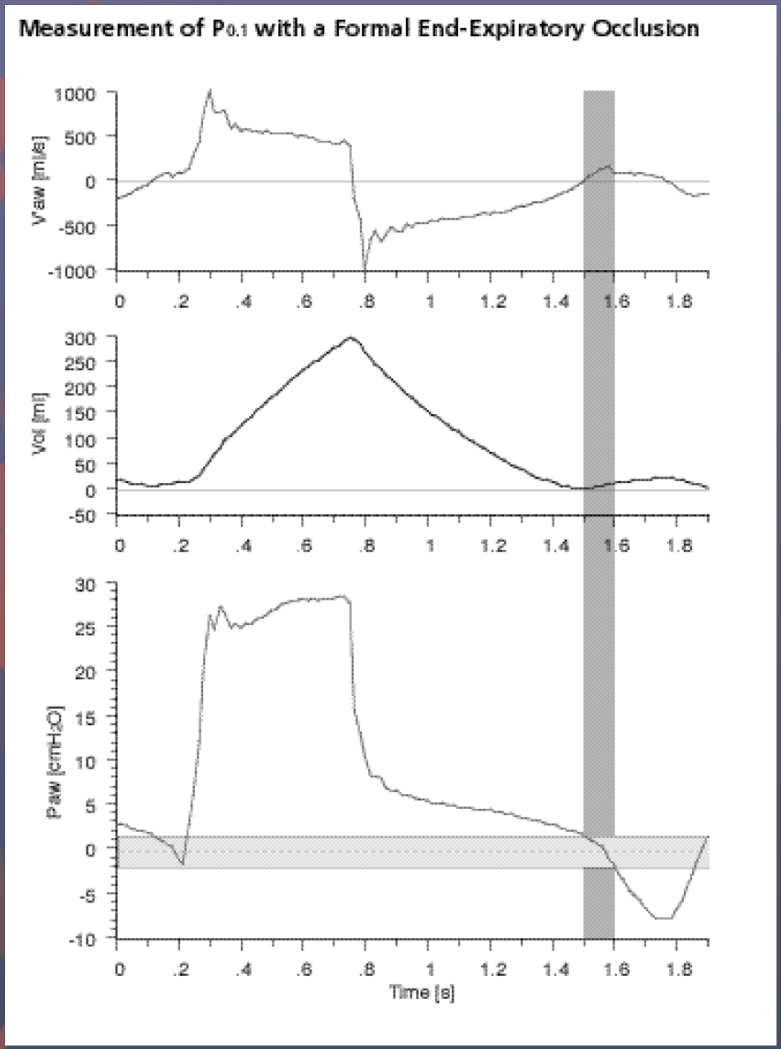


FIGURE 3. Recordings of Paw, Pg, and Pe from five levels of PSV in six patients. Paw in PS0 was deleted because airway was opened. Pe in PS20 was shifted upward at the end of inspiration.

Transdiaphragmatic pressure = Pes – Pgastric
Pgastric is measured by a gastric balloon

Kimura T, et al. Chest 1991

Occlusion pressure at 0.1 sec

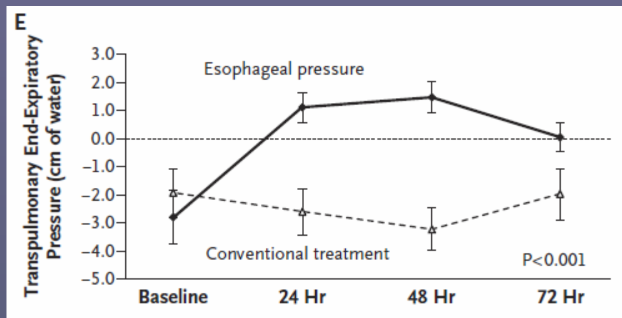


- Corresponds to the drop in Paw, or in Pes, observed during the first 100ms of an inspiratory effort performed against the occluded airway opening, with the occlusion performed at the end of exhalation
- In conscious patients, no relevant reaction to an unexpected occlusion before 200ms from start of inspiratory effort
- P0.1: A mechanical index of respiratory drive, directly expresses the force applied by the inspiratory muscles, an index of the motor output of the respiratory centres
- Since gas flow is zero during occlusion, P0.1 is independent from resistance and compliance
- Interpretation

1. High: high patient workload and high central respiratory drive
2. Low: if alveolar V normal, then it’s normal; if alveolar v is low, it means motor output is low

Other applications OF respiratory mechanics

Transpulmonary pressure



The NEW ENGLAND JOURNAL of MEDICINE

ESTABLISHED IN 1812 NOVEMBER 13, 2008 VOL. 359 NO. 20

Mechanical Ventilation Guided by Esophageal Pressure in Acute Lung Injury

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CONCLUSIONS

As compared with the current standard of care, a ventilator strategy using esophageal pressures to estimate the transpulmonary pressure significantly improves oxygenation and compliance. Multicenter clinical trials are needed to determine whether this approach should be widely adopted. (ClinicalTrials.gov number, NCT00127491.)

The primary endpoint of this study was improvement in oxygenation c/w ARDS Network protocol, not recruitment of decruitment per se.
Critique: absolute value of Pes may not be equal to actual Ppl, also different at different levels of the lung, cannot be ascertained

Talmor D et al. 2008 NEJM

Summary

1. Basic knowledge: volume, flow, pressure, their derivation and relationship
2. Lung parenchymal condition:
3. Airway condition: FEV1/FVC, Resistance, Flow pattern
4. Chest wall condition: Chest wall compliance
5. Interaction of all factors: PV curve of whole system, Time constant, Flow-time curve, Flow-volume curve, Static and Dynamic hyperinflation, intrinsic PEEP, EELV
6. Work of breathing: Campbell diagram, Pressure-Time Product (PTP)
7. The force of breathing: SVC, FVC, MIP, MEP, Trans-diaphragmatic pressure, P0.1
8. Other application of respiratory mechanics: Transpulmonary pressure

End

Thank you