Advanced monitoring during mechanical ventilation
Let's look at the other side

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Objectives

- **Electrical Impedance Tomography EIT**
- **Esophageal Balloon Manometry**
- **Volumetric Capnometry**

Goal

Personalized Mechanical Ventilation

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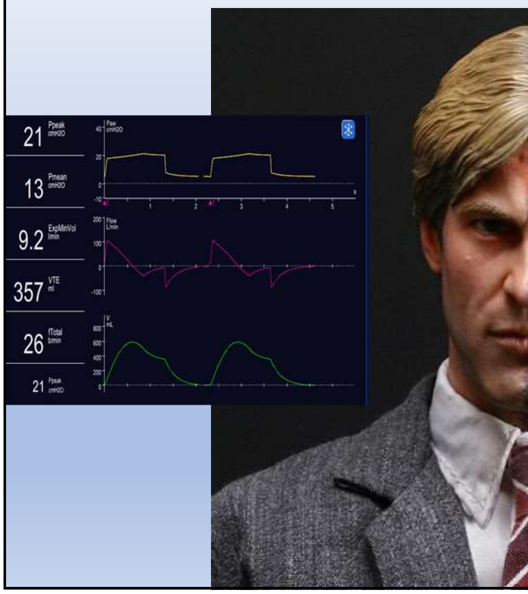
Are we seeing the full picture?



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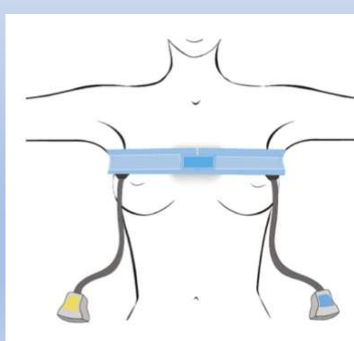
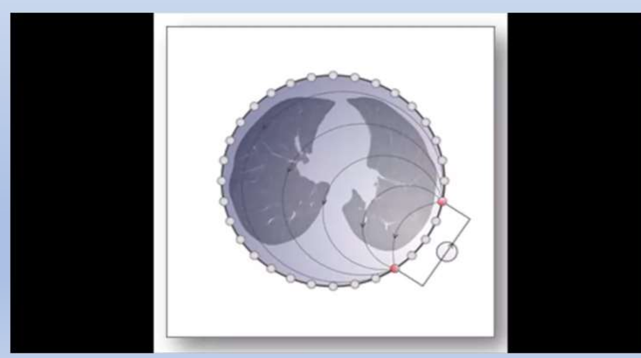
Electrical Impedance Tomography EIT

EIT devices apply known amounts of low-frequency, high amplitude electric currents through multiple pairs of electrodes (16-32) applied circumferentially to the surface of the thorax. These currents allow the device to determine the conductivity (impedance) of the cross section of the thorax, creating a two dimensional image of the area under the electrodes

Noninvasive, radiation free imaging technique that is mainly used for bedside monitoring of the changes in the ventilation and perfusion of lung tissue. EIT is a bedside lung imaging technology that can be used to assess lung volume changes in real time in a repetitive manner

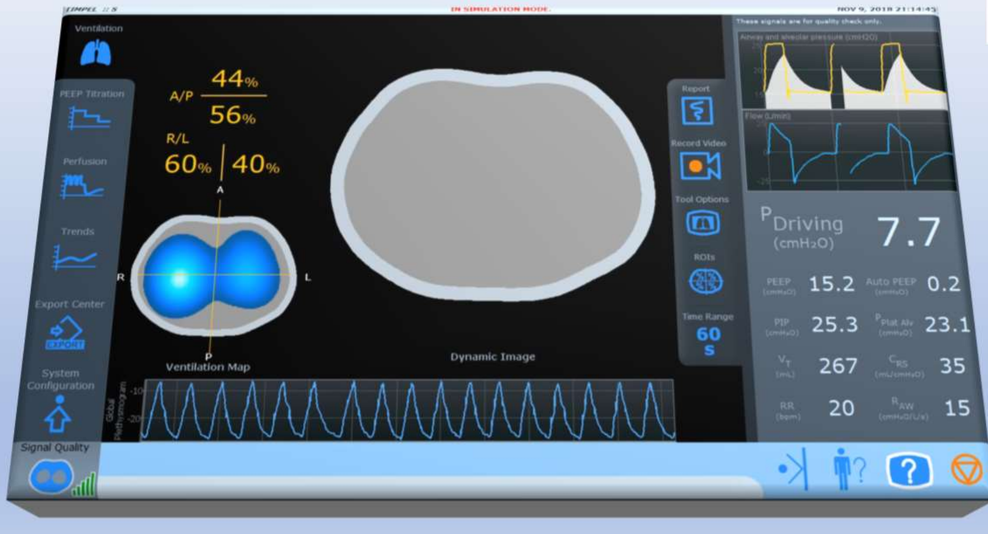




Simonpietri M, wt al. Electrical Impedance Tomography: the future of mechanical ventilation? J Mech Vent 2021; 2(2):64-70.

4

Ventilation map



Credit TIMPLE Medical with permission

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Terms

Ventilation map

Global Ventilation

ΔZ

ITVI

RVDI

Perfusion map

Regional Compliance

Regional Time Constant

ROI

ΔEELZ

COV

Global inhomogeneity index

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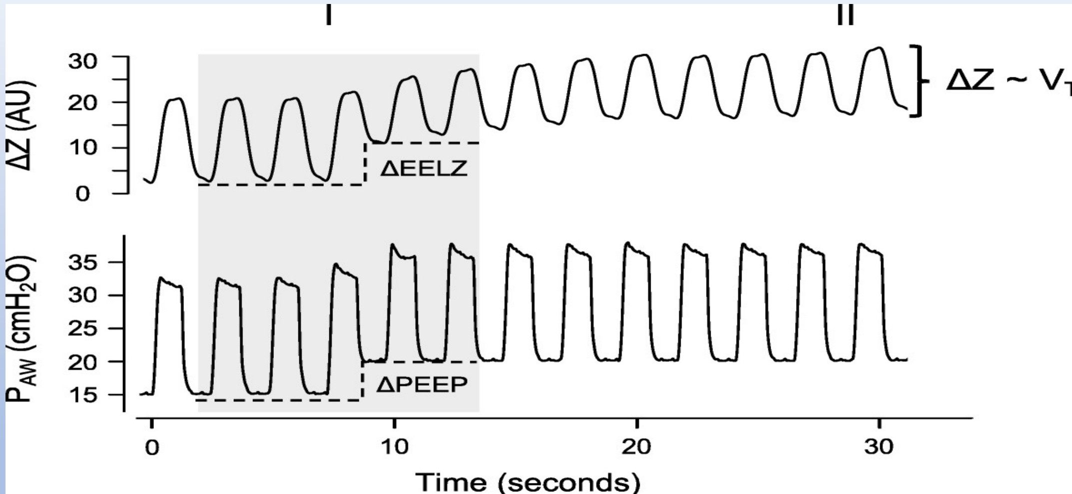
Plethysmography / Lung volumes change

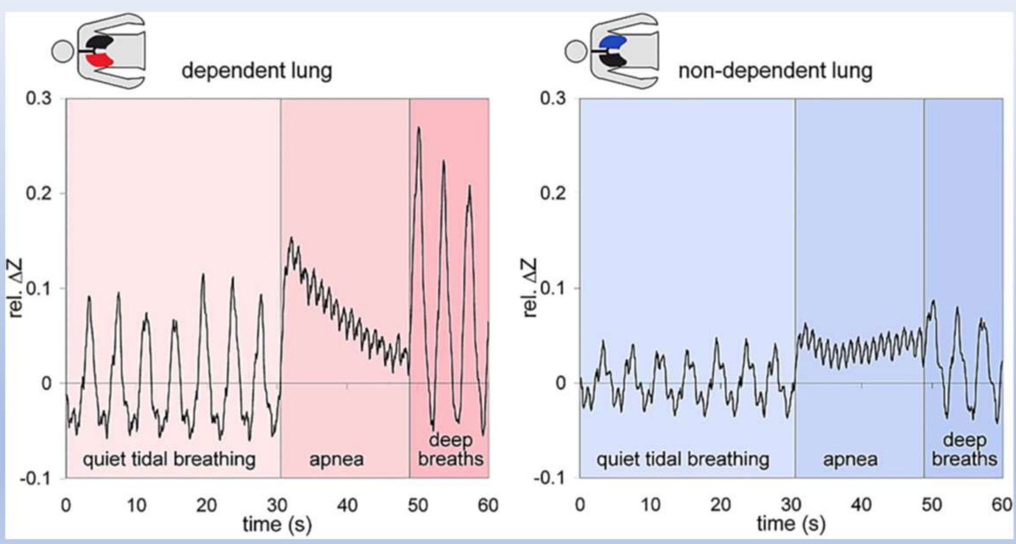


Global (whole image) plethysmogram and airway pressure (PAW) waveforms. (I) Increment in positive end-expiratory pressure (PEEP) increased end-expiratory lung volume (ΔEELZ). (II) Ventilatory cyclical variation (ΔZ) tracks changes in tidal volume (VT)

Bachmann MC, et al. Electrical impedance tomography in acute respiratory distress syndrome. Crit Care. 2018 Oct 25;22(1):263.

7

Assessing ventilation inhomogeneity



Frerichs I, et al. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy groupThorax 2017;72:83-93.

