ELECTRICAL IMPEDANCE TOMOGRAPHY IN RESPIRATORY FAILURE

Dr Akshay Raut

SR Pulmonary Medicine

1. Introduction to thoracic EIT
2. EIT basic tools
3. **EIT in ARDS**

Application of EIT in

4. Pneumothorax
5. Monitor effects of ET aspiration
6. Ventilator desynchrony
7. Pulmonary perfusion
8. COPD

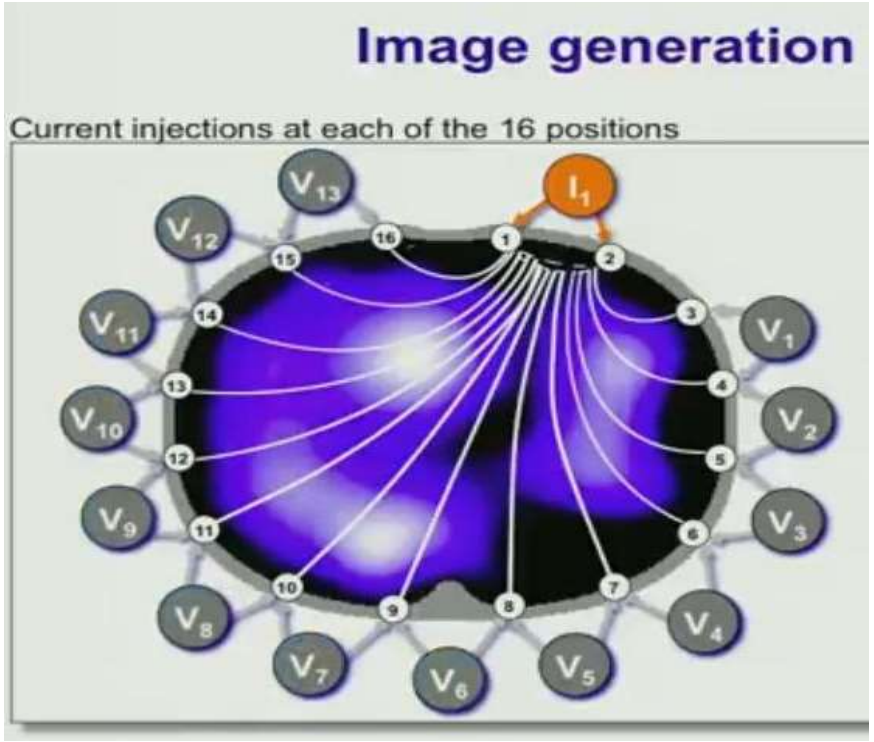
Thoracic EIT – Introduction

- EIT is a low-cost noninvasive, radiation-free imaging method
- It reconstructs images of a specific region in the human body based on the electrical conductivity of biological tissue
- EIT allows continuous bedside monitoring of the regional mechanical properties by measuring changes in impedance associated with ventilation

- For EIT, an electrode belt containing 16 or 32 electrodes is placed around the chest at around 4th to 6th intercostal space

Nicolo Sella et al 2021

- A defined AC (typically 5mA at a frequency of 50 kHz) is applied to a first pair of electrodes and the resulting voltages are measured using other electrode pairs

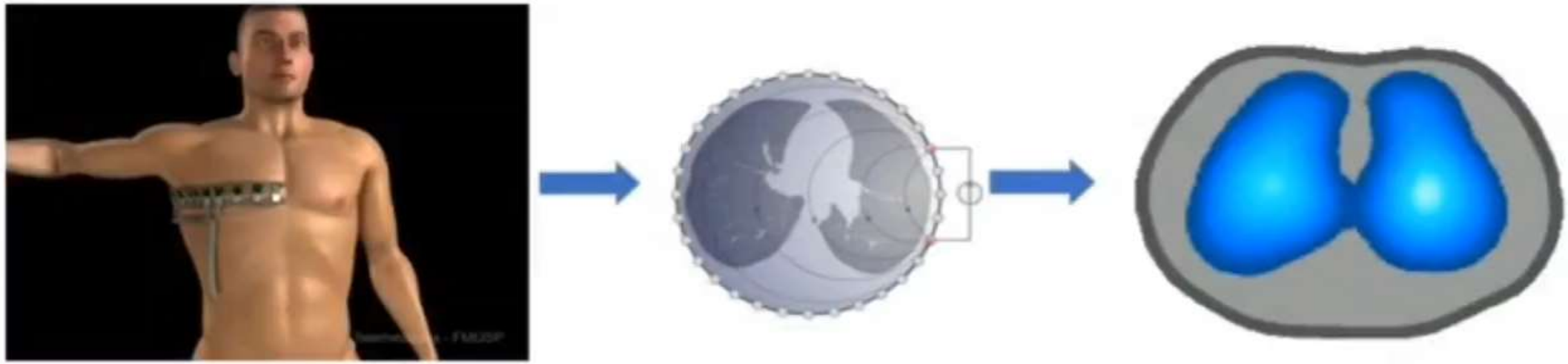


- The location of the current injection and voltage measurements is rotated continuously around the chest

- Bioelectrical impedance between the injecting and the measuring electrode pairs is calculated from the known applied current and the measured voltages

Nicolo Sella et al 2021

Simple. Non Invasive. Bedside.



- **Bioimpedance**

  Bioimpedance can be defined as the voltage response of biological tissue to an externally applied alternating electric current (AC)

- **EIT frame** - The EIT data set which is recorded during one cycle of AC applications, It Contains voltage measurements to generate raw EIT image

Table 1. Electrical resistivity of thoracic tissues.

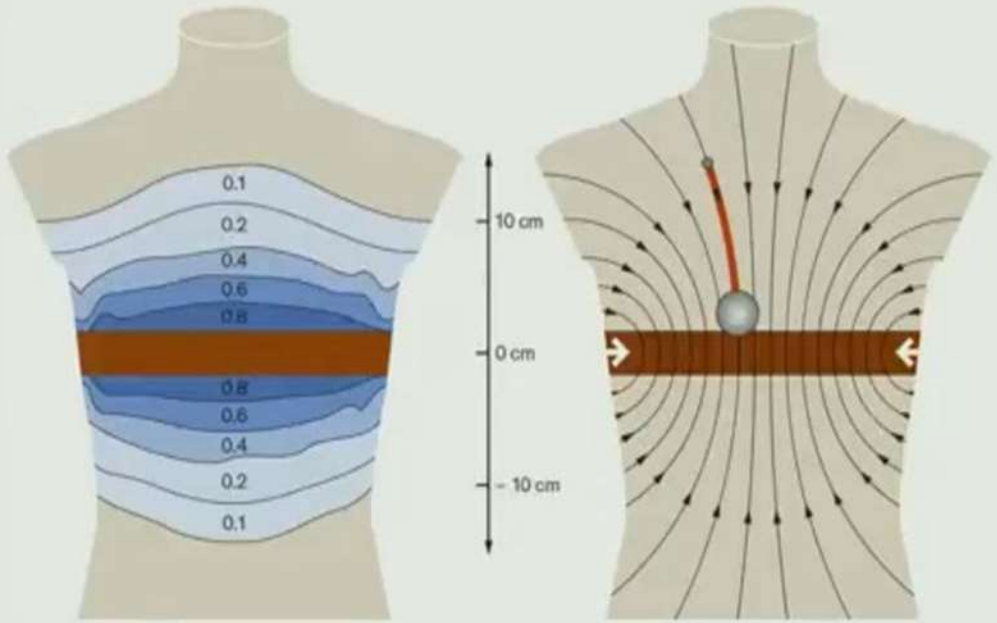
Tissue	Resistivity (Ω·cm)
Blood	150
Lungs, inspiration	2400
Lungs, expiration	700
Heart muscle, longitudinal	125
Heart muscle, transversal	1800
Skeletal muscle, longitudinal	160–575
Skeletal muscle, transversal	420–5200
Fat	2000–2700
Bone	16,600

- **Frame rate** – It reflects the number of EIT frames recorded per second

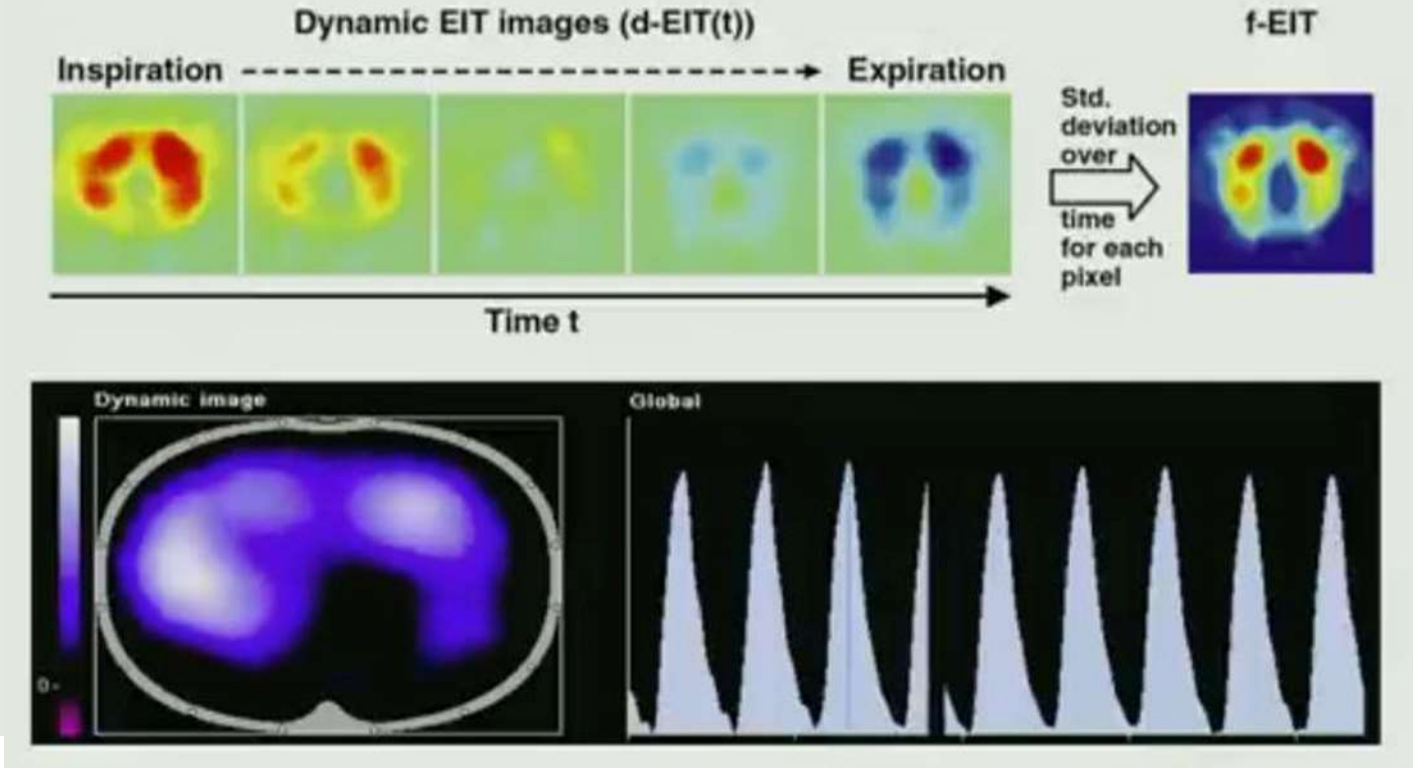
  Frame rates of at least 10 images/s are required to monitor ventilation and 25 images/s to monitor cardiac function or perfusion

Christian Putenson et al J. Clin. Med. 2019

EIT ‘slice’



What does the EIT image represent ?



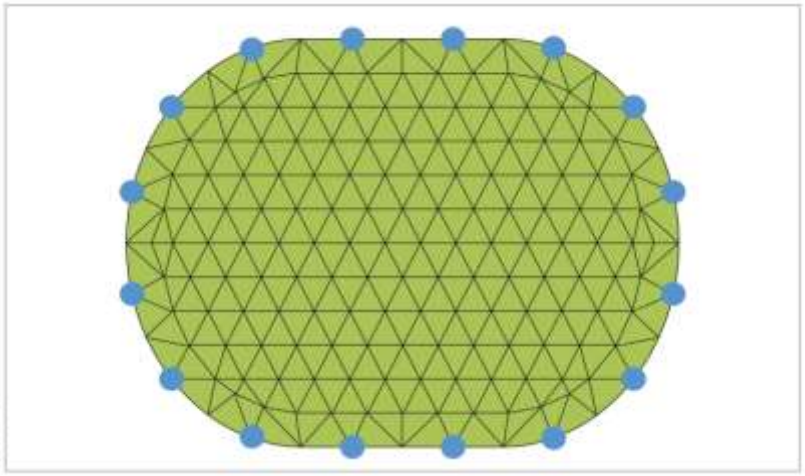
Nicolo Sella et al 2021

Table 2. Commercially available electrical impedance tomography (EIT) devices.