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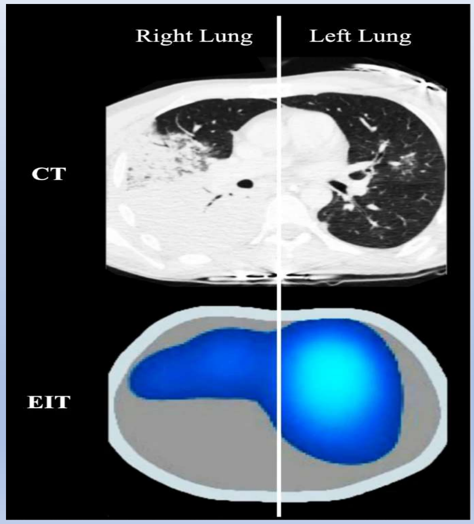
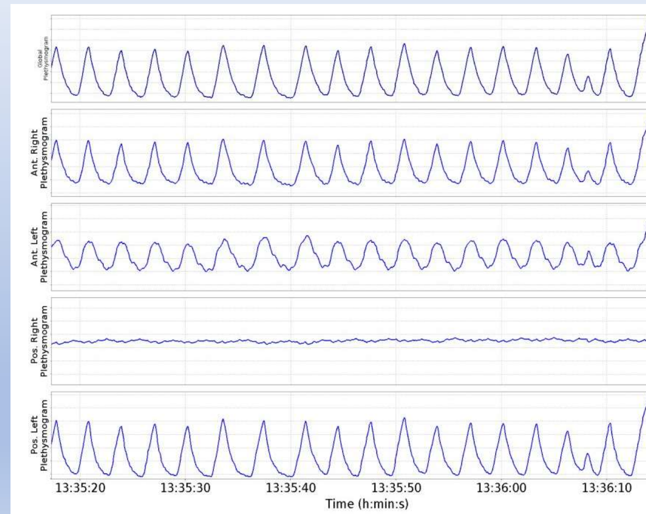
Assessing ventilation inhomogeneity





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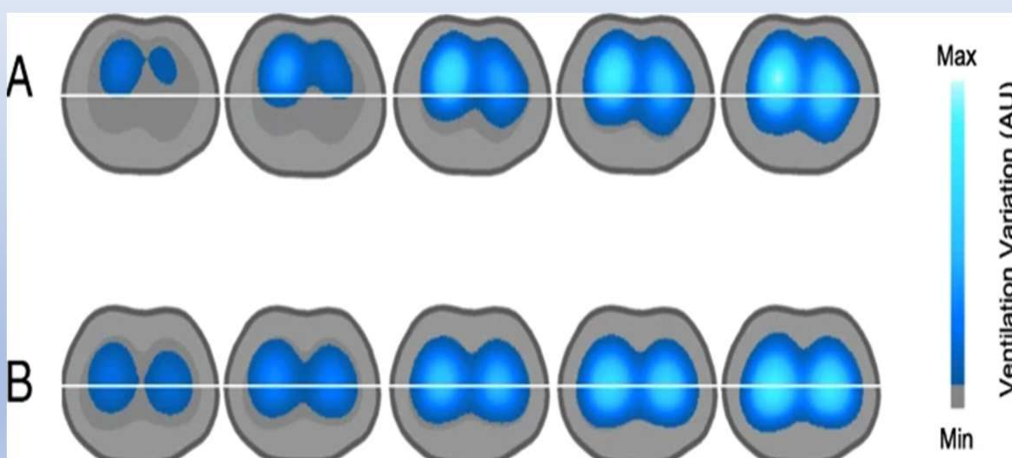
Assessing ventilation inhomogeneity



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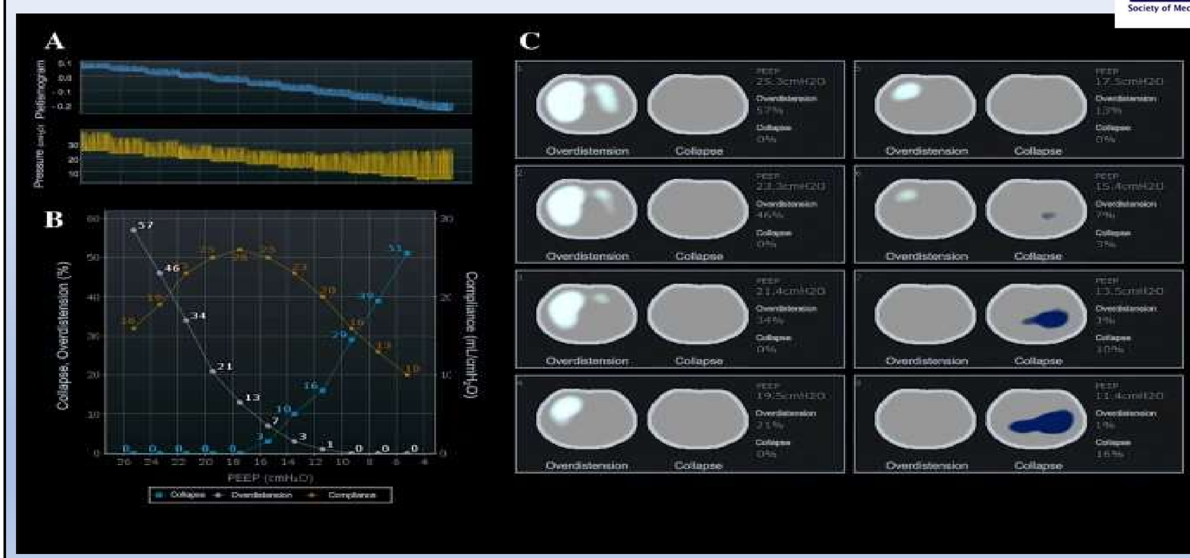
Setting PEEP



Frerichs I, et al. Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: consensus statement of the TRanslational EIT developmeNt stuDy groupThorax 2017;72:83-93.

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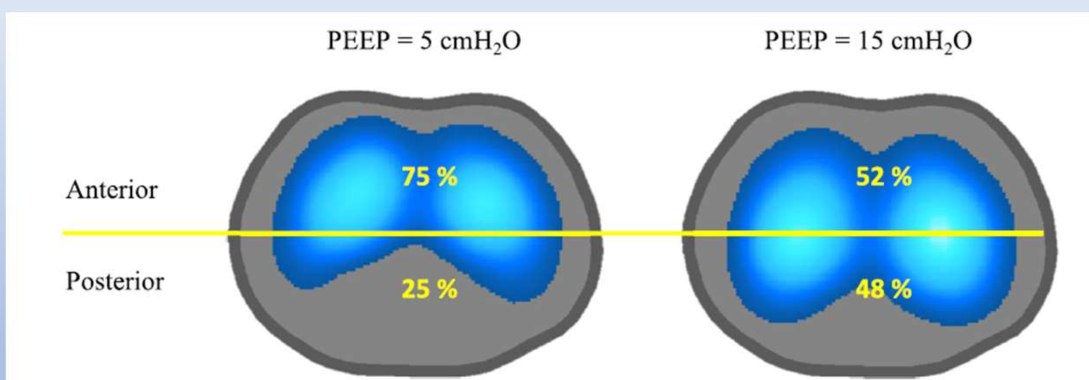
Setting PEEP



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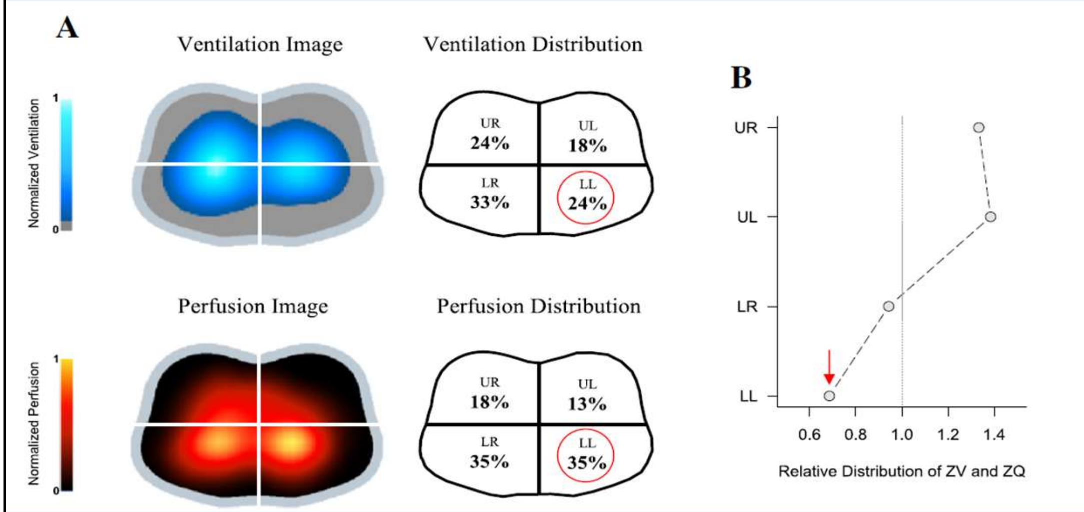
Ventilation & Perfusion



Bachmann MC, et al. Electrical impedance tomography in acute respiratory distress syndrome. Crit Care. 2018 Oct 25;22(1):263.

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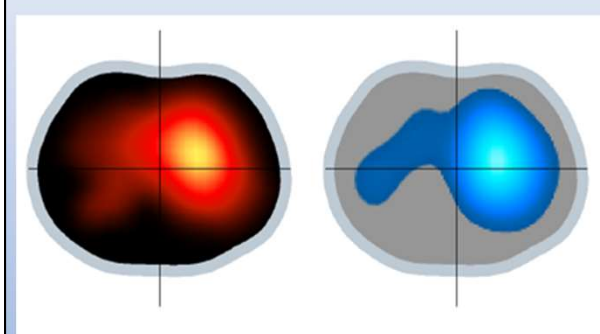
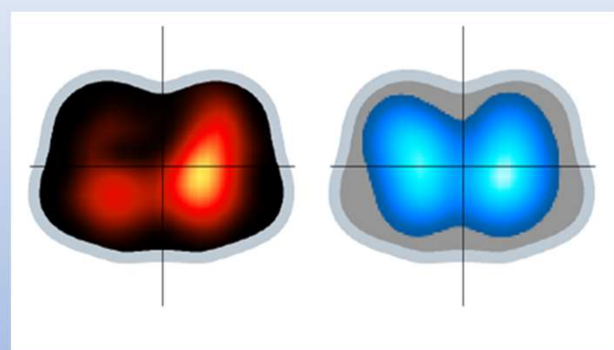
Ventilation & Perfusion



Atelectasis
(Pulmonary Vasoconstriction Reflex)



Pulmonary Thromboembolism

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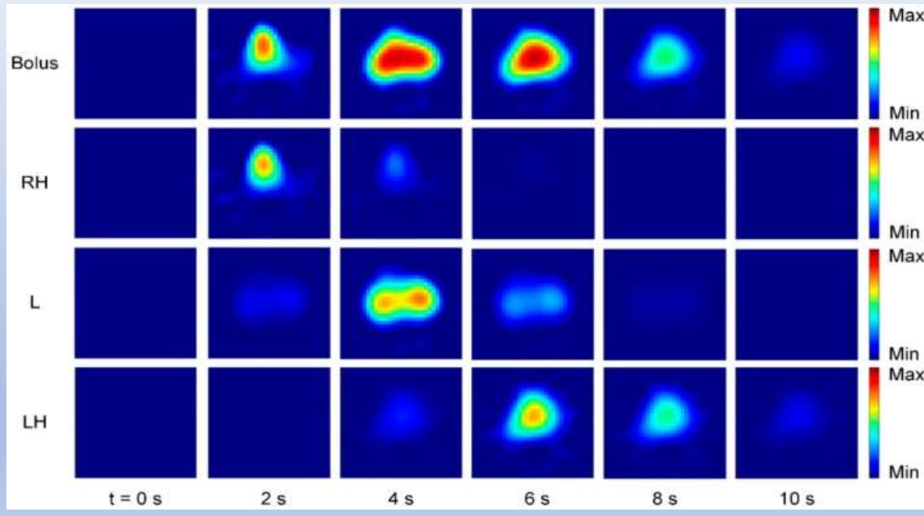
Cardiac function / Cardiac output



Putensen C, et al. Electrical Impedance Tomography for Cardio-Pulmonary Monitoring. J Clin Med. 2019 Aug 7;8(8):1176.