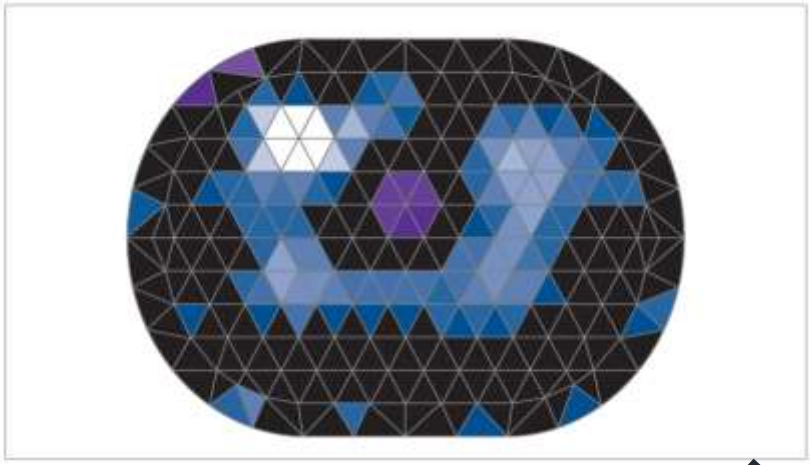
Manufacturer	EIT System	Electrodes		Image Reconstruction Algorithm	Measurement and Data Acquisition
		Number	Configuration		
Swisstom AG	BB^2	32	electrode belt	Graz consensus reconstruction algorithm for EIT (GREIT) algorithm for EIT (GREIT)	pair drive (adjustable skip) serial measurement
Timpel SA	Enlight	32	electrode stripes	Finite Element Method-based Newton-Raphson method	pair drive (3-electrode skip) parallel measurement
CareFusion	Goe-MF II	16	individual electrodes	Sheffield back-projection	pair drive (adjacent) serial measurement
Dräger Medical	PulmoVista 500	16	electrode belt	Finite Element Method-based Newton-Raphson method	pair drive (adjacent) serial measurement
Maltron Inc	Mark 1	16	individual electrodes	Sheffield back-projection	pair drive (adjacent)
	Mark 3.5	8	individual electrodes		serial measurement

Christian Putenson et al J. Clin. Med. 2019

Image Reconstruction

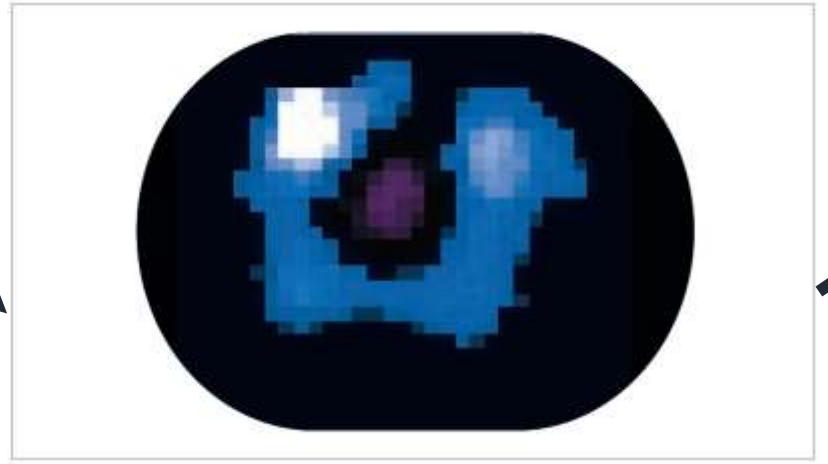


2D Mesh



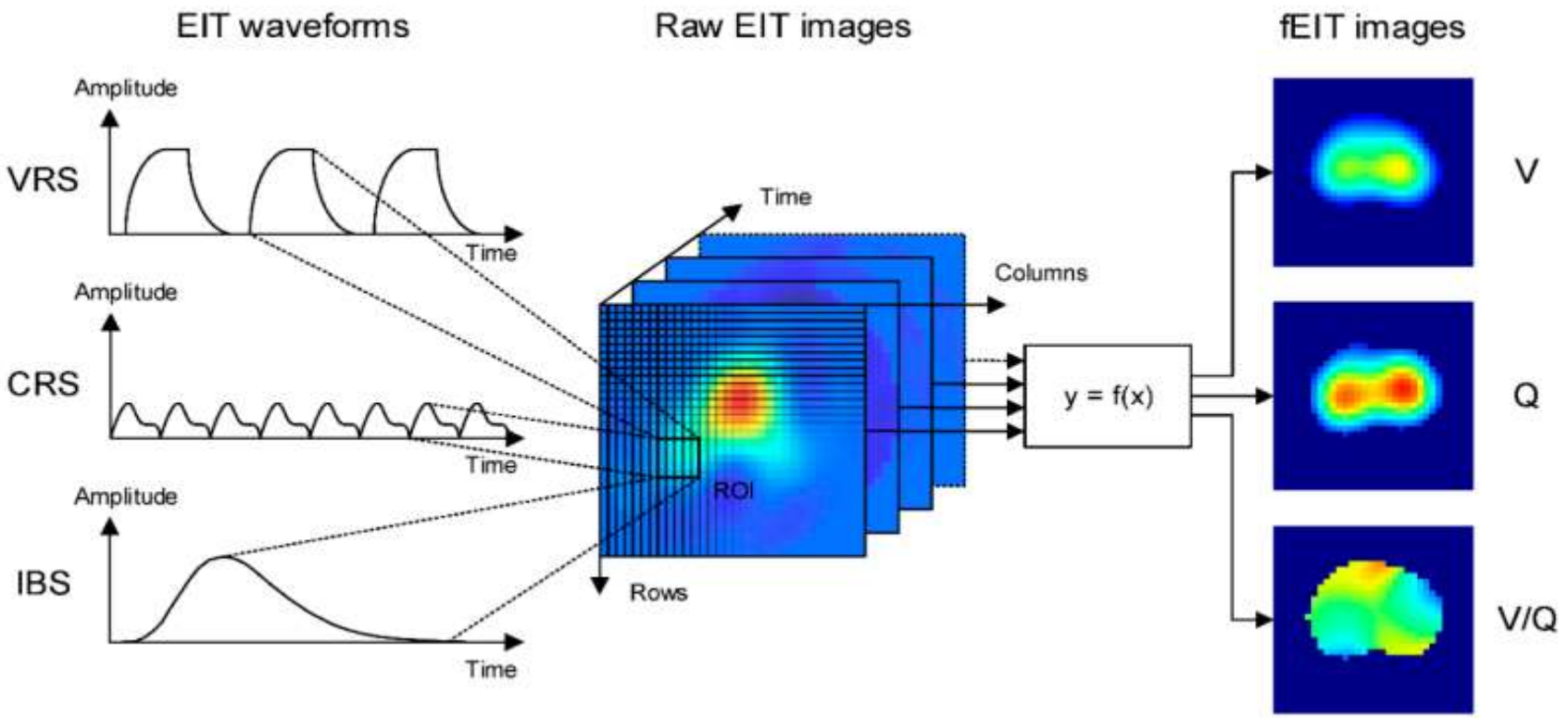
FEM based reconstruction

Coregistration and damping



Smoothing by Gaussian filtering

Bilinear Filtering



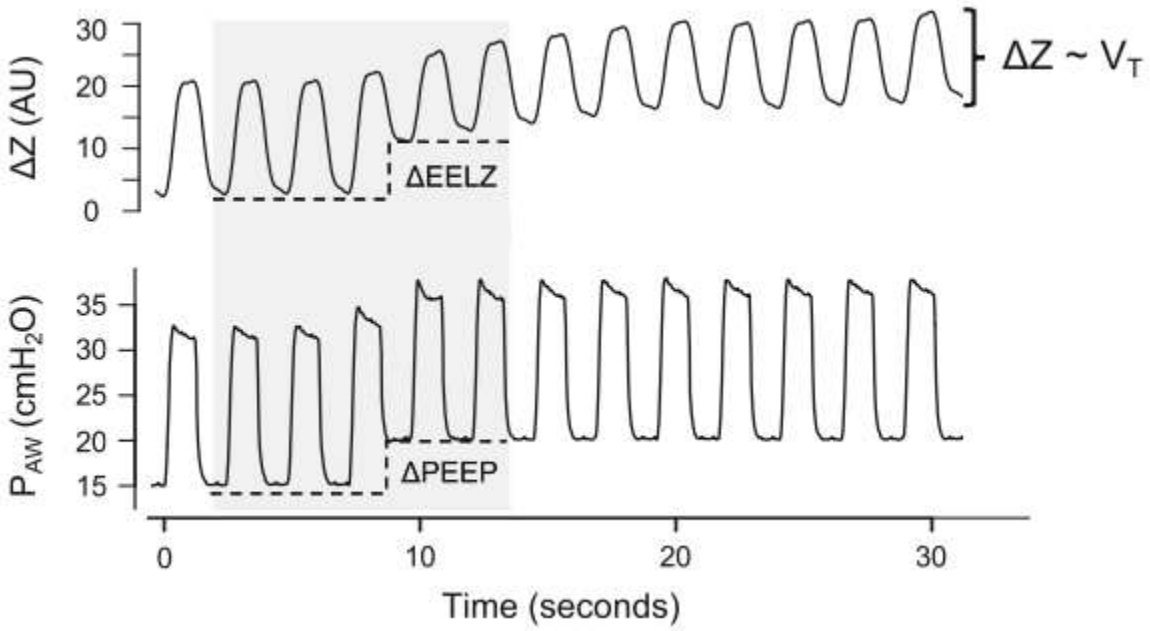
EIT images display regional physiological parameters, such as ventilation (V) and perfusion (Q)

Conductivity changes result naturally from ventilation (VRS) or cardiac activity (CRS) but can also be induced artificially, e.g., by bolus injection (IBS) for perfusion measurement

Christian Putenson et al J. Clin. Med. 2019

EIT Basic Tools

- **EIT Plethysmogram**

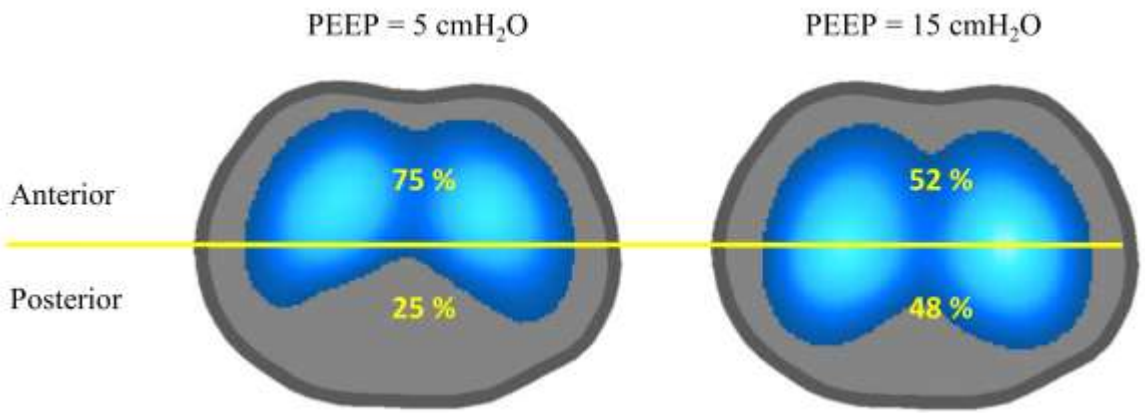


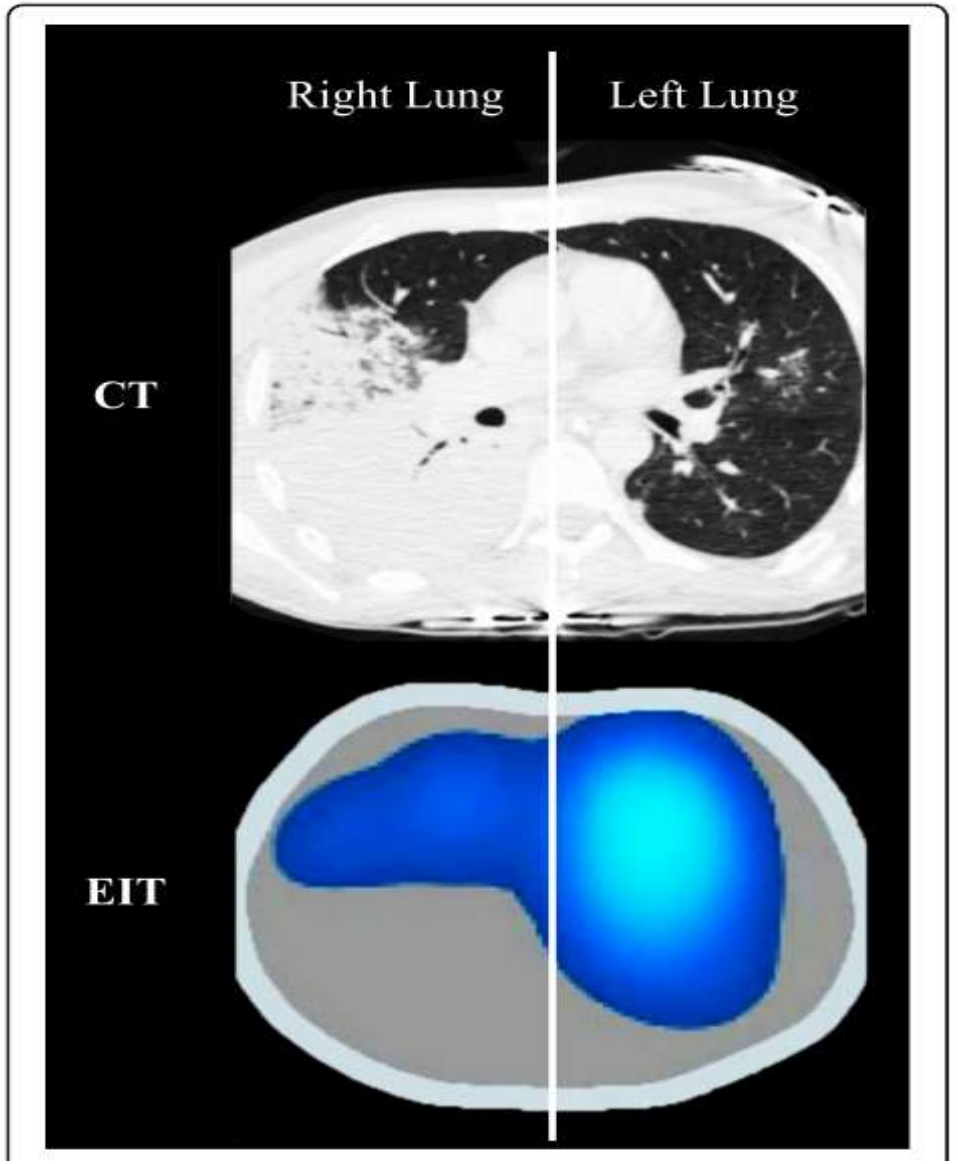
- Waveform derived from the sum of all pixels within a given ROI plotted against time
- It represents the amount of air that moves in and out of the ROI
- Delta Z - tidal oscillation in the global plethysmogram caused by each respiratory cycle
- EIT monitors Delta Z i.e pulmonary ventilation and Delta EELZ i.e. it identifies changes in pulmonary aeration

Bachmann et al. Critical Care (2018) 22:263

Ventilation Map or Functional Image

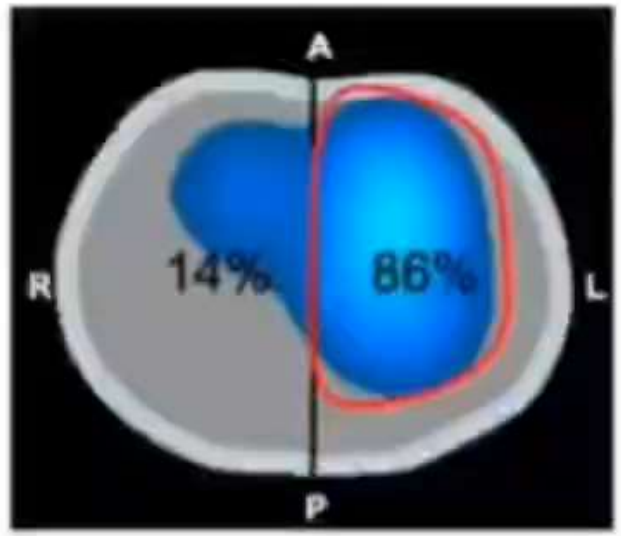
- It is a color map of the pixel-wise ΔZ
- Representation of the tidal changes in impedance pixel by pixel
- Commonly used to identify heterogeneity, the distribution of ventilation caused by pathologies and/or ventilatory settings



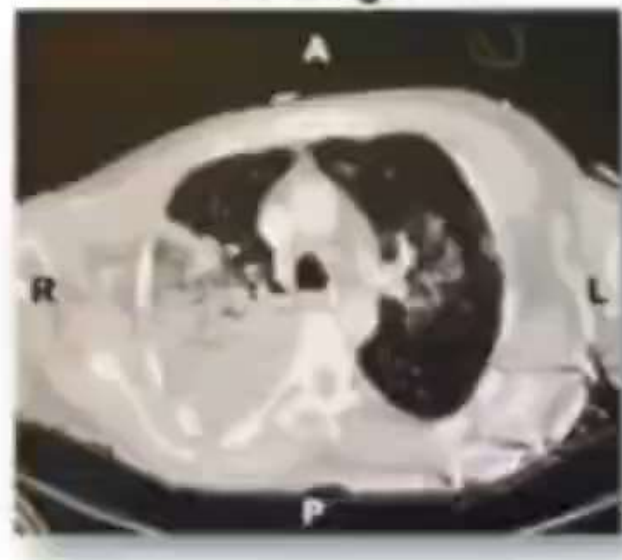


Bachmann et al. Critical Care (2018) 22:263

EIT image



CT image



C Bachmann, C Morais, et al. *et al.* Crit Care 2018.

Heterogeneity of regional inflection points from pressure-volume curves assessed by electrical impedance tomography

Gaetano Scaramuzzo[1], Savino Spadaro[1*], Andreas D. Waldmann[2], Stephan H. Böhm[2], Riccardo Ragazzi[1], Elisabetta Marangoni[1], Valentina Alvisi[1], Elena Spinelli[3], Tommaso Mauri[3] and Carlo Alberto Volta[1]

- VILI – Mechanism -high volumes, high pressures, and cyclic opening and closing of the peripheral airways
- P-V curve - explores changes in the respiratory system compliance along a wide range of Paw (e.g., between 0 and 40 cmH2O)
- The region between the the LIP and UIP as safe for mechanical ventilation to prevent Barotrauma and atelectotrauma

Scaramuzzo et al. Critical Care (2019) 23:119

- But this approach considers the respiratory system as a whole
- Regional P-V curves obtained by EIT would provide different information
- In this study P-V curves for each pixel row from non-dependent to dependent lung regions of patients of AHRF and ARDS were constructed using EIT

Scaramuzzo et al. Critical Care (2019) 23:119

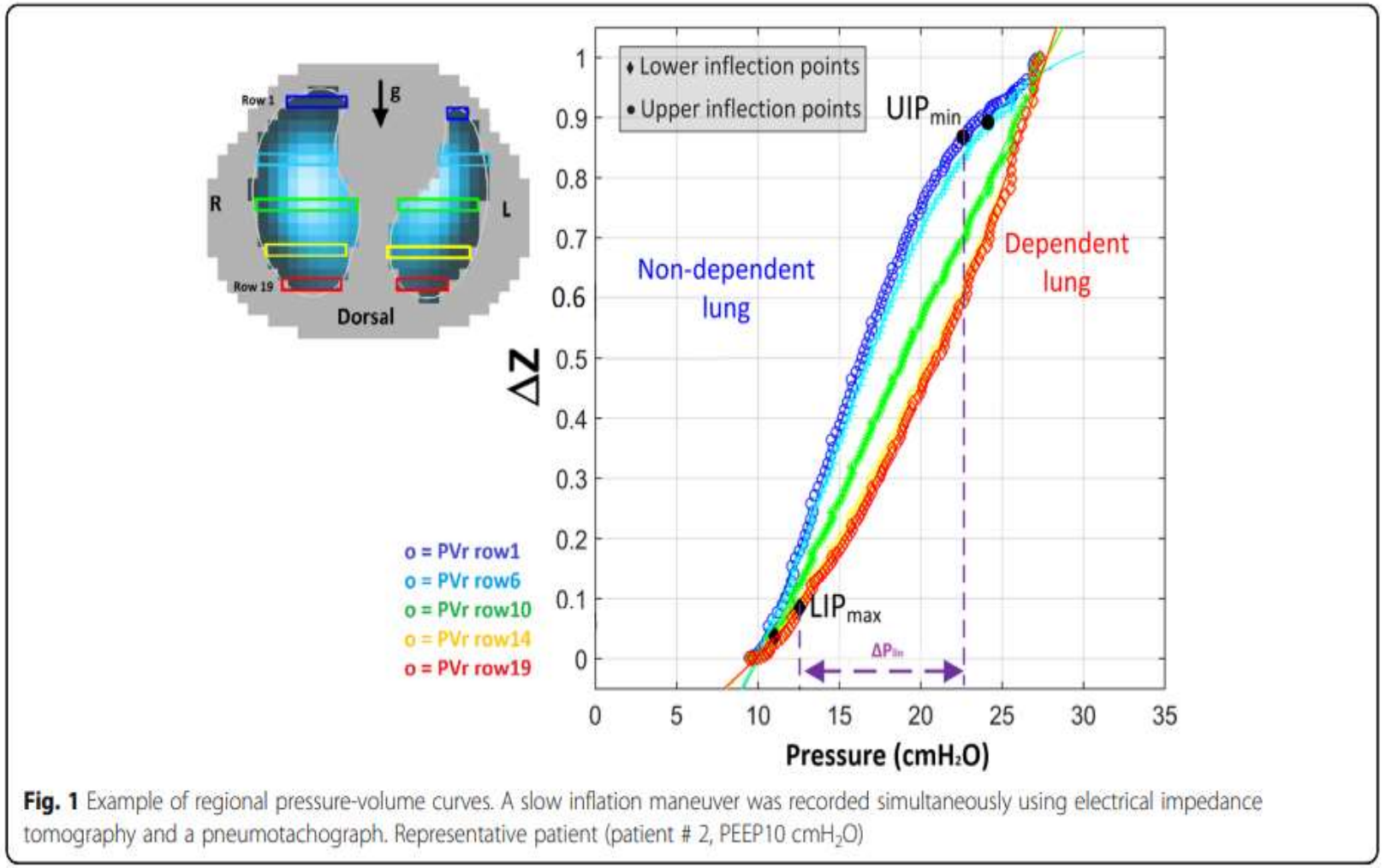


Fig. 1 Example of regional pressure-volume curves. A slow inflation maneuver was recorded simultaneously using electrical impedance tomography and a pneumotachograph. Representative patient (patient # 2, PEEP10 cmH_2O)

LIPr values increased from the non-dependent to the dependent lung

UIPrMIN located in the most non-dependent lung and LIPrMAX in the most dependent

Scaramuzzo et al. Critical Care (2019) 23:119

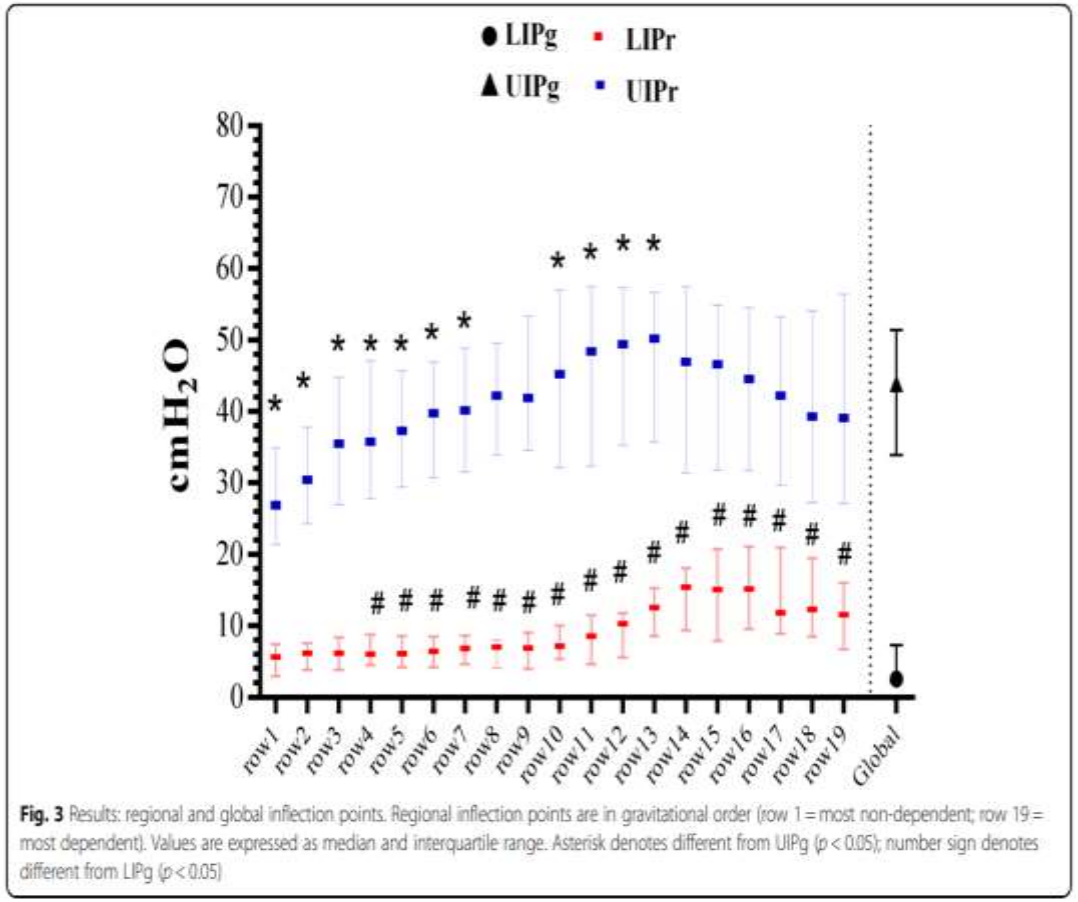
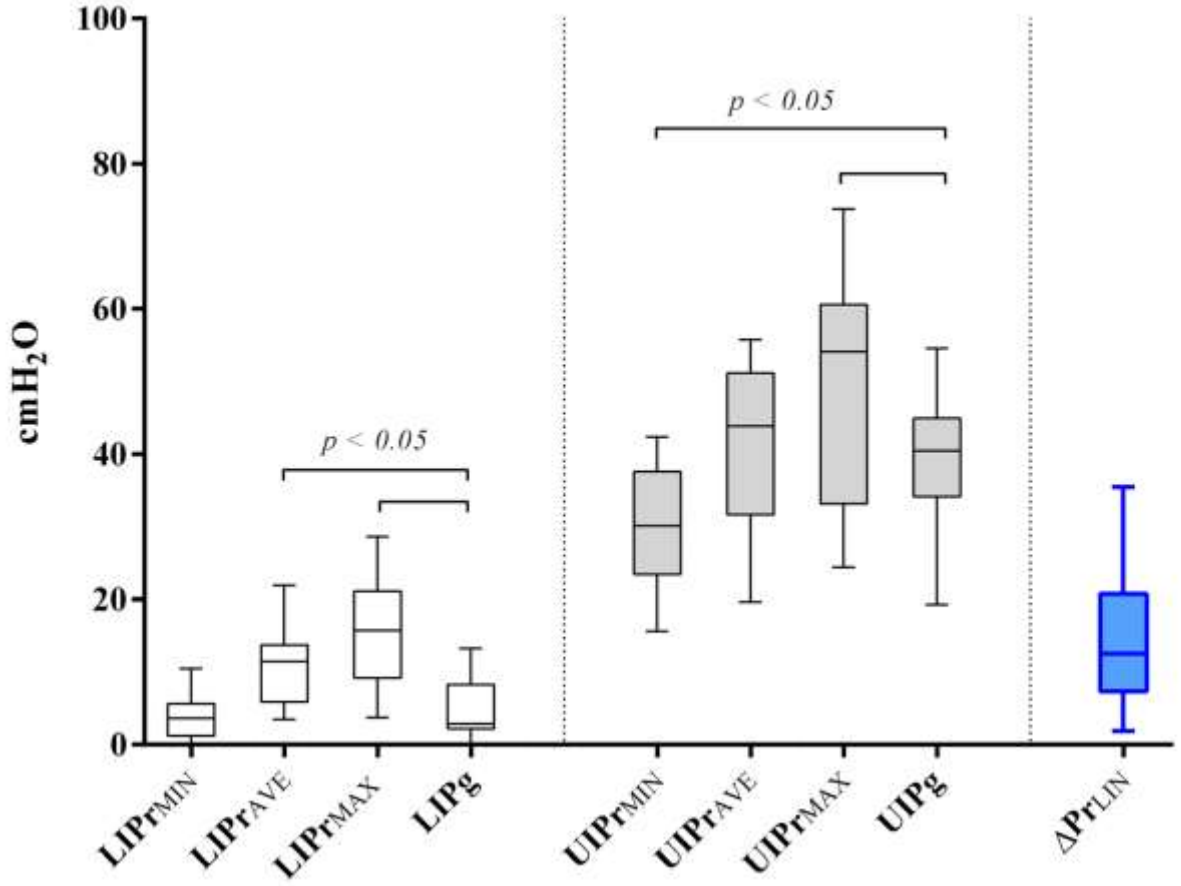