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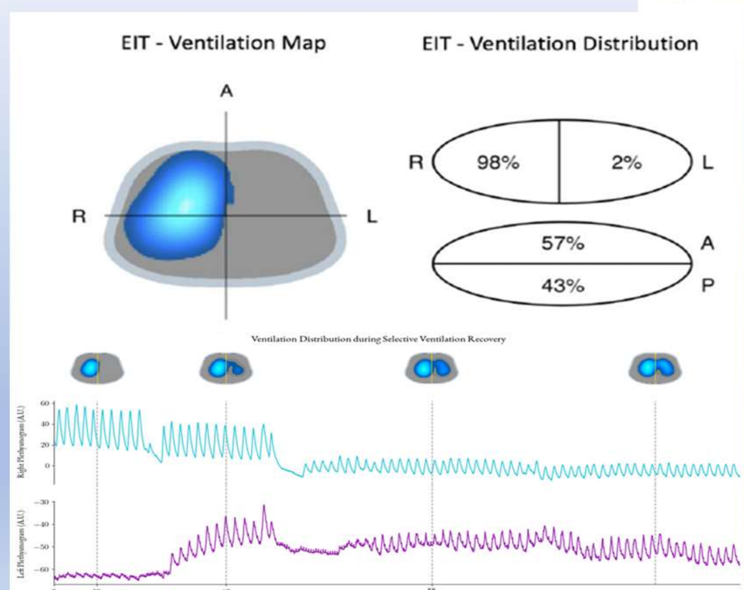
During Intubation



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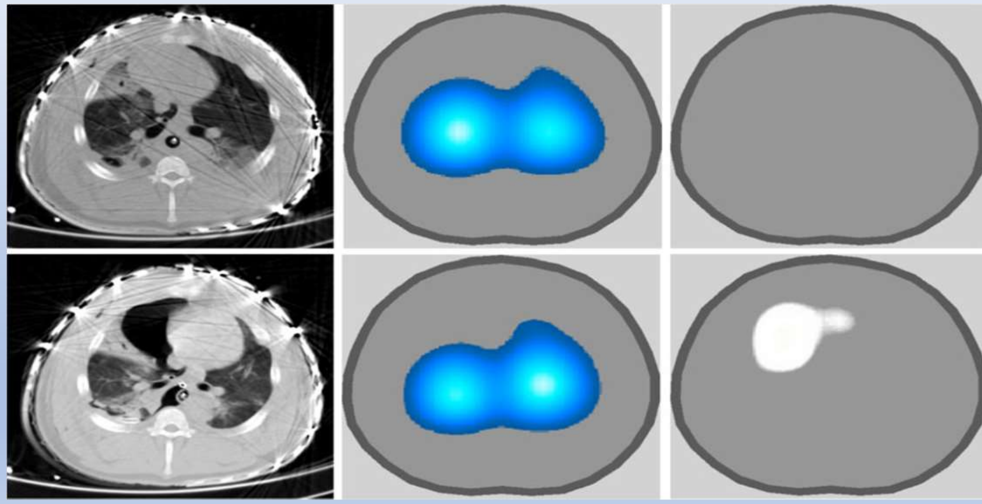
Pneumothorax

CT scan | Ventilation map | Aeration change map



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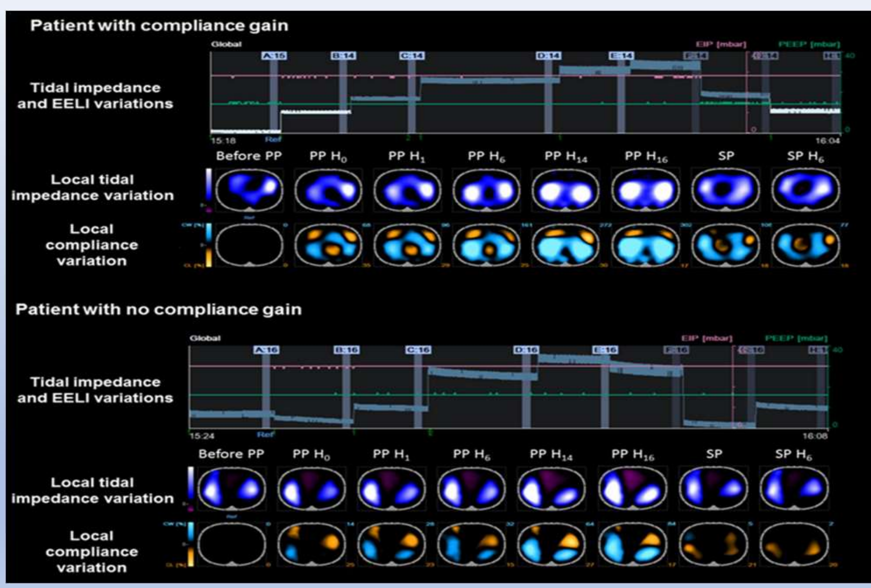
Prone Position



Franchineau G, et al. Prone positioning monitored by electrical impedance tomography in patients with severe acute respiratory distress syndrome on veno-venous ECMO. Ann Intensive Care. 2020 Feb 3;10(1):12.

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Asynchronies

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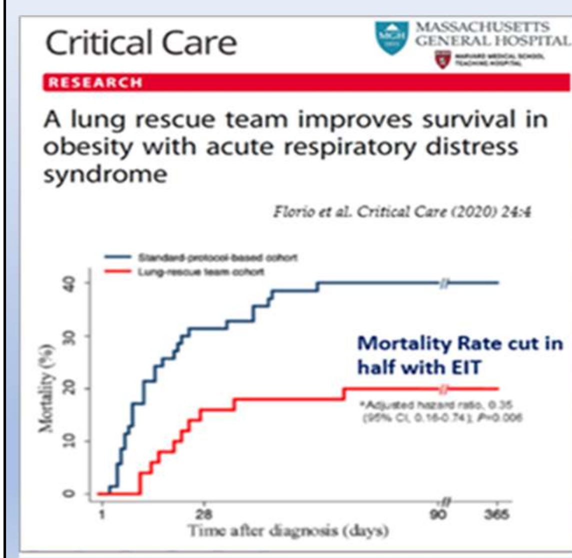
Evidence



Standard protocol: ARDS PEEP-FiO2 table

Rescue team protocol: PEEP : Recruitment maneuver
Decremental PEEP
Esophageal balloon
EIT

- Mortality rate by 50%
- Avoid the need for ECMO by >80%
- Shorter duration of mechanical ventilation
- Shorter ICU length of stay
- Inotropic & Vasopressor Agents lower doses
- No change in the Standard Protocol Group

Florio G *et al.* A lung rescue team improves survival in obesity with acute respiratory distress syndrome. *Crit Care* **24**, 4 (2020).

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Evidence

ORIGINAL CLINICAL REPORT

OPEN

Individualized Multimodal Physiologic Approach to Mechanical Ventilation in Patients With Obesity and Severe Acute Respiratory Distress Syndrome Reduced Venovenous Extracorporeal Membrane Oxygenation Utilization

CONCLUSIONS: In this hypothesis-generating study, individualized optimization of mechanical ventilation of patients with acute respiratory distress syndrome and obesity by a lung rescue team was associated with a decrease in the utilization of venovenous extracorporeal membrane oxygenation, duration of mechanical ventilation, and ICU length of stay. Mortality was not modified by the lung rescue team intervention.

Outcomes	Total, *n* = 33	Standard-of-Care Cohort, *n* = 20	Lung Rescue Team Cohort, *n* = 13	*p*
ECMO utilization, *n* (%)	23 (70)	20 (100)	3 (23)	< 0.001
ECMO duration, d, median (interquartile range)	8 (5–14)	2 (1–14)	9 (6–18)	0.22
Neuromuscular blockade duration, hr mean ± SD	45 ± 27	50 ± 35	41 ± 20	0.38
Pulmonary vasodilator use, *n* (%)	24 (73)	14 (70)	10 (75)	1.0
Occurence of reintubation, *n* (%)	9 (27)	7 (35)	2 (15)	0.26
Acute kidney injury, *n* (%)	27 (82)	15 (75)	12 (92)	0.36
Of which required renal replacement therapy	16 (59)	9 (60)	7 (58)	0.93
Duration of mechanical ventilation, d, median (interquartile range)	16 (8–22)	20 (12.5–29.5)	9 (5–16)	0.03
ICU LOS after consult, d, median (interquartile range)	17 (11–27)	21 (13–35)	13 (11–16)	0.03
Hospital LOS after consult, d, median (interquartile range)	26 (14–44)	32 (14.5–57)	21 (14–27)	0.19
ICU mortality, *n* (%)	10 (30)	7 (35)	3 (23)	0.70

Zadek F, et al. Individualized Multimodal Physiologic Approach to Mechanical Ventilation in Patients With Obesity and Severe Acute Respiratory Distress Syndrome Reduced Venovenous Extracorporeal Membrane Oxygenation Utilization. Crit Care Explor. 2021 Jun 29;3(7):e0461.

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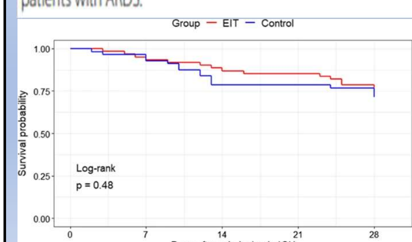
Evidence

RESEARCH Open Access

Early individualized positive end-expiratory pressure guided by electrical impedance tomography in acute respiratory distress syndrome: a randomized controlled clinical trial

Conclusion: Our study showed a 6% absolute decrease in mortality in the EIT group: a statistically non-significant, but clinically non-negligible result. This result along with the showed improvement in organ function might justify further reserach to validate the beneficial effect of individualized EIT-guided PEEP setting on clinical outcomes of patients with ARDS.