Fig. 3 Results: regional and global inflection points. Regional inflection points are in gravitational order (row 1 = most non-dependent; row 19 = most dependent). Values are expressed as median and interquartile range. Asterisk denotes different from UIPg ($p < 0.05$); number sign denotes different from LIPg ($p < 0.05$)

The global P-V and the regional P-V curves do not provide the same information, and the inflection points of the global P-V curve are different from those of the PVr - suggest heterogeneity of the inflection points of the different lung region

Scaramuzzo et al. Critical Care (2019) 23:119



- Delta PrLIN - the maximal pressure range which avoids regional overinflation and derecruitment

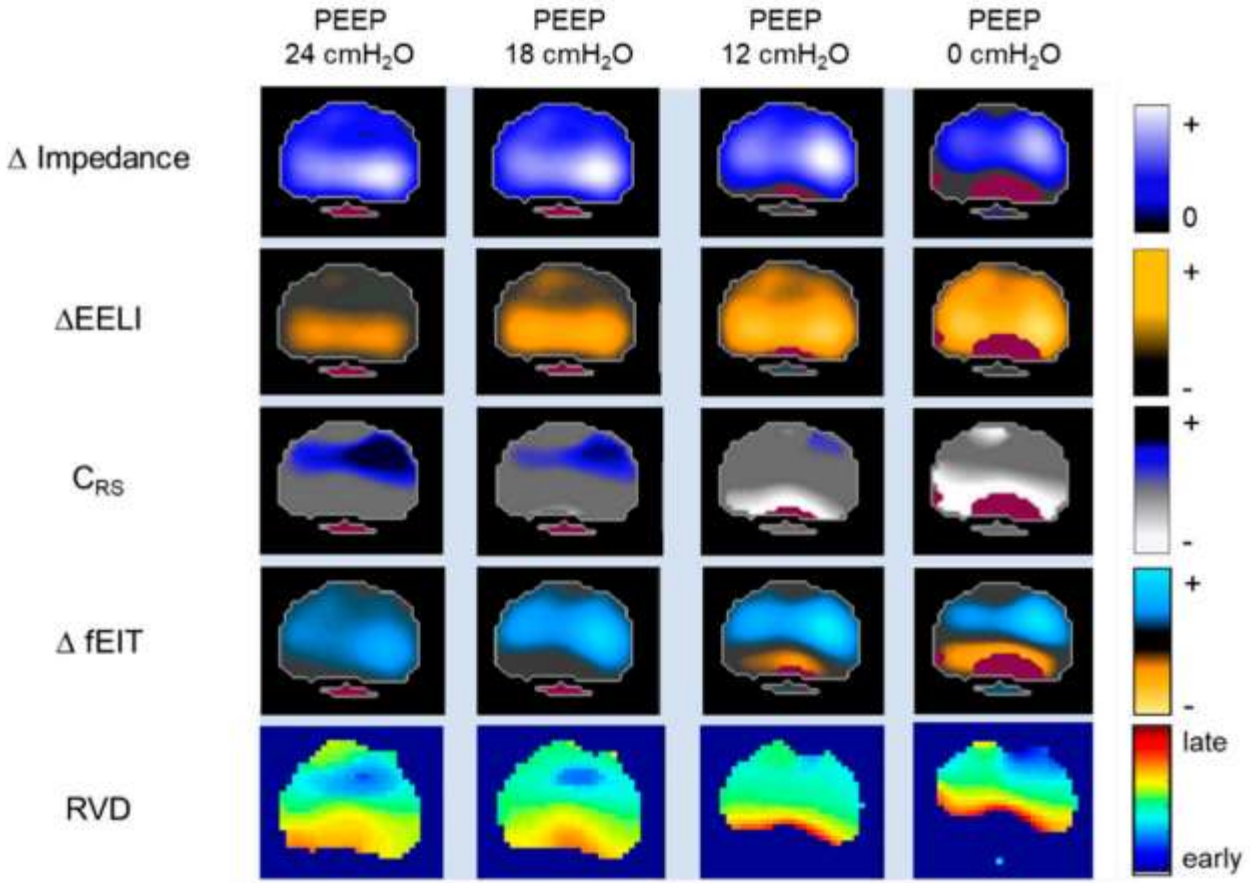
- A statistically significant difference was also found between the LIPg and LIPrMAX
- A statistically significant difference was found between UIPg and UIPrMIN
- Hypothesis- LIPrMAX can be helpful in setting PEEP while UIPrMIN can represent a pressure limit to avoid regional overstretch

Scaramuzzo et al. Critical Care (2019) 23:119

EIT in ARDS

- EIT is a monitoring tool that allows one to evaluate at the bedside the distribution of pulmonary ventilation continuously, in real-time
- Useful in optimizing mechanical ventilation parameters in critically ill patients

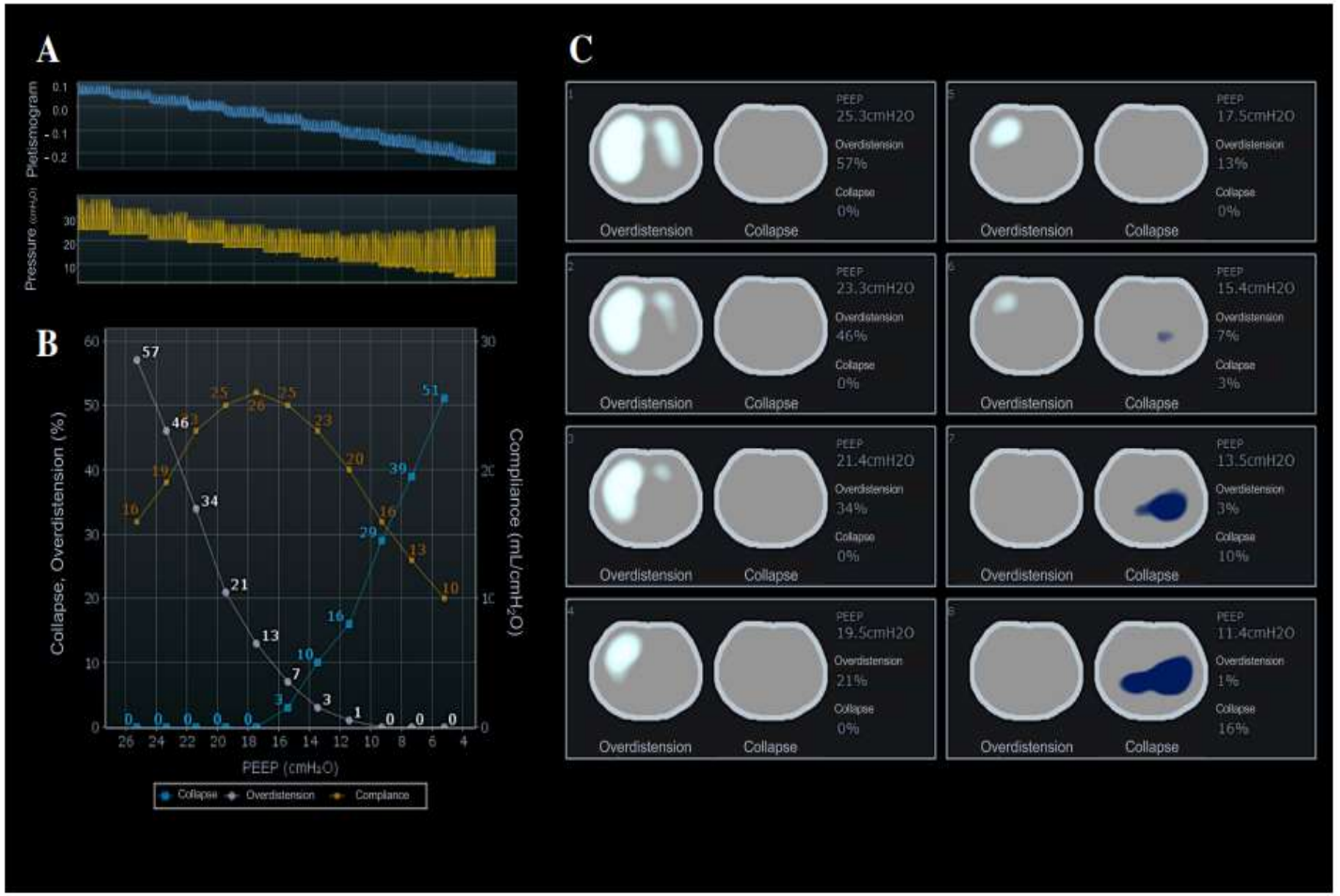
Subtracting fEIT images from previous image



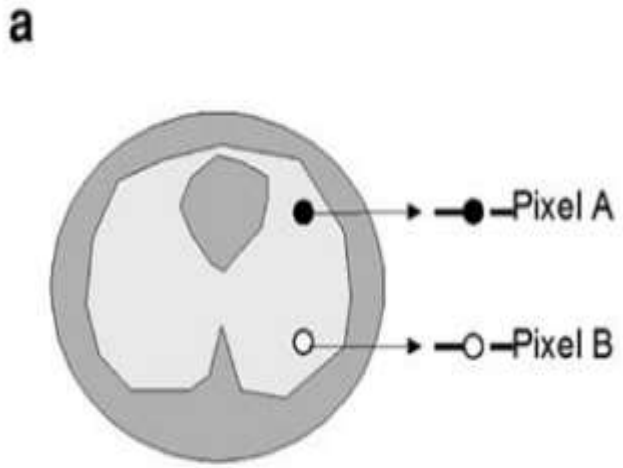
Bachmann et al. Critical Care (2018) 22:263

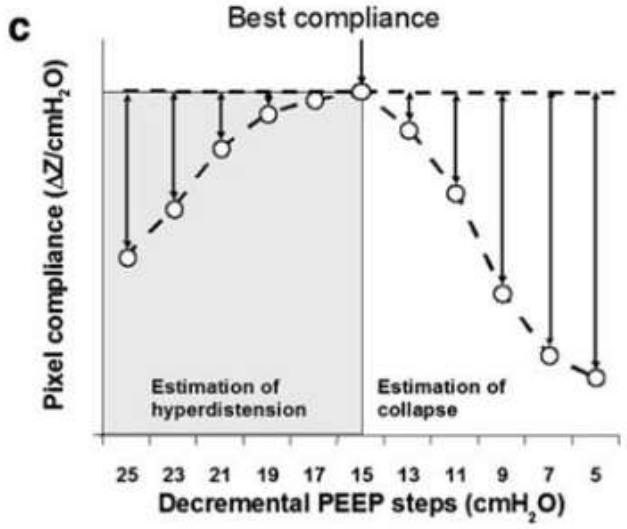
Estimation of lung collapse and overdistension

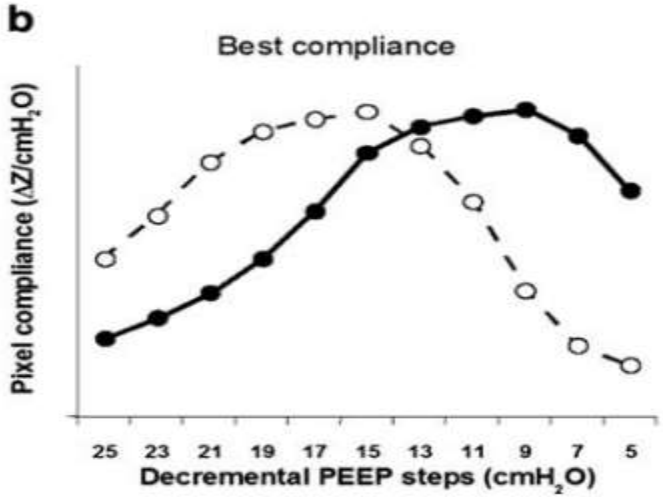
- By EIT one can estimate pulmonary collapse and overdistension using regional information (pixel compliance) during a decremental PEEP maneuver
- Compliance of each EIT pixel = ΔZ/Pplateau - PEEP



Costa et al 2009, estimation of lung collapse and overdistention by EIT







Pixel A – Non-dependent pixel
Pixel B – Dependent Pixel

Costa et al 2009, estimation of lung collapse and overdistention by EIT

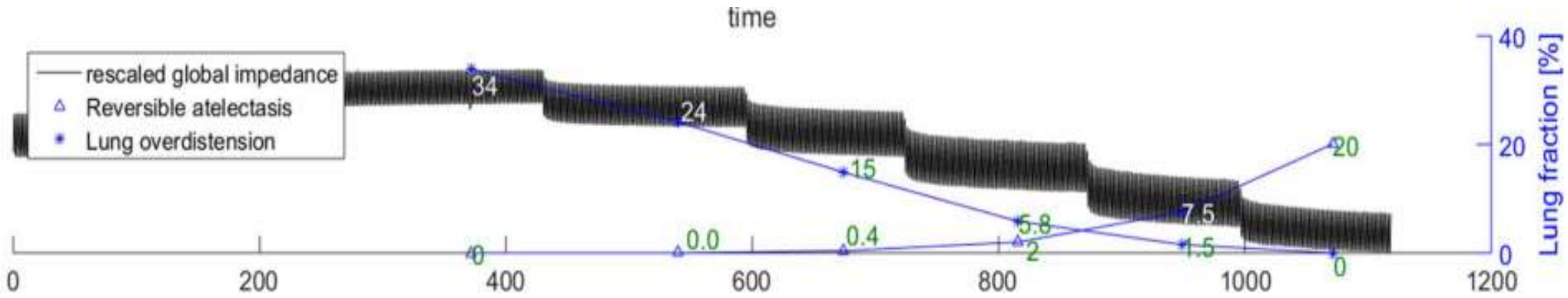
Trials	Intervention	Outcome
Early individualized peep guided by EIT in ARDS - RCT He et al 2021 (crit care)	N = 126, 1:1 PEEP by low peep fio2 table vs EIT	Primary endpoint – All-cause mortality(28d) - 13(21%) vs 15(27%), p = 0.63 VFD and length of ICU stay – No significant diff D1, D2 SOFA score , p = 0.0001
PEEP titration with EIT and P-V curve – RCT, Hui et al	N = 87, 1:1 PEEP by EIT vs P-V tool	Primary outcome – Respiratory mechanics (compliance) – No significant difference Significantly lower Pd and hospital mortality rate
Lung recruitment assessed by EIT RECRUIT study (COVID 19) – ATS 2023	N = 108, mod to severe ARDS PEEP set by EIT – crossing point of overdistention and collapse curves	• Recruitability varied from 0.3% to 66.9% and was unrelated to ards severity

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

Huaiwu He[1], Yi Chi[1], Yingying Yang[1], Siyi Yuan[1], Yun Long[1*], Pengyu Zhao[2], Inéz Frerichs[3], Feng Fu[4], Knut Möller[5] and Zhanqi Zhao[4,5*]

He et al Crit Care 2021

- 126 Patients were randomly assigned in a 1:1 ratio to the EIT or the control group (PEEP setting by low PEEP/FiO2 table)
- PEEP titration by EIT was performed at the enrollment. The optimal PEEP determined by EIT was applied for 24 h
- PEEP was set based on the low PEEP/FiO2 table
- EIT group – PEEP was set as the intercept point of cumulated collapse and overdistension percentage curves



Primary endpoint - all-cause mortality within 28 days after randomization

Secondary endpoints - the number of ventilator-free days at day 28,ICU length of stay, new onset barotrauma

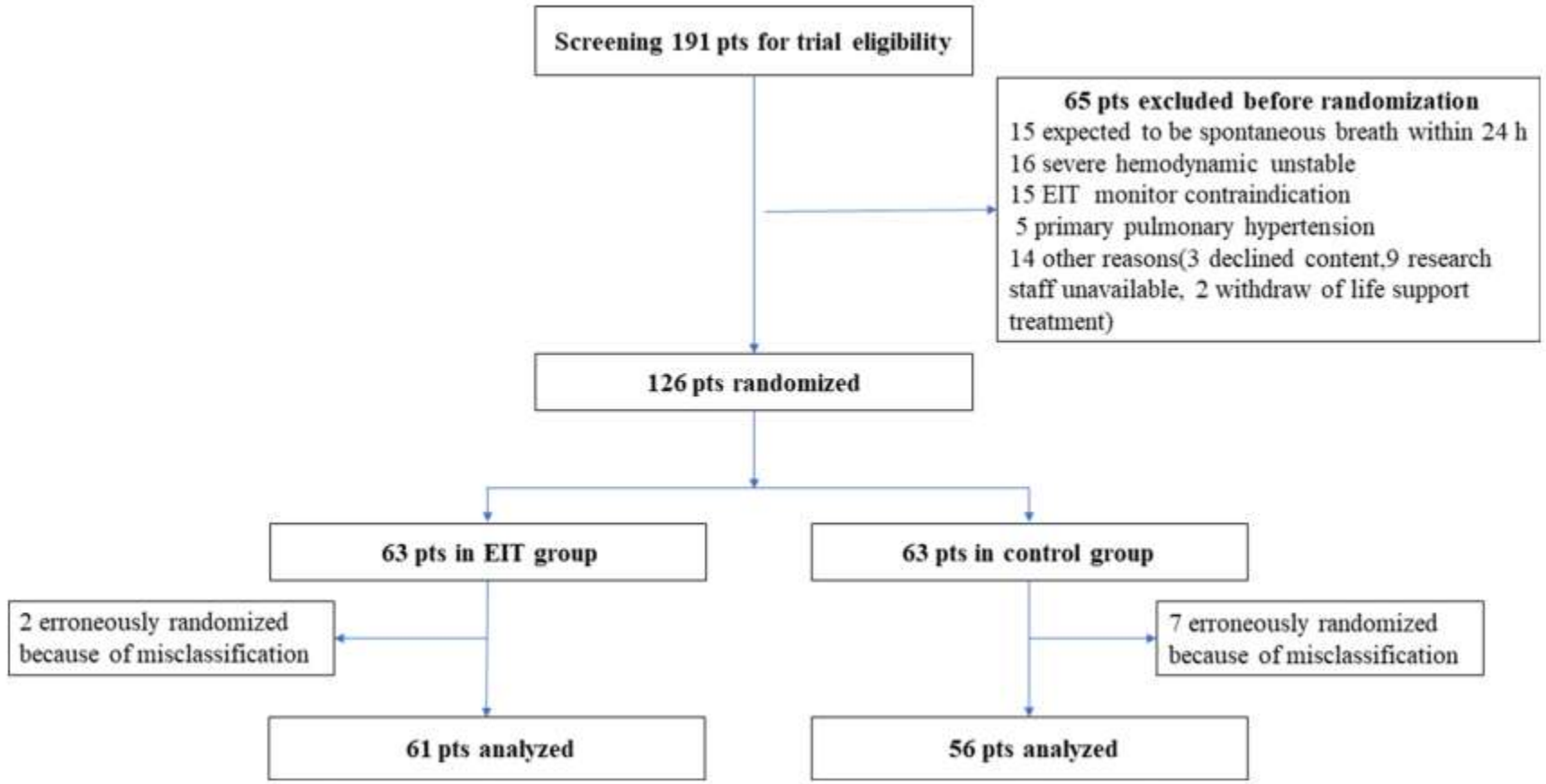

Screening 191 pts for trial eligibility
65 pts excluded before randomization
15 expected to be spontaneous breath within 24 h
16 severe hemodynamic unstable
15 EIT monitor contraindication
5 primary pulmonary hypertension
14 other reasons(3 declined content,9 research staff unavailable, 2 withdraw of life support treatment)
126 pts randomized
63 pts in EIT group
63 pts in control group
2 erroneously randomized because of misclassification
7 erroneously randomized because of misclassification
61 pts analyzed
56 pts analyzed

Table 1 Baseline clinical characteristics and demographics of patients

Variables	EIT group ($n=61$)	Control group ($n=56$)	p value
Age (years)	61.0 (44.0, 68.0)	66.5 (50.0, 73.0)	0.074
Female Sex	19/61	21/56	0.597
Body mass index (kg/m^2)	26.0 (22.9, 29.1)	26.0 (22.9, 28.6)	0.933
APACHE II score	19.0 (15.0, 25.0)	18.0 (15.0, 21.2)	0.568
Reason for ARDS			
Pneumonia	28/61	24/56	0.884
Extrapulmonary sepsis	10/61	15/56	0.252
Severe acute pancreatitis	0/61	1/56	0.972
Post-cardiac operation	14/61	8/56	0.231
Others	9/61	8/56	0.848
Mild ARDS	18/61	23/56	0.292
Moderate ARDS	28/61	25/56	0.960
Severe ARDS	15/61	8/56	0.161

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

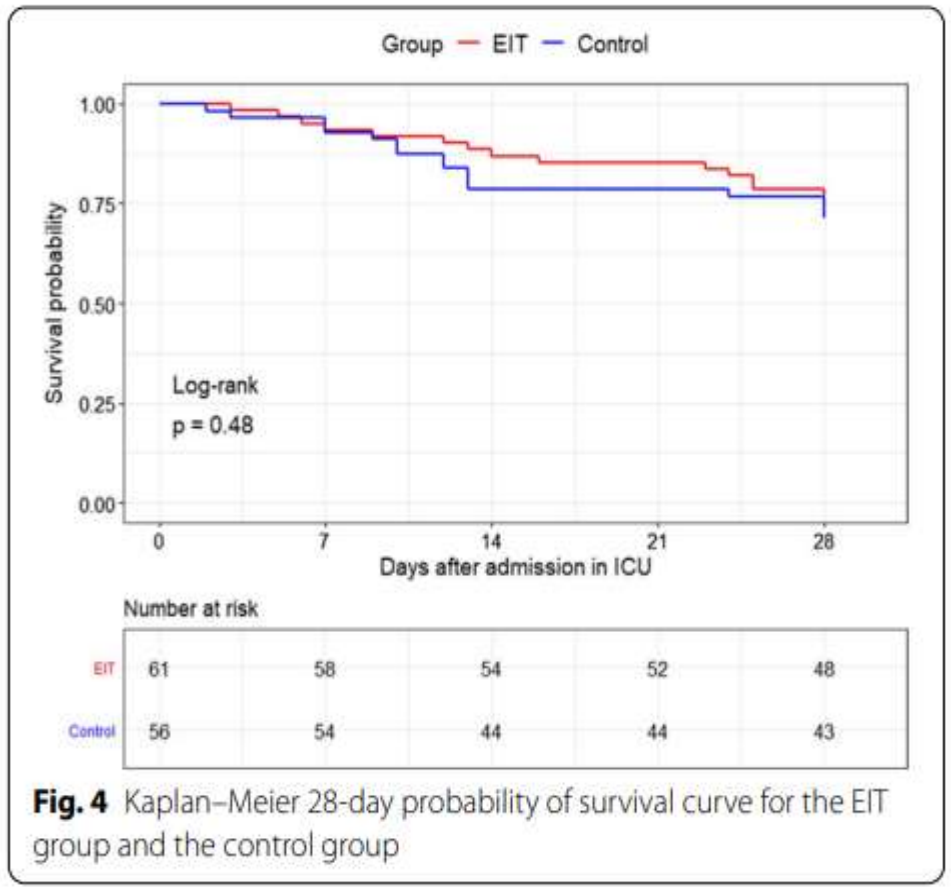


Fig. 4 Kaplan–Meier 28-day probability of survival curve for the EIT group and the control group

Positive end-expiratory pressure titration with electrical impedance tomography and pressure–volume curve: a randomized trial in moderate to severe ARDS -

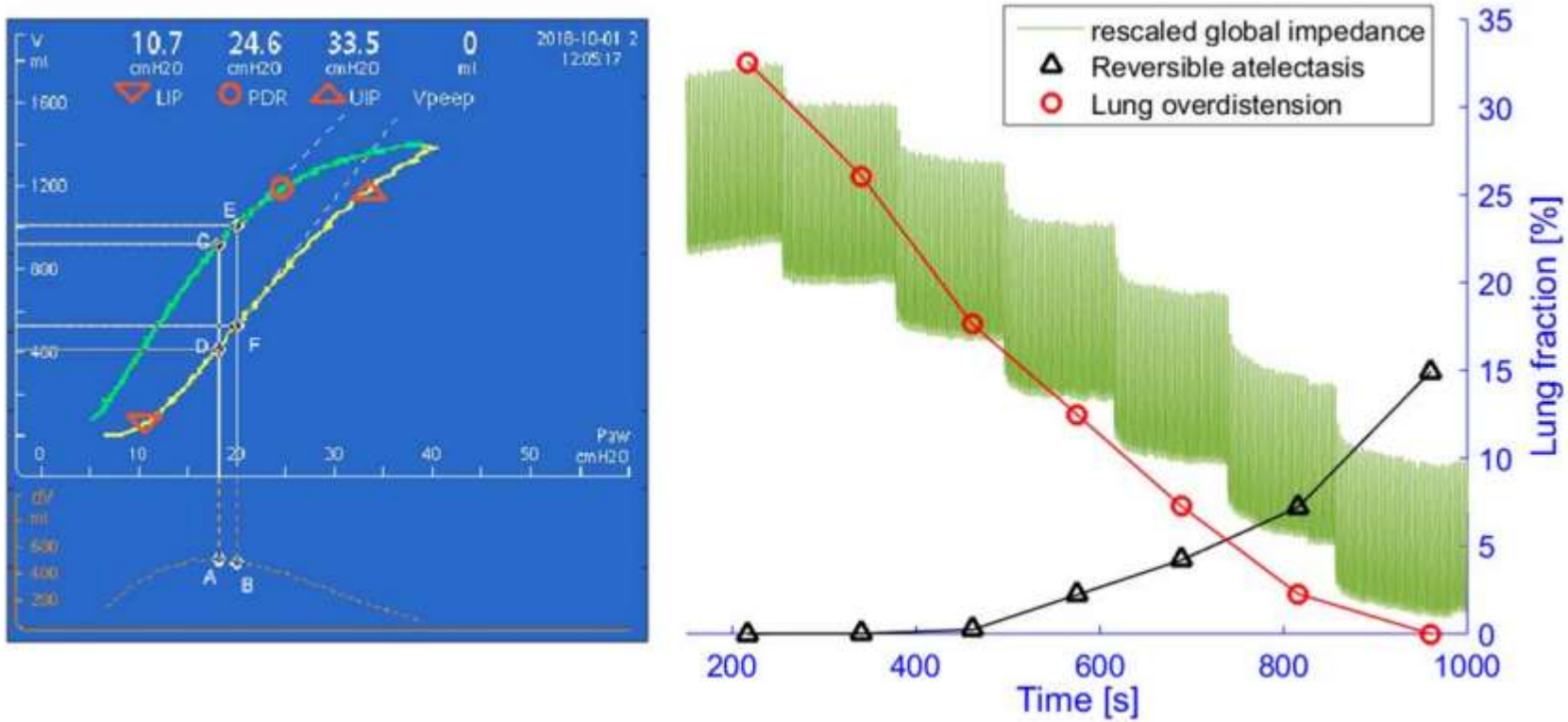
- Aim - To compare titration of PEEP with EIT and with ventilator-embedded PV loop in moderate to severe ARDS
- 87 moderate to severe ARDS patients were randomized to either EIT group (n = 42) or PV group (n = 45)
- Primary outcomes - Respiratory mechanics(compliance)
- Secondary outcomes - oxygenation, all-cause hospital mortality, and weaning success rate (unassisted breathing without ventilator support for 5 days)