Variables	EIT group N = 61	Control group N = 56	*p* value
Clinical outcome			
28-day mortality (*n*, %)	13 (21%)	15 (27%)	0.634
Ventilator-free days at day 28 (D)	14.0 (0.0, 23.0)	18.5 (0.0, 24.0)	0.764
Length of ICU stay (D)	13.0 (7.0, 25.0)	10.0 (7.0, 14.8)	0.169
ΔD1 SOFA score	0 (− 1, 1)	0.5 (− 1, 2.75)	0.021*
ΔD2 SOFA score	− 1 (− 3.5, 0)	1 (− 2, 2)	< 0.0001*
Successful extubation (*n*, %)	30 (49%)	31 (55%)	0.629
Tracheostomy (*n*, %)	17 (28%)	11 (20%)	0.409
Adjuvant therapy			
Neuromuscular blocker (*n*, %)	12 (20%)	5 (9%)	0.166
Prone position (*n*, %)	30 (49%)	23 (41%)	0.487
Glucocorticoid therapy (*n*, %)	11 (18%)	6 (11%)	0.390

He H, et al. Early individualized positive end-expiratory pressure guided by electrical impedance tomography in acute respiratory distress syndrome: a randomized controlled clinical trial. Crit Care. 2021 Jun 30;25(1):230.

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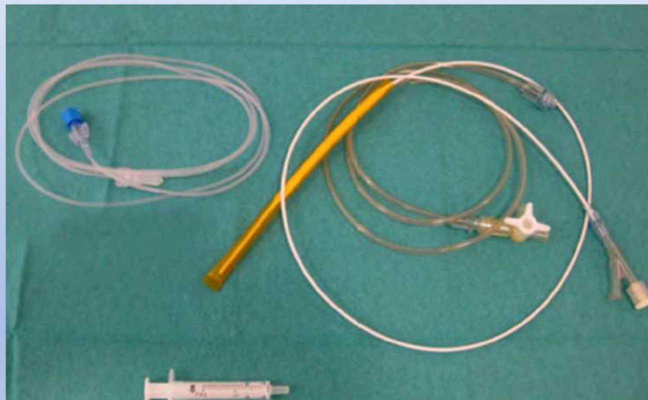
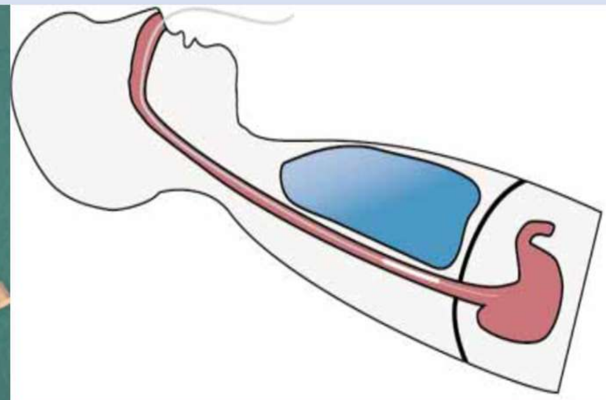
Esophageal Balloon Manometry





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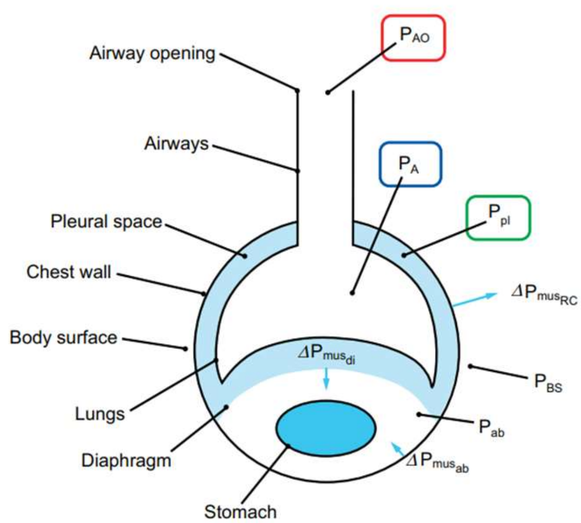
Esophageal Balloon Manometry



Transmural pressure

$P_{in} - P_{out} = P_{across}$

Trans-alveolar pressure difference

$P_A - P_{pl} = P_{TA}$

Trans-pulmonary pressure difference

$P_{AO} - P_{pl} = P_{TP}$

In static conditions $P_{TP} \approx P_{TA}$

Mireles-Cabodevila E, et al. Esophageal Pressure Measurement: A Primer. Respir Care. 2023 Sep;68(9):1281-1294.

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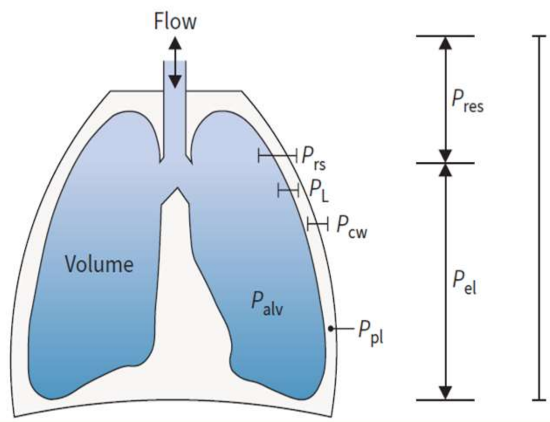
Equation of motion



$P_{tot}=P_{res}+P_{el}+P_0$

$P_{tot}=P_{res}+(P_L+P_{cw})+P_0$

$P_{tot}=(\text{flow}\times\text{resistance})+((\text{volume}\times E_L)+(\text{volume}\times E_{cw}))+P_0$

Resistive pressure (Pres) is the pressure needed to overcome airway resistance.
Elastic pressure (Pel) is the pressure needed to expand the lungs and the chest wall.
P0 is the pressure inside the respiratory system at the end of expiration, (zero in non-ventilated patients, total PEEP in ventilated patients. Palv: alveolar pressure; Prs: transrespiratory system pressure); PL: transpulmonary pressure; Pcw: transmural pressure of the chest wall, Ppl: pleural pressure; EL: lung elastance; Ecw: chest wall elastance.

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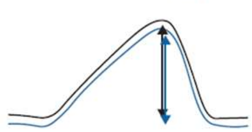
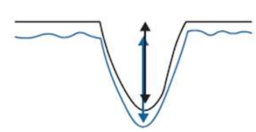
Trans-Pulmonary Pressures

Passive patient
1) Perform an end-expiratory occlusion
2) Apply a gentle bilateral thoracic compression
3) Measure the increase in P_{aw} and P_{oes}



Actively breathing patient
1) Perform an end-expiratory occlusion
2) Wait for the next occluded inspiratory effort
3) Measure the decrease in P_{aw} and P_{oes}



4) Check if $\Delta P_{aw}/\Delta P_{oes}$ ratio is within the 0.8–1.2 range
The closer the ratio is to 1, the more precise the P_{oes} measurement is

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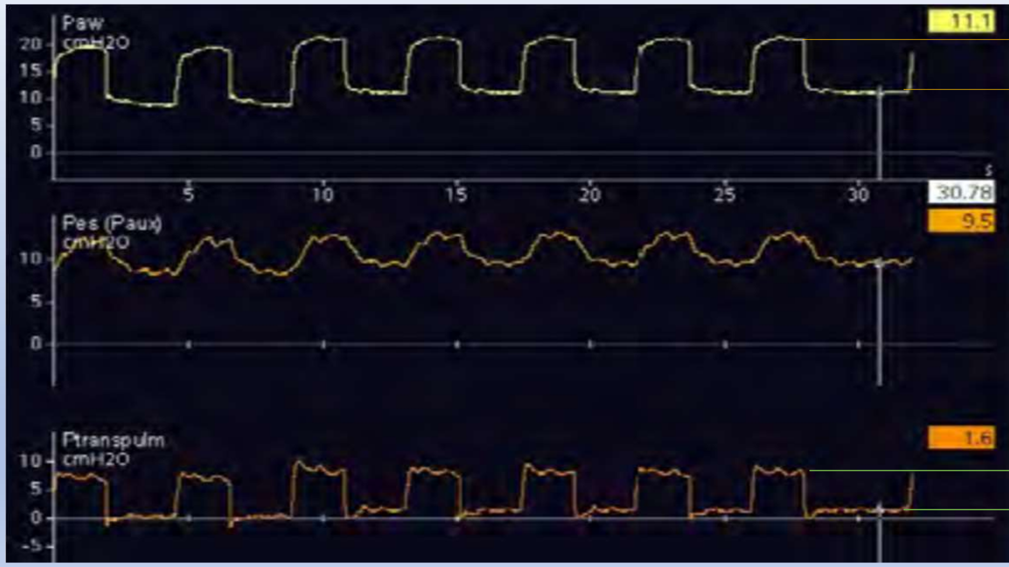
Trans-Pulmonary Pressures (PL)



Plateau

PEEP
(Driving pressure
Respiratory System
Stress)

Insp PL
Exp PL
Ppl Driving
pressure Lung
Stress

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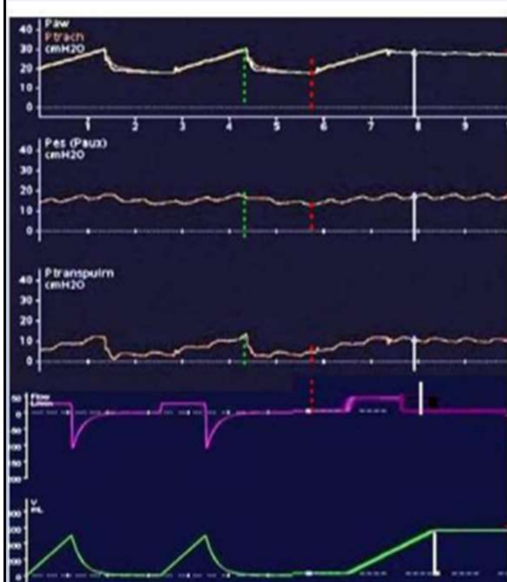
Calculation of Respiratory Mechanics



Peak Inspiratory pressure 31 cmH2O
Plateau Pressure 27 cmH2O
PEEP 15 cmH2O

End Inspiratory Esophageal Pressure 17 cmH2O
End Expiratory Esophageal Pressure 12 cmH2O
Peak Esophageal Pressure 18 cmH2O

End Inspiratory Trans-pulmonary Pressure 10 cmH2O
End Expiratory Trans-pulmonary Pressure 3 cmH2O
Peak Inspiratory Trans-pulmonary Pressure 13 cmH2O

Peak inspiratory flow 45 L/min
End Inspiratory & Expiratory flow pause 0 L/min

Tidal Volume 500 ml

Total respiratory compliance
= VT / Paw - $PEEP_T$
= 500 / 27 - 15
= 41.6 ml/cmH_2O

Total respiratory resistance
= P_{PIP} - P_{plat} / V'
= 31 - 27 / 0.75 (45 L/min = 0.75 l/s)
= 5.3 cmH_2O/l/s

Chest wall compliance
= VT / End inspiratory P_{es} - End expiratory P_{es}
= 500 / 17 - 12
= 100 ml/cmH_2O

Chest wall resistance
= Peak P_{es} - End inspiratory P_{es} / V'
= 18 - 17 / 0.75
= 1.3 cmH_2O/l/s

Lung compliance
= VT / End inspiratory P_{PL} - End expiratory P_{PL}
= 500 / 7
= 71.4 ml/cmH_2O

Lung resistance
= Peak P_{PL} - End inspiratory P_{PL} / V'
= 13 - 10 / 0.75 (45 L/min = 0.75 l/s)
= 4 cmH_2O/l/s

Shokry M, et al. Can you calculate the total respiratory, lung, and chest wall respiratory mechanics? J Mech Vent 2020; 1(1):24-25.