Hui-Ju Hsu et al 2021 Physiol

Optimal PEEP selection

- Airway pressure at the time point of maximal hysteresis(i.e. largest volume difference in the PV loop)was defined as optimal PEEP for this group of patients
- During EIT measurement, intercept point of cumulated collapse and overdistension percentages curves

Hui-Ju Hsu et al 2021 Physiol



Hui-Ju Hsu et al 2021 Physiol

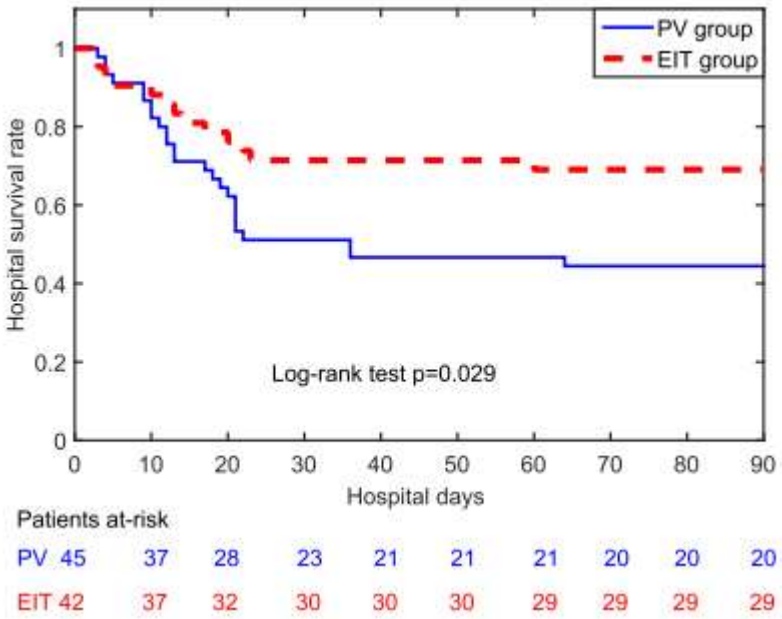
Characteristics	Total ($n = 87$)	PV ($n = 45$)	EIT ($n = 42$)
Age (year)	59.0 ± 16.2	62.2 ± 15.3	55.7 ± 16.6
Height (cm)	164.7 ± 8.5	164.7 ± 9.4	164.7 ± 7.4
Weight (kg)	69.0 ± 19.3	70.0 ± 20.7	68.0 ± 17.6
BMI ($kg\ m^{-2}$)	25.6 ± 6.2	26.2 ± 6.7	24.9 ± 5.6
Gender (male/female)	64/23	36/9	28/14
Severe n (%)	66 (75.9)	34 (75.6)	32 (76.2)
Moderate n (%)	21 (24.1)	11 (24.4)	10 (23.8)

Cst (ml/cmH_2O)			
Admission	29.5 ± 9.5	28.8 ± 8.4	0.75
24 h	30.8 ± 10.4	30.8 ± 7.9[b]	0.97
48 h	32.5 ± 11.6[b]	33.7 ± 7.6[b]	0.61
Resistance ($cmH_2O/L/s$)			
Admission	14.4 ± 4.1	13.4 ± 4	0.28
24 h	13.4 ± 4	12.8 ± 3.1	0.42
48 h	13.1 ± 4.3[b]	12.6 ± 3.4	0.57

Table 2. Comparison of clinical data and other follow-up outcome measures and ventilation strategies between the study groups at baseline, 24 and 48 h after PEEP optimization.

Parameters	PV ($n = 45$)	EIT ($n = 42$)	P value
PEEP setting (cmH_2O)			
Admission	12.6 ± 2.2	12.3 ± 2.7	0.65
After optimization	17.4 ± 1.7	16.2 ± 2.6	**0.02**[a]
PaO_2/FiO_2 (mmHg)			
Admission	119.4 ± 38.9	129.5 ± 39.4	0.24
24 h	196.3 ± 95.8[b]	214.2 ± 90.7[b]	0.38
48 h	226.9 ± 109.5[b]	234.9 ± 85.5[b]	0.71
P_{driv} (cmH_2O)			
Admission	16.7 ± 5.6	17.7 ± 7	0.48
24 h	13 ± 3.3[b]	12.1 ± 2.9[b]	0.18
48 h	12.4 ± 3.6[b]	10.9 ± 2.5[b]	**0.04**[a]
RR (/min)			
Admission	23.3 ± 4.7	20.7 ± 4.9	**0.01**[a]
24 h	23.8 ± 5.2	20.5 ± 4.7	**<0.01**[a]
48 h	23.7 ± 5.0	20.0 ± 4.6	**<0.01**[a]

Outcome			
Survival *n* (%)[c]	20 (44.4)	29 (69.0)	**0.02**[a]
Weaning success *n* (%)	18 (40)	25 (59.5)	0.07
Barotrauma *n* (%)	0 (0)	0 (0)	—
ICU length of stay[d]	19.9 ± 9.6	20.2 ± 9.1	0.90
Length of MV[d]	20.6 ± 11.7	25.3 ± 14.4	0.23
Ventilation strategies			
INO *n* (%)	23 (51.1)	23 (54.8)	0.73
INO days	4.1 ± 2.1	3.0 ± 2.3	0.13
INO dose	34.3 ± 7.7	37.8 ± 5.9	0.10
ECMO *n* (%)	5 (11.1)	16 (38.1)	**<0.01**[a]
ECMO days	11.2 ± 6.7	9.3 ± 4.6	0.50
Tracheotomy *n* (%)	0 (0.0)	6 (14.3)	**0.01**[a]
Prone position *n* (%)	3 (6.7)	2 (4.8)	1.00
NMBA *n* (%)	45 (100)	42 (100)	—



Both PEEP titration methods improved PaO2/FiO2, APACHE II score, driving pressure

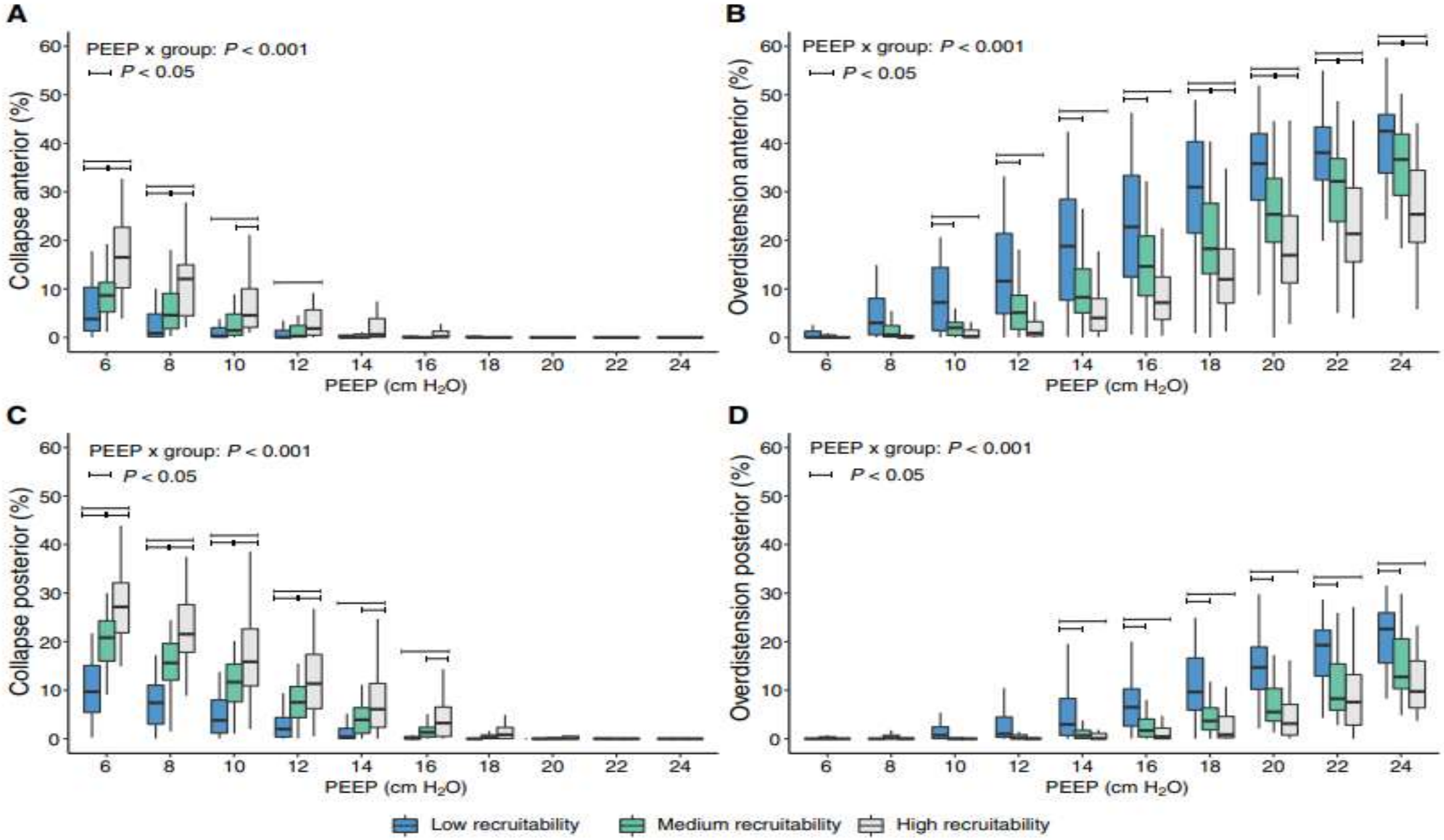
EIT-guided PEEP titration was associated with significantly lower driving pressure and hospital mortality rate

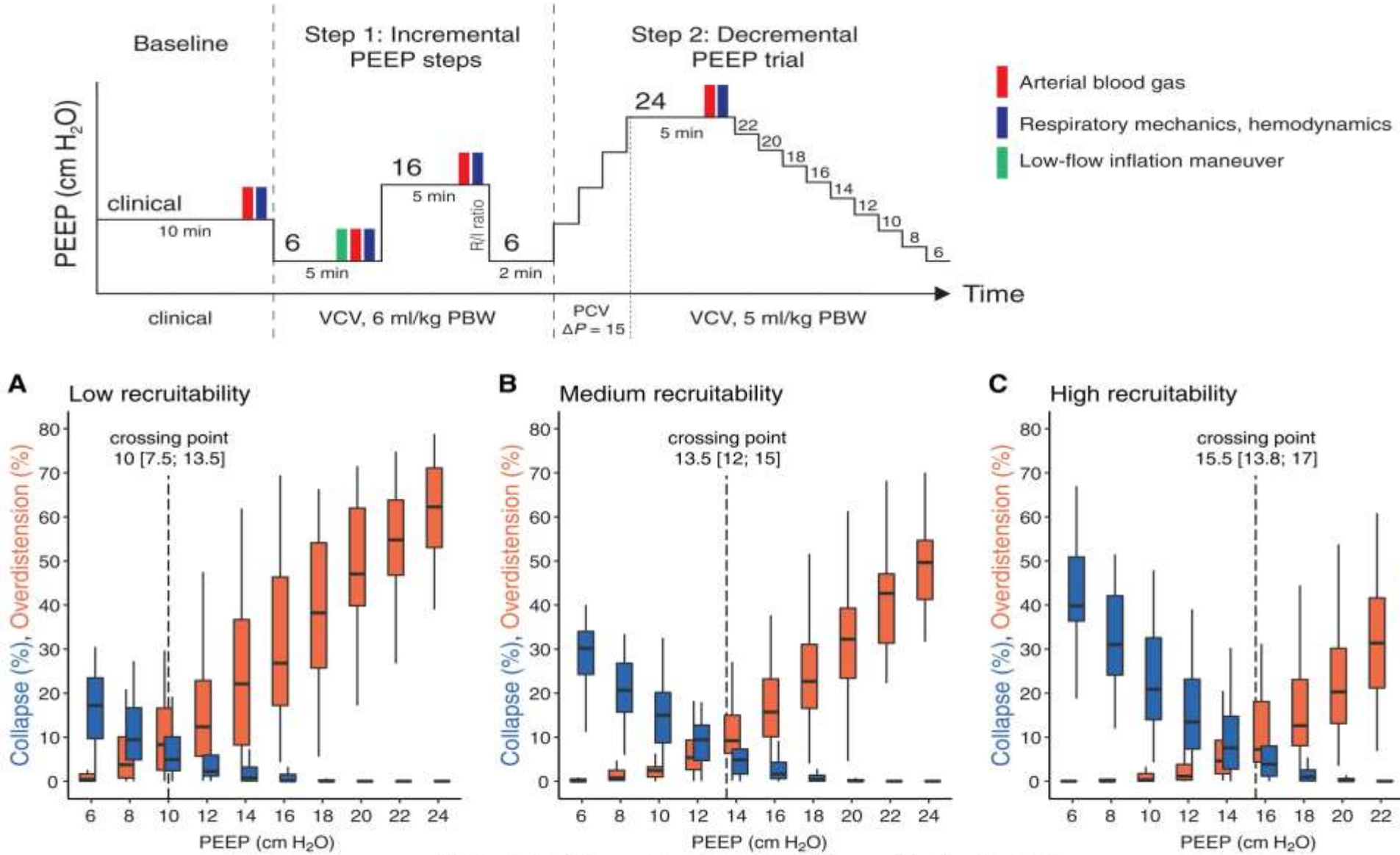
Hui-Ju Hsu et al 2021 Physiol

🔓 Lung Recruitment Assessed by Electrical Impedance Tomography (RECRUIT): A Multicenter Study of COVID-19 Acute Respiratory Distress Syndrome