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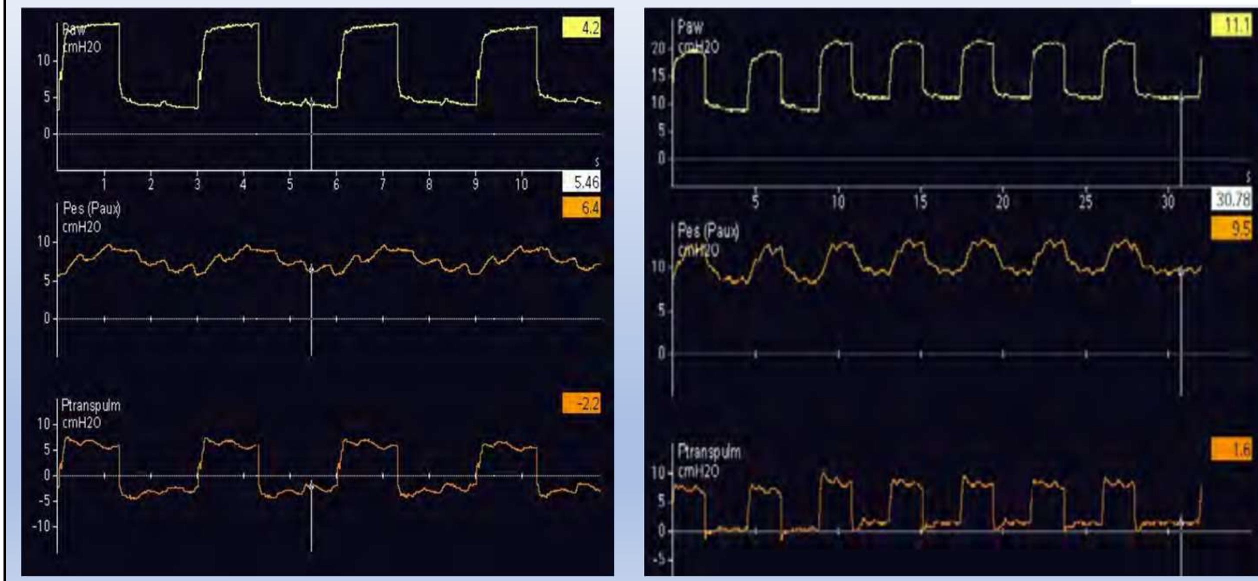
Setting PEEP (avoid lung collapse and Atelectrauma)

End Exp P_L 0 ± 2 cmH_2O



Talmor D, et al. Mechanical ventilation guided by esophageal pressure in acute lung injury. N Engl J Med. 2008 13;359(20):2095-104.

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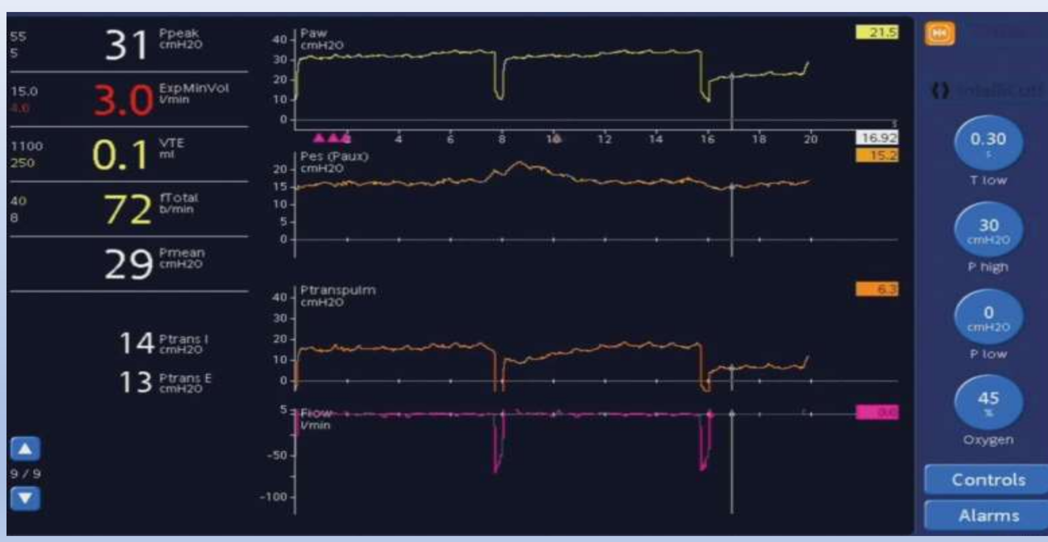
Setting T-Low in APRV (Auto-PEEP)



Daoud EG, et al. Esophageal pressure balloon and transpulmonary pressure monitoring in airway pressure release ventilation: a different approach. Can J Respir Ther. 2018 ;54(3):62-65.

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PEEP guided by Trans-Pulmonary pressure

EPVent-1 trial

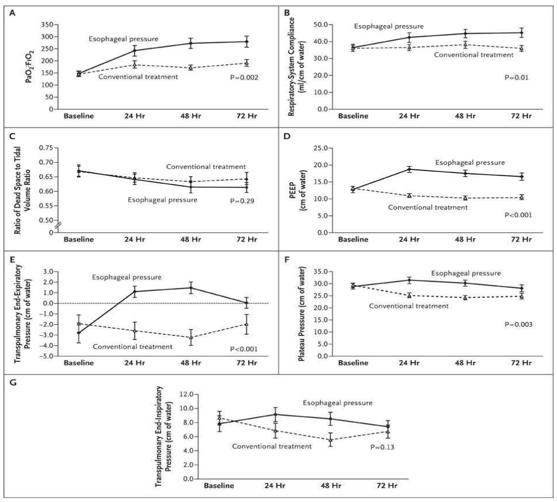

Table 4. Clinical Outcomes.*

Outcome	Esophageal-Pressure–Guided (N=30)	Conventional Treatment (N=31)	P Value
28-Day mortality — no. (%)	5 (17)	12 (39)	0.055
180-Day mortality — no. (%)	8 (27)	14 (45)	0.13
Length of ICU stay — days			0.16
Median	15.5	13.0	
Interquartile range	10.8–28.5	7.0–22.0	
No. of ICU-free days at 28 days			0.96
Median	5.0	4.0	
Interquartile range	0.0–14.0	0.0–16.0	
No. of ventilator-free days at 28 days			0.50
Median	11.5	7.0	
Interquartile range	0.0–20.3	0.0–17.0	
No. of days of ventilation among survivors			0.71
Median	12.0	16.0	
Interquartile range	7.0–27.5	7.0-20.0	

* For patients who were deceased at day 28, a value of 0 days was assigned. ICU denotes intensive care unit.

Talmor D, et al. Mechanical ventilation guided by esophageal pressure in acute lung injury. N Engl J Med. 2008 13;359(20):2095-104.

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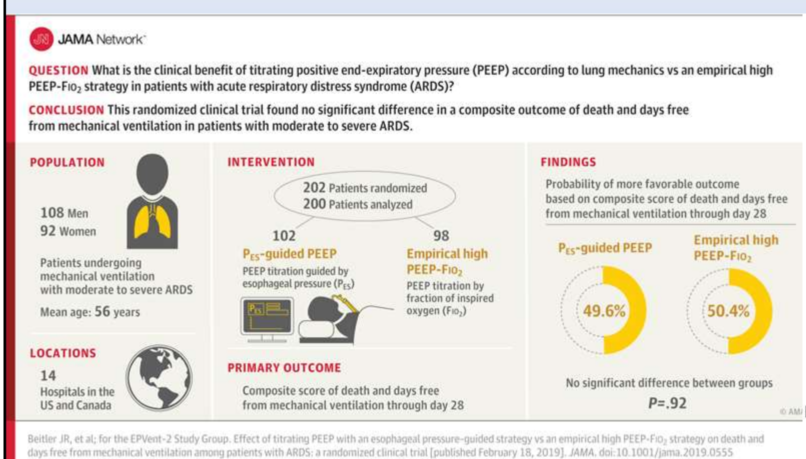
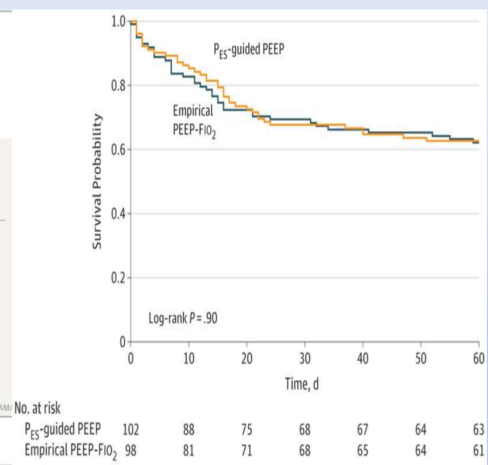
PEEP guided by Trans-Pulmonary pressure

EPVent-2 trial





Beitler JR,; EPVent-2 Study Group. Effect of Titrating Positive End-Expiratory Pressure (PEEP) With an Esophageal Pressure-Guided Strategy vs an Empirical High PEEP-Fio2 Strategy on Death and Days Free From Mechanical Ventilation Among Patients With Acute Respiratory Distress Syndrome: A Randomized Clinical Trial. JAMA. 2019 Mar 5;321(9):846-857.

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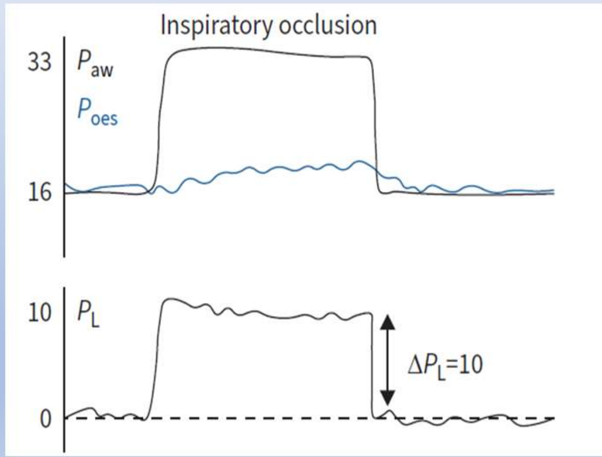
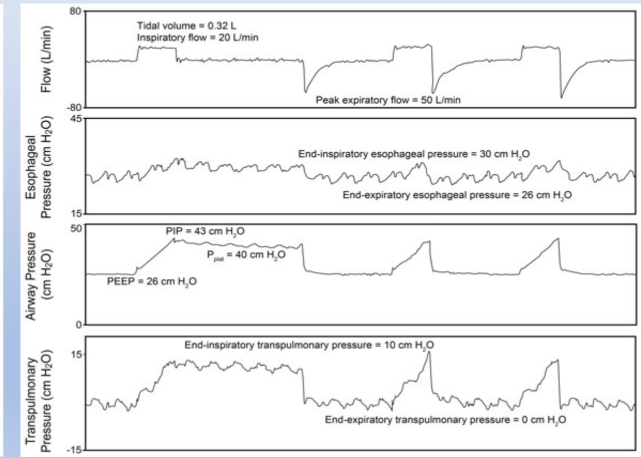
Limiting stress applied to the lung (ARDS & Obesity)

End Insp PL < 10-12 cmH2O





Hess D. Respiratory Mechanics in Mechanically Ventilated Patients. Respir Care 2014;59:1773-1794

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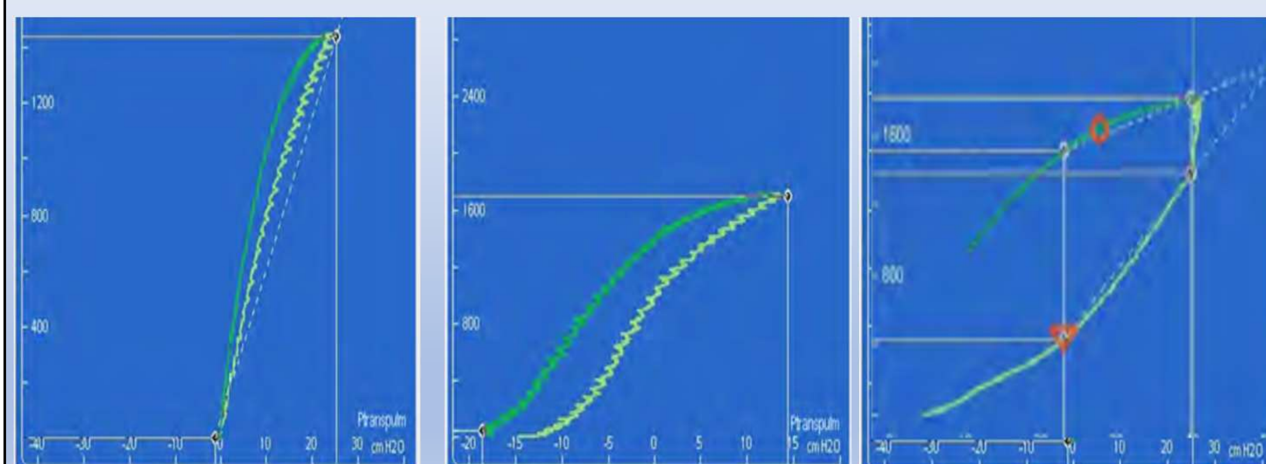
Lung Recruitability



Baedorf Kassis E, et al. Recruitment maneuvers: using transpulmonary pressure to help Goldilocks. Intensive Care Med. 2017 Aug;43(8):1162-1163.

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Effect of position (Prone & Trendelenburg)

Effects of the Prone Position on Respiratory Mechanics and Gas Exchange during Acute Lung Injury

Table 4. RESPIRATORY MECHANICS VALUES DURING THE STUDY*

	Baseline 0 min	Prone 30 min	Prone 120 min	Supine 30 min	Supine 120 min
EELV, L	1.17 ± 0.41	1.25 ± 0.49	1.29 ± 0.57	1.20 ± 0.58	1.29 ± 0.66
IAP, cm H_2O	11.4 ± 7.2	—	14.8 ± 6.6	—	10.4 ± 7.2
Cst,rs, ml/cm H_2O	38.4 ± 13.7	36.8 ± 11.8	35.9 ± 10.7	42.3 ± 14.4‡,§	43.0 ± 15.2†
Cst,L, ml/cm H_2O	52.4 ± 23.3	55.3 ± 26.2	53.9 ± 23.6	57.5 ± 25.1‡,§	58.5 ± 27.3†
Cst,w, ml/cm H_2O	204.8 ± 97.4	146.8 ± 55.5	135.9 ± 52.5‡	219.1 ± 100.9	232.0 ± 84.0
Rtot,rs, cm H_2O/L/s	17.5 ± 6.4	17.6 ± 4.8	17.6 ± 5.7	17.9 ± 5.2	16.6 ± 4.5
Rtot,L, cm H_2O/L/s	15.2 ± 6.5	15.1 ± 5.3	15.0 ± 5.5	15.8 ± 5.7	14.5 ± 4.5
Rtot,w, cm H_2O/L/s	2.3 ± 1.8	2.5 ± 1.6	2.6 ± 1.3	2.1 ± 1.4	2.1 ± 1.2

JMV

Effect of Trendelenburg position during prone ventilation in fifteen COVID-19 patients. Observational study

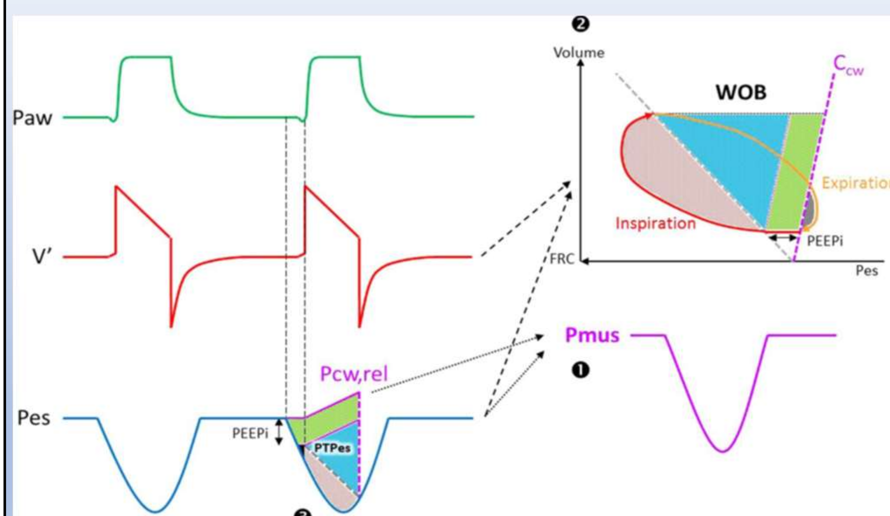
	Reverse Trendelenburg (RT)	Trendelenburg (T)	Difference	P value
Tidal volume (ml)	391.3 ± 52.7	471.6 ± 60.9	80.26 (20.5%)	0.001
Tidal volume (m/Kg)	6.1 ± 0.4	7.27 ± 0.8	1.17 (19%)	0.001
CRS (ml/cmH₂O)	34.6 ± 4.7	39.5 ± 4.6	4.9 (14%)	0.001
CL (ml/cmH₂O)	66.6 ± 1.7	83.3 ± 3.3	16.7 (25%)	0.001
CCW (ml/cmH₂O)	65 ± 1.4	66.5 ± 2.3	1.5 (2%)	0.085

Pelosi P, et al. Effects of the prone position on respiratory mechanics and gas exchange during acute lung injury. Am J Respir Crit Care Med. 1998 Feb;157(2):387-93.

Su M, et al. Effect of Trendelenburg position during prone ventilation in fifteen COVID-19 patients. J Mech Vent 2021; 2(4):125-130.

35

Calculation of Muscle pressure (Pmus), WOB, PTP



Resistive (red area), Elastic (blue area), PEEPi (green area) and related to active expiration (grey area).

Pmus = Pcw, rel − Pes

WOB = ∫ (Pcw – Pes) x Δ V

PTPes = ∫ Pmus · dt

Pcw: relaxed chest wall compliance
Pes: esophageal pressure
ΔV: change in tidal volume
dt: time

Shokry M, et al. Calculating the work of breathing during mechanical ventilation. J Mech Vent 2021; 2(2):71-72.

Jonkman AH, ET AL. The oesophageal balloon for respiratory monitoring in ventilated patients: updated clinical review and practical aspects. Eur Respir Rev. 2023 May 17;32(168):220186.