- **Rationale:** Defining lung recruitability is needed for safe PEEP selection in mechanically ventilated patients
- **Objectives:** To describe the range of recruitability using EIT, the effects of PEEP on recruitability
- Included 108 patients of COVID-19 with mod to severe ards
- EIT-based optimal PEEP was defined as the crossing point of the overdistension and collapse curves during a decremental PEEP trial

Annemijn H. Jonkman et al ATS Journal 2023


A
PEEP x group: P < 0.001
P < 0.05
Collapse anterior (%)
PEEP (cm H2O)
B
PEEP x group: P < 0.001
P < 0.05
Overdistension anterior (%)
PEEP (cm H2O)
C
PEEP x group: P < 0.001
P < 0.05
Collapse posterior (%)
PEEP (cm H2O)
D
PEEP x group: P < 0.001
P < 0.05
Overdistension posterior (%)
PEEP (cm H2O)
Low recruitability
Medium recruitability
High recruitability



Annemijn H. Jonkman et al ATS Journal 2023

Table 1. Patient Characteristics

Characteristics	Total Population ($N = 108$)	Low Recruitability ($n = 36$)	Medium Recruitability ($n = 36$)	High Recruitability ($n = 36$)	*P* Value
Sex, M/F	65/42	23/13	22/14	20/15	0.8530
BMI, kg/m^2	30.4 [25.9; 32.9]	28.4 [24.8; 31.5]	30.1 [26.6; 31.9]	32.9*† [27.2; 39.4]	**0.0134**
Age, yr	61 [51; 68]	65 [57.6; 70]	61 [54; 65]	55* [46; 63.5]	**0.0051**
Pa_{O_2}/Fi_{O_2} ratio at ICU admission, mm Hg	114 [98; 140]	113 [97; 134]	120 [100; 142]	113 [99; 141]	0.9070
SAPS II	52.5 [45; 59]	53 [47; 60]	50 [45; 62]	53 [42.8; 56]	0.4792
SOFA score at study enrollment	6 [4; 8]	7 [4; 8]	5 [4; 8]	5 [4; 8]	0.5678
Days ventilated before study, d	2 [1; 3]	2 [1; 3]	1 [1; 2]	2 [1; 4]	0.1299
Total ventilation duration, d	15 [9; 24.8]	17 [12; 31]	13 [7; 23]	13 [8.5; 24.3]	0.1112
ICU length of stay, d	23 [12; 38]	29 [16; 39]	20 [12; 33]	15.5 [10; 36.5]	0.0878
ICU mortality,‡ %	39% (*n* = 38 of 98)	45% (*n* = 15 of 33)	36% (*n* = 12 of 33)	33% (*n* = 11 of 32)	0.2167
VFD Day 28, d	5 [0; 18]	0 [0; 13]	11 [0; 20]	11 [0; 17.3]	0.1410
Respiratory mechanics at study baseline (clinical settings)					
Total PEEP, cm H_2O	11 [10; 14]	11 [10; 14]	11 [10; 14]	11 [10; 13.8]	0.5604
Driving pressure, cm H_2O§	13 [11; 16]	15 [12; 18]	14 [11.5; 16]	12* [11; 13.8]	**0.0196**
Crs, ml/cm H_2O	27.4 [22.4; 34.8]	24.6 [18.9; 31.7]	28.4 [23.3; 37.0]	28.1 [23.6; 32.9]	0.0817
Normalized elastance, cm H_2O/(ml/kg PBW)	2.20 [1.85; 2.68]	2.42 [1.99; 3.15]	2.20 [2.0; 2.64]	2.04* [1.76; 2.27]	**0.0211**
Pa_{O_2}/Fi_{O_2} ratio, mm Hg	114 [92; 140]	115.4 [98.7; 138.3]	108.5 [89.2; 145.6]	115.3 [89.4; 140.6]	0.8592
Ventilatory ratio	1.75 [1.52; 2.02]	1.89 [1.67; 2.18]	1.57* [1.38; 1.85]	1.75 [1.55; 2.00]	**0.0175**
Recruitability					
$\Delta Collapse_{24-6}$, %	32.0 (min-max, 0.3–66.9)	16.9 [11.1; 22.2]	32.0 [27.3; 34.9]	46.4 [42.5; 51.6]	—
R/I ratio (ventilator based)	0.71 [0.51; 0.94] (*n* = 98)	0.59 [0.43; 0.70] (*n* = 33)	0.79 [0.54; 0.95]* (*n* = 35)	0.83 [0.68; 1.05]* (*n* = 30)	**0.0012**
R/I ratio (EIT based)	0.94 [0.79; 1.17] (*n* = 77)	0.82 [0.59; 1.09] (*n* = 24)	0.90 [0.84; 1.10] (*n* = 31)	1.08 [0.95; 1.35]* (*n* = 22)	**0.0055**

Table 2. Mechanics during Decremental Positive End-Expiratory Pressure Trial and at Crossing Point

	Low Recruitability	Medium Recruitability	High Recruitability	*P* Value
Crossing point PEEP level, cm H_2O	10 [7.5; 13.5]	13.5* [12; 15]	15.5*† [13.8; 17]	**<0.001**
PEEP level with highest Crs, cm H_2O	9 [6; 12]	12* [10; 14]	16*† [12; 18]	**<0.001**
PEEP level with most homogeneous ventilation distribution, cm H_2O	18 [13.8; 22]	16 [13.5; 22]	16 [11.8; 20.5]	0.615
Mechanics at the crossing point PEEP				
Crs, ml/cm H_2O	29.2 [24.4; 38.4]	37.4 [28.2; 46.6]	35.6 [30.8; 39.5]	0.054
ΔPaw, cm H_2O‡	8.2 [7.5; 9.7]	8.6 [7.1; 10.1]	8.4 [7.1; 10.9]	0.923
Collapse, %	4.8 [3.1; 7.2]	6.0 [4.4; 7.3]	4.5 [3.2; 5.8]	0.216
Overdistension, %	8.3 [4.9; 9.9]	8.0 [7.0; 10.1]	6.3 [4.8; 7.9]	0.053
Normalized elastance, cm H_2O/(ml/kg PBW)	1.87 [1.61; 2.53]	1.71 [1.42; 2.04]	1.56 [1.40; 1.87]	0.158
Drop in ΔPaw vs. PEEP 6 cm H_2O (end PEEP trial), cm H_2O	−0.4 [0.0; −0.9]	−1.4* [−0.7; −2.5]	−2.7*† [−1.7; −4.0]	**<0.001**
RR during PEEP trial, breaths/min	25 [23.5; 26]	24 [21.5; 25]	23 [20; 25]	0.0645
Set V_T during PEEP trial, ml	258 [239; 319]	319 [271; 348]*	297 [260; 331]	**0.0268**

- Patients were classified as low, medium, or high recruiters.
- Recruitability varied from 0.3% to 66.9% and was unrelated to ards severity
- Median EIT-based PEEP differed between groups: 10 versus 13.5 versus 15.5 cm H_2O for low versus medium versus high recruitability ($P < 0.05$)

Annemijn H. Jonkman et al ATS Journal 2023

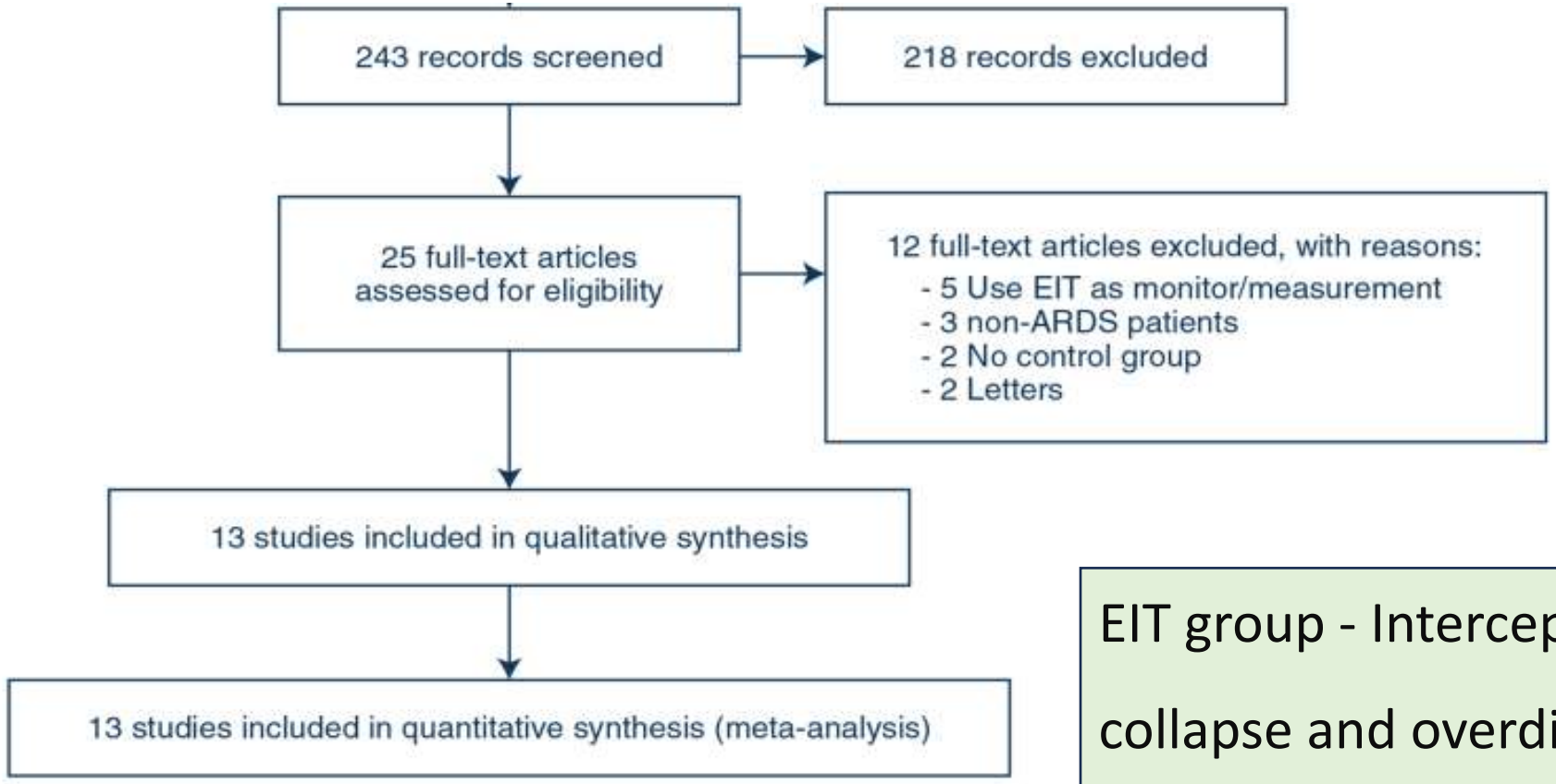
- EIT is a feasible bedside technique for defining the potential of lung recruitment over a clinical range of PEEP
- Recruitability varies widely and is not related to ARDS severity or general severity
- EIT allows the differentiation of patients with different responses to PEEP, including regional information
- EIT therefore could allow personalized PEEP selection at the bedside

SYSTEMATIC REVIEW

Electrical impedance tomography-guided positive end-expiratory pressure titration in ARDS: a systematic review and meta-analysis

Nickjaree Songsangvorn[1,2], Yonghao Xu[1,3*], Cong Lu[1], Ori Rotstein[1,4], Laurent Brochard[1,5], Arthur S. Slutsky[1,5], Karen E. A. Burns[1,5] and Haibo Zhang[1,5,6,7*]

Studies comparing EIT-guided PEEP selection with conventional PEEP titration methods and reported at least one primary or secondary outcome of interest were included



EIT group - Intercept point of cumulated collapse and overdistension percentages curves by Costa et al. to guide PEEP titration