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Weaning

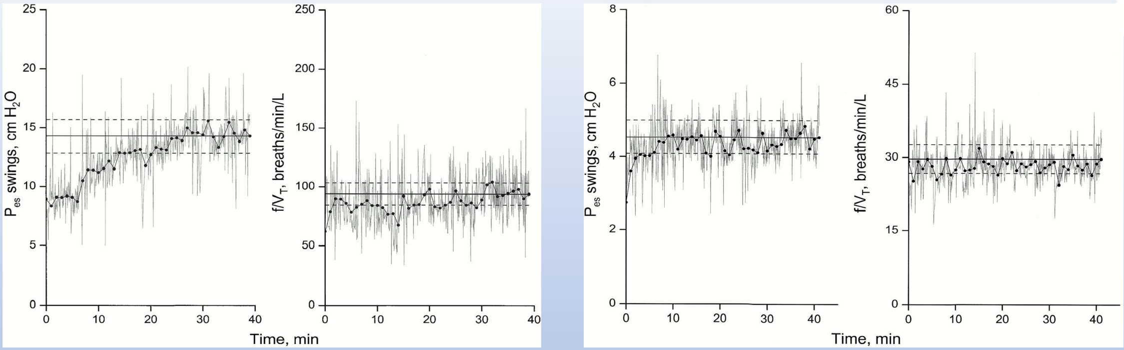


TABLE 2. Accuracy of the indexes used to predict weaning outcome in the validation dataset

Index	Sensitivity	Specificity	Positive Predictive Value	Negative Predictive Value	Likelihood Ratio (*95% CI*)
Pes swings during first minute, cm H_2O	0.18	0.89	0.50	0.64	1.6 (0.3–8.3)
f/VT, breaths/min/L	0.82	0.67	0.60	0.86	2.5 (1.2–5.2)
Pes trend index, a.u.	0.91	0.89	0.83	0.94	8.2 (2.7–29.6)

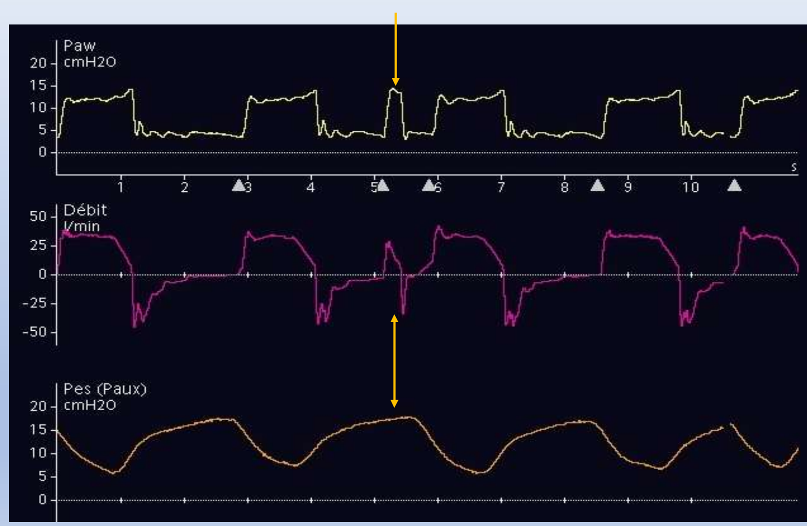
Definition of abbreviations: a.u. = arbitrary unit; CI = confidence interval; f/VT = frequency-to-VT ratio; Pes = esophageal pressure.

Jubran A, et al. Weaning prediction: esophageal pressure monitoring complements readiness testing. Am J Respir Crit Care Med. 2005 Jun 1;171(11):1252-9.

37

Asynchronies

Autotrigger



Mireles-Cabodevila E, Fischer M, Wiles S, Chatburn RL. Esophageal Pressure Measurement: A Primer. Respir Care. 2023 Jul 11:respcare.11157.

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Asynchronies

Double trigger

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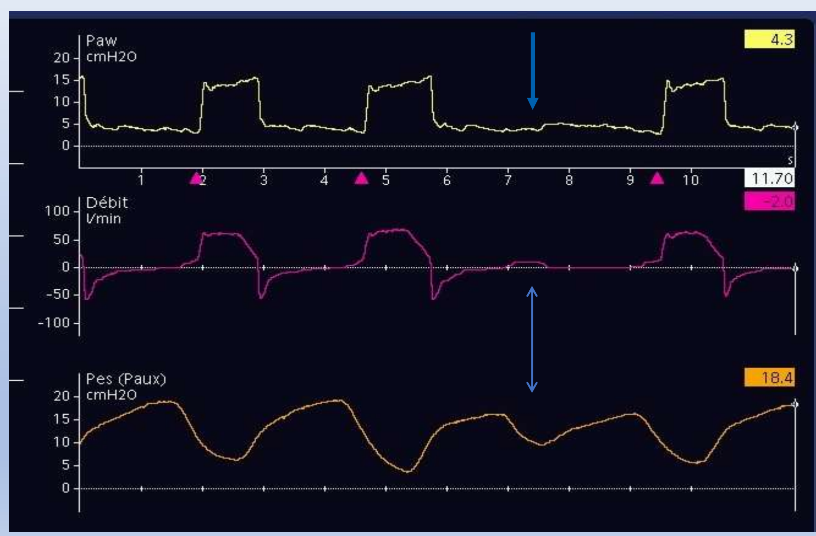
Asynchronies

Missed trigger



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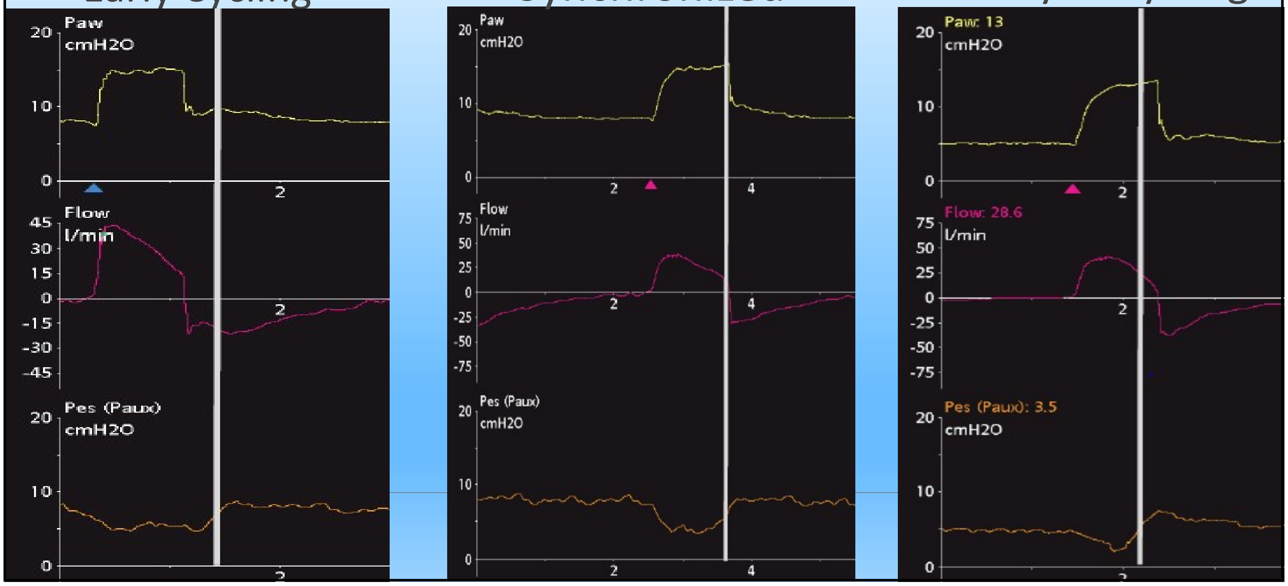
Asynchronies

Early Cycling | Synchronized | Delayed Cycling



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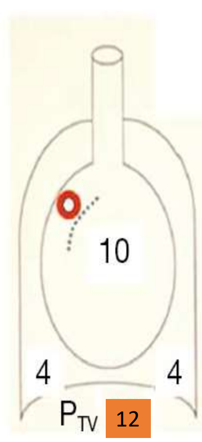
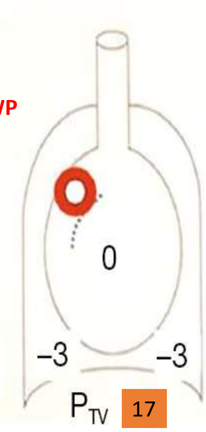
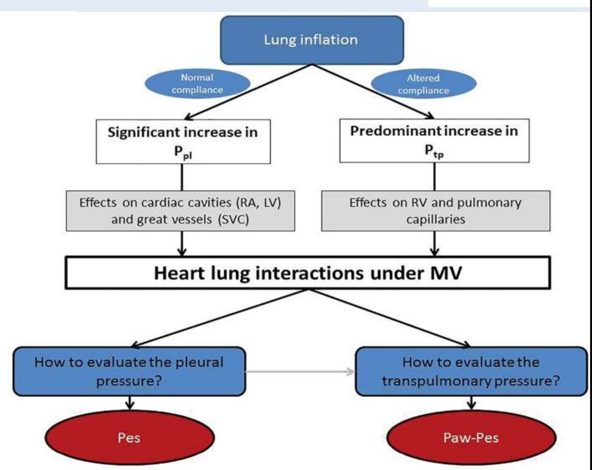
Trans-Vascular / Trans-Mural pressures
Heart – Lung Interactions



CVP/RAP/PAWP
15 mmHg





15 – 2.93 = 12

15 – (-2.2) = 17

1 = 0.735559

Centimeter of water | Millimeter of mercury

Vieillard-Baron A, et al. Experts' opinion on management of hemodynamics in ARDS patients: focus on the effects of mechanical ventilation. *Intensive Care Med* 2016;42:739-49.

42

Summary

Case-scenario	Relevant Pes-derived measure[a]	Clinical significance	Clinical recommendation
Passively ventilated patient	Tidal ΔP_L	Measure of the tidal stress applied to lung parenchyma	Possibly keep below 10–12 cmH_2O in ARDS patients
	End Inspiratory P_L	Measure of the total stress applied to lung parenchyma	Possibly keep below 20–25 cmH_2O in ARDS patients
	End expiratory P_L	Negative value possibly indicating tendency of the alveoli and/or airways to collapse	Possibly keep above 0 cmH_2O in ARDS patients
	Transmural pulmonary vascular pressure	Effective pressure driving blood flow in intrathoracic vascular structures	Consider delta between CVP and end-expiratory Pes rather than CVP per se to better understand volume status of the patient
	Periodically interspersed negative Pes swings after passively delivered ventilator breaths	Detection of reverse triggering	Consider paralysis or modify sedation (reduce sedation to let the patient trigger)
Ventilated patient with active breathing	Transmural pulmonary vascular pressure	Effective pressure across intrathoracic vascular structures	Consider delta between CVP and end-expiratory Pes rather than CVP per se to better understand volume status of the patient
	End inspiratory P_L	Measure of the tidal stress applied to lung parenchyma	Possibly keep below 20–25 cmH_2O in ARDS patients
	Pmus	Measure of the pressure generated by the patient's inspiratory muscles	Normal values are between 5 and 10 cmH_2O
	Work of breathing	Measure of patient's total work during the respiratory cycle	Normal values are around 0.35 or 2.4 J min^{-1}
	PTPes	Measure of patient's respiratory muscles effort to breathe	Normal values are around 100 cmH_2O s min^{-1}
	Negative Pes swings without ventilator pressurization	Ineffective effort	Titrate PEEP and/or decrease support and/or consider NAVA
	Pes inspiratory time longer than ventilator inspiratory time	Double triggering or premature cycling	Increase ventilator Ti up to 0.8–1.0 s or consider switching to NAVA or PAV. Rule out non-ventilatory causes (metabolic acidosis, encephalopathy, etc.)
	No Pes swing prior to ventilator pressurization	Auto-triggering	Check for leaks, trigger settings, ventilator tubing (water in circuits) and/or decrease sedation
	Increasing PTPes and/or Pes swings along spontaneous breathing trial	High likelihood of failure to wean	Differentiate whether resistive or elastic workload increased and treat consequently. Reconnect to ventilator

Mauri T, et al. PLeUral pressure working Group (PLUG—Acute Respiratory Failure section of the European Society of Intensive Care Medicine). Esophageal and transpulmonary pressure in the clinical setting: meaning, usefulness and perspectives. Intensive Care Med. 2016 Sep;42(9):1360-73.

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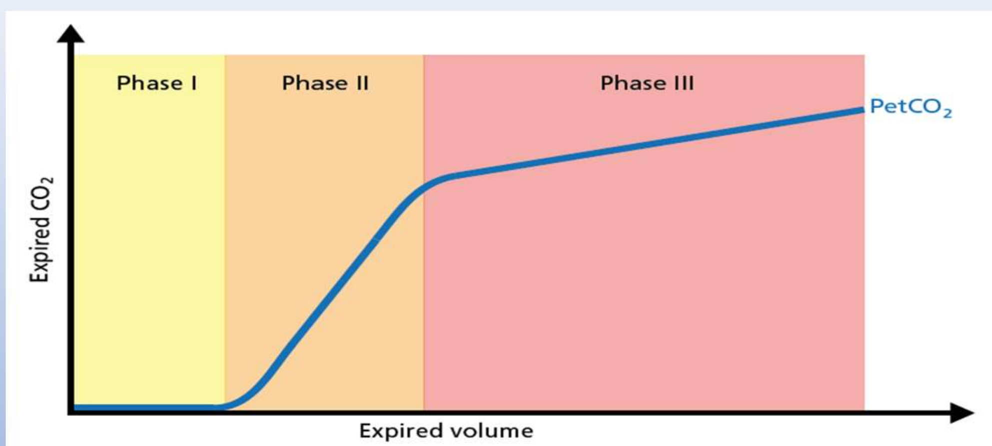
Volumetric Capnography



Phase I - Anatomical dead space
Phase II - Transition phase: gas from proximal lung areas and fast emptying lung areas
Phase III - Plateau phase: gas from alveoli and slow emptying areas

Credit Hamilton Medical with permission

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Calculation of Anatomical, Alveolar dead space and Alveolar tidal volume

Verscheure S, et al. Volumetric capnography: lessons from the past and current clinical applications. Crit Care. 2016 Jun 23;20(1):184.

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Information

[redacted]

[redacted]

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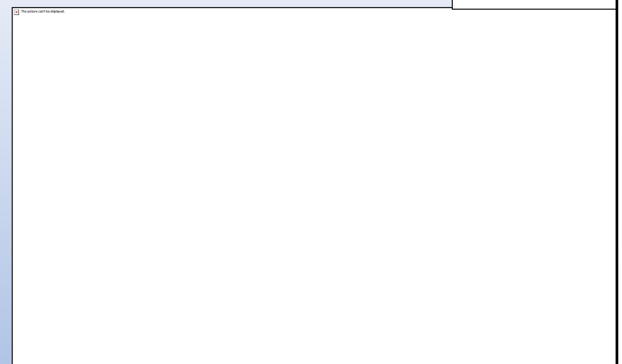
VCO2 Volume of CO2 eliminated/minute

Area X represents the actual volume of CO_2 exhaled in one breath (VeCO2). Adding up all of the single breaths in one minute gives you the total elimination of CO_2 per minute (V‘CO2). If cardiac output, lung perfusion, and ventilation are stable, this is an assessment of the production of CO_2 called V‘CO2. The V‘CO2 value displayed on the ventilator can be affected by any change in CO_2 production, cardiac output, lung perfusion, and ventilation. It indicates instantly how the patient’s gas exchange responds to a change in ventilator settings. Monitoring trends allows for detection of sudden and rapid changes in V‘CO2.



Decreasing V‘CO2

Hypothermia, deep sedation, hypothyroidism, paralysis, brain death decrease CO_2 production and induce a decrease in V‘CO2.
Decreasing V‘CO2 can also be due to a decrease in cardiac output or blood loss, and may also suggest a change in blood flow: PE

Increase in V‘CO2

is usually due to bicarbonate infusion or an increase in CO_2 production that can be caused by:
Fever, Sepsis, Seizures, Hyperthyroidism, Insulin therapy, Bicarbonate infusion

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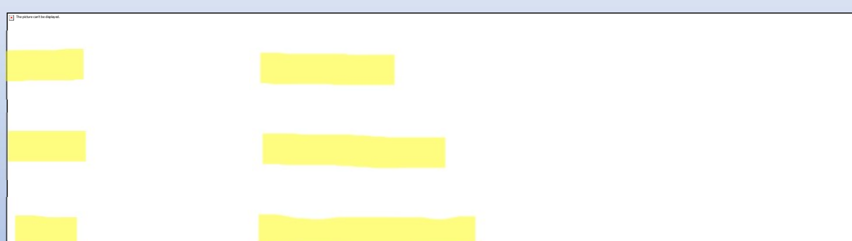
Normal values



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Diagnosis of lung conditions

Erikson, L, Wollmer, P, Olsson, CG, et al. Diagnosis of pulmonary embolism based upon alveolar dead space analysis. Chest1989;96,357-362.

Yaron M, Padyk P, Hutsinpiller M, Cairns CB. Utility of the expiratory capnogram in the asses of bronchospasm. Ann Emerg Med. 1996 Oct;28(4):403-7.

49

Setting PEEP

Determination of Optimal PEEP by Carbon Dioxide Production (VCO2) in ARDS Patients. , J Anesth Clin Res 2019, 10:2

50

Recruitment maneuver

Tusman G, et al. (2011). Volumetric capnography for monitoring lung recruitment and PEEP titration. In J. Gravenstein, M. Jaffe, N. Gravenstein, & D. Paulus. *Capnography* (pp. 160-168). Cambridge

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Weaning

Predictors of failing

- Increasing PECO2
- Decreasing VCO2
- Increasing VD/VT ratio

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PetCO2 & VCO2

If the PetCO2 trend moves up while the V'CO2 trend decreases for a while and then returns to baseline, this indicates a worsening of ventilation.
If the PetCO2 trend moves down while the V'CO2 trend increases for a while and then returns to baseline, this indicates an improvement of ventilation.

Rising PetCO2 and V'CO2 trends indicate increasing CO2 production (agitation, pain, fever).

Falling PetCO2 and V'CO2 trends indicate a decrease in CO2 production.

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Alveolar Mechanics and Mechanical Power

Society of Mechanical Ventilation

Alveolar compliance
VT – VDanat / Trans-alveolar DP
VTalv / Trans-alveolar DP

Alveolar flow
V̇ alv = VTalv/Tinsp

Alveolar resistance
Ralv = Trans-Pulmonary pressure (PPL) - TransAlveolar pressure (PTA) / V̇ alv

MPAlv
(0.098 X RR) x {2 VTAlv x ½ EAlv + (VTAlv x PEEP)}

Daoud EG, Franck CL. Alveolar mechanics: A new concept in respiratory monitoring. J Mech Vent 2022; 3(4):178-188.

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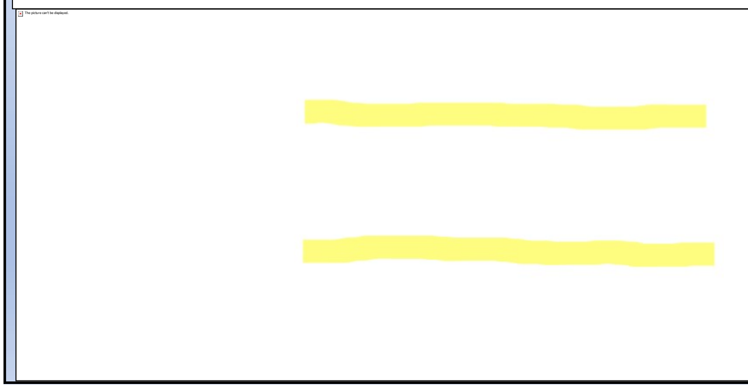
Hemodynamics and Fluid responsiveness



Young A, et al. Journal of Cardiothoracic and Vascular Anesthesia, Vol 27, No 4 (August), 2013: pp 681-684

55

Continuous measurement of Cardiac Output

Volume capnography can provide quantitative measurements of cardiac output using a technique called "partial CO_2 rebreathing". This method is based on a modification of the Fick principle, which states that the rate of CO_2 excretion by the lungs must equal the difference between the rate at which CO_2 is delivered by the mixed venous blood ($\dot{V}dCO_2$) and the rate at which it leaves in the arterial blood ($\dot{V}aCO_2$).

$\dot{V}ECO_2 = \dot{V}DCO_2 - \dot{V}aCO_2$

$\dot{Q}T = (\Delta\dot{V}ECO_2/\Delta CaCO_2) + \dot{Q}S$

$\dot{Q}T = (\Delta\dot{V}ECO_2/\Delta CaCO_2)/(1 - \dot{Q}S/\dot{Q}T)$

Philip J, et al. Noninvasive, Automated and Continuous Cardiac Output Monitoring by Pulmonary Capnodynamics: Breath-by-breath Comparison with Ultrasonic Flow Probe. Anesthesiology 2006; 105:72–80

56

Calculating Caloric requirements based on VCO2

Modified Weir's equation to calculate EE $(3.941 * VCO2/RQ + 1.106 * VCO2) * 1440$

Yatabe, T. Strategies for optimal calorie administration in critically ill patients. j intensive care 7, 15 (2019).

57

Evidence

Verscheure S, et al. Volumetric capnography: lessons from the past and current clinical applications. Crit Care. 2016 Jun 23;20(1):184.

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THANK YOU
Questions

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