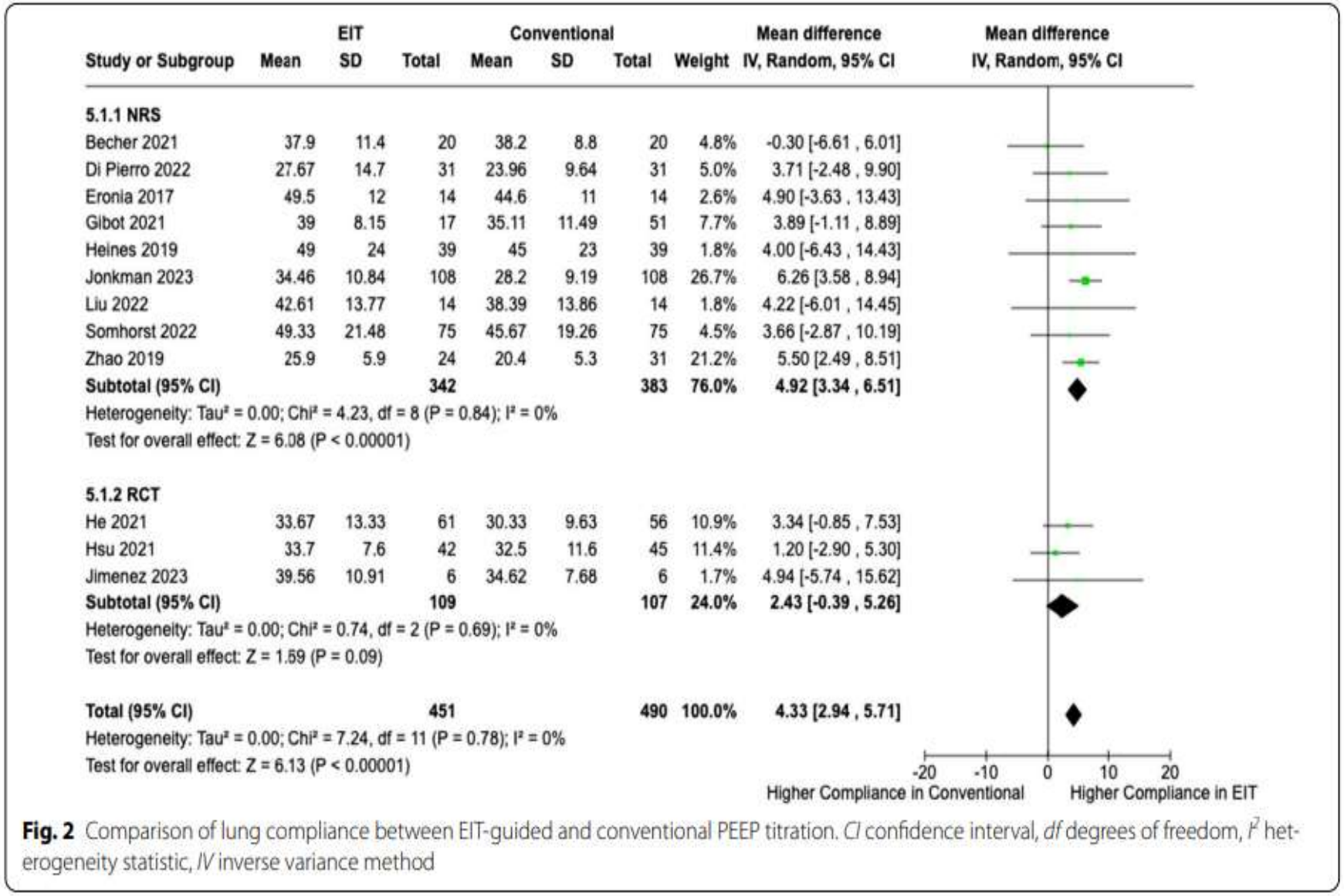


Fig. 2 Comparison of lung compliance between EIT-guided and conventional PEEP titration. *CI* confidence interval, *df* degrees of freedom, I^2 heterogeneity statistic, *IV* inverse variance method

<u>Primary outcome –</u>

Respiratory mechanics and mechanical power

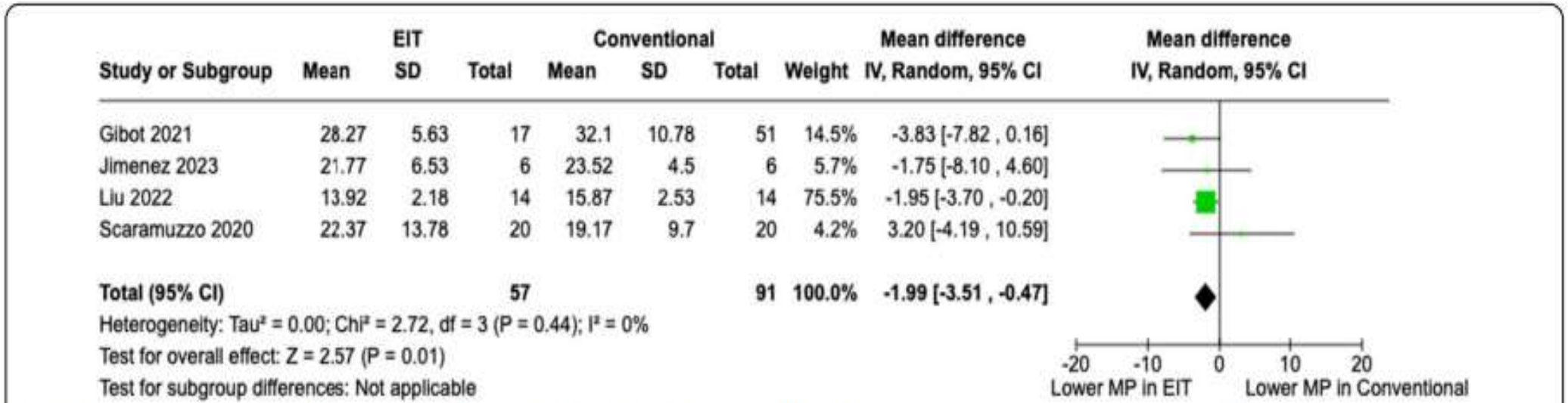
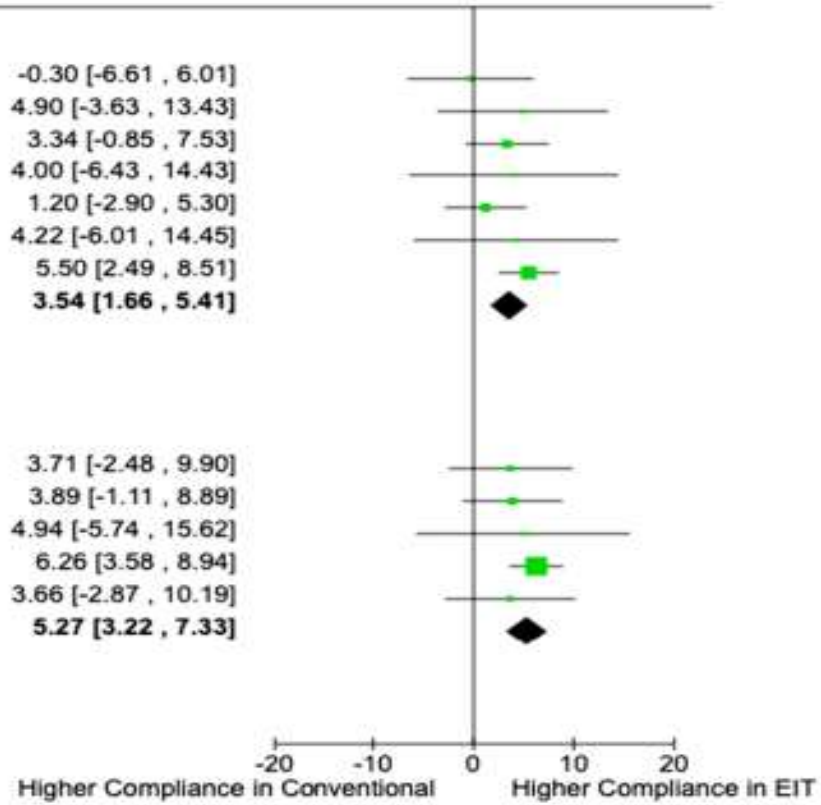


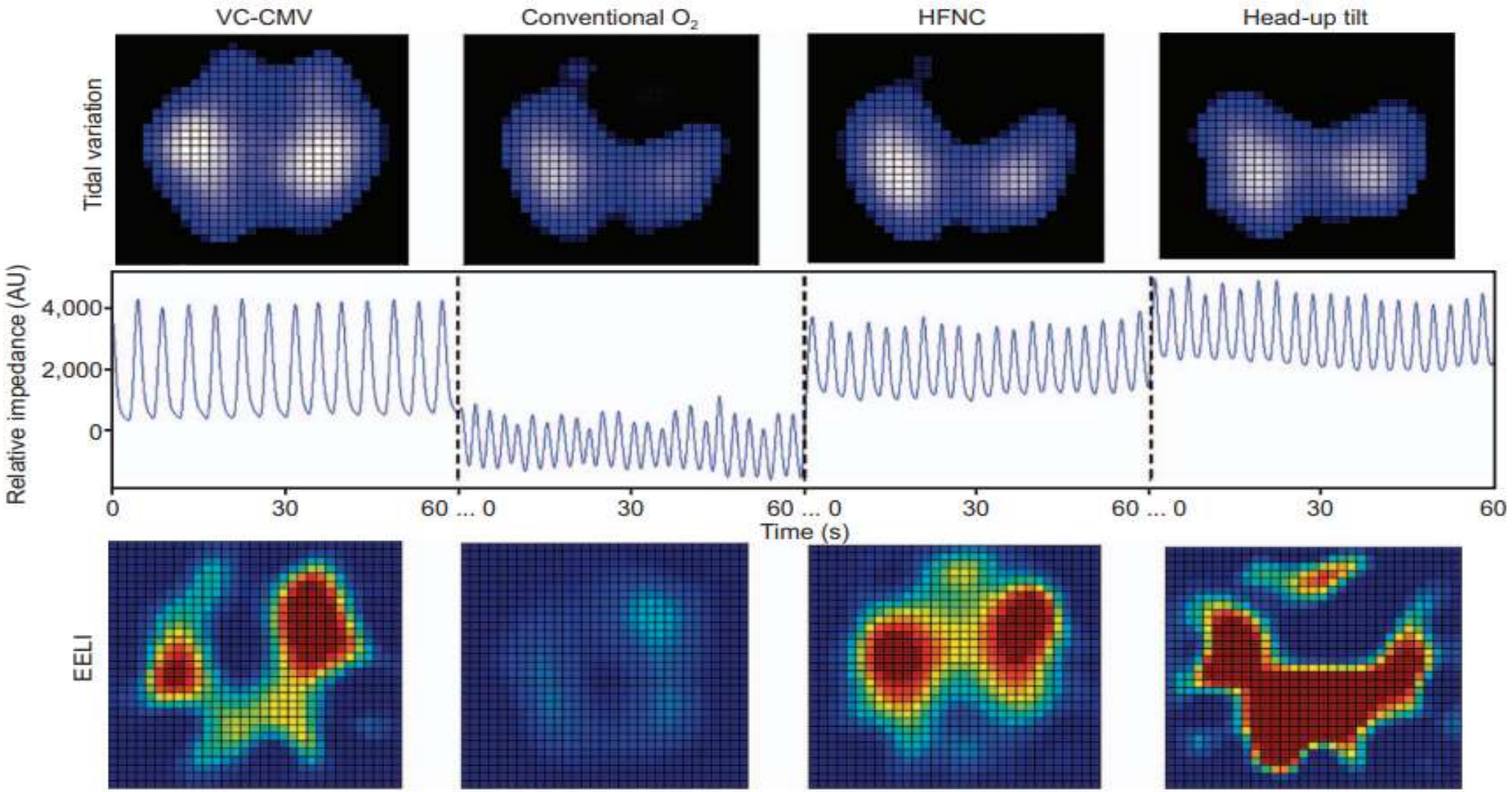
Fig. 3 Comparison of mechanical power between EIT-guided and conventional PEEP titration. *MP* mechanical power, *CI* confidence interval, *df* degrees of freedom, I^2 heterogeneity statistic, *IV* inverse variance method

Study or Subgroup	EIT Mean	EIT SD	EIT Total	Conventional Mean	Conventional SD	Conventional Total	Weight	Mean difference IV, Random, 95% CI
5.1.1 BMI less than 30								
Becher 2021	37.9	11.4	20	38.2	8.8	20	8.8%	-0.30 [-6.61 , 6.01]
Eronia 2017	49.5	12	14	44.6	11	14	4.8%	4.90 [-3.63 , 13.43]
He 2021	33.67	13.33	61	30.33	9.63	56	20.0%	3.34 [-0.85 , 7.53]
Heines 2019	49	24	39	45	23	39	3.2%	4.00 [-6.43 , 14.43]
Hsu 2021	33.7	7.6	42	32.5	11.6	45	20.9%	1.20 [-2.90 , 5.30]
Liu 2022	42.61	13.77	14	38.39	13.86	14	3.4%	4.22 [-6.01 , 14.45]
Zhao 2019	25.9	5.9	24	20.4	5.3	31	38.8%	5.50 [2.49 , 8.51]
Subtotal (95% CI)			**214**			**219**	**100.0%**	**3.54 [1.66 , 5.41]**
Heterogeneity: Tau² = 0.00; Chi² = 4.44, df = 6 (P = 0.62); I² = 0%								
Test for overall effect: Z = 3.70 (P = 0.0002)								
5.1.2 BMI more than 30								
Di Pierro 2022	27.67	14.7	31	23.96	9.64	31	11.0%	3.71 [-2.48 , 9.90]
Gibot 2021	39	8.15	17	35.11	11.49	51	16.9%	3.89 [-1.11 , 8.89]
Jimenez 2023	39.56	10.91	6	34.62	7.68	6	3.7%	4.94 [-5.74 , 15.62]
Jonkman 2023	34.46	10.84	108	28.2	9.19	108	58.6%	6.26 [3.58 , 8.94]
Somhorst 2022	49.33	21.48	75	45.67	19.26	75	9.9%	3.66 [-2.87 , 10.19]
Subtotal (95% CI)			**237**			**271**	**100.0%**	**5.27 [3.22 , 7.33]**
Heterogeneity: Tau² = 0.00; Chi² = 1.30, df = 4 (P = 0.86); I² = 0%								
Test for overall effect: Z = 5.04 (P < 0.00001)								



- By using EIT we can monitor the ventilation in real-time
- We can assess the ventilation distribution
- Regional ventilation properties can be assessed with regional compliance
- PEEP titration by EIT showed promising results such as better compliance, reduced driving pressure and mechanical power

EFFECTS OF OXYGEN THERAPY AND BODY POSITION ON EIT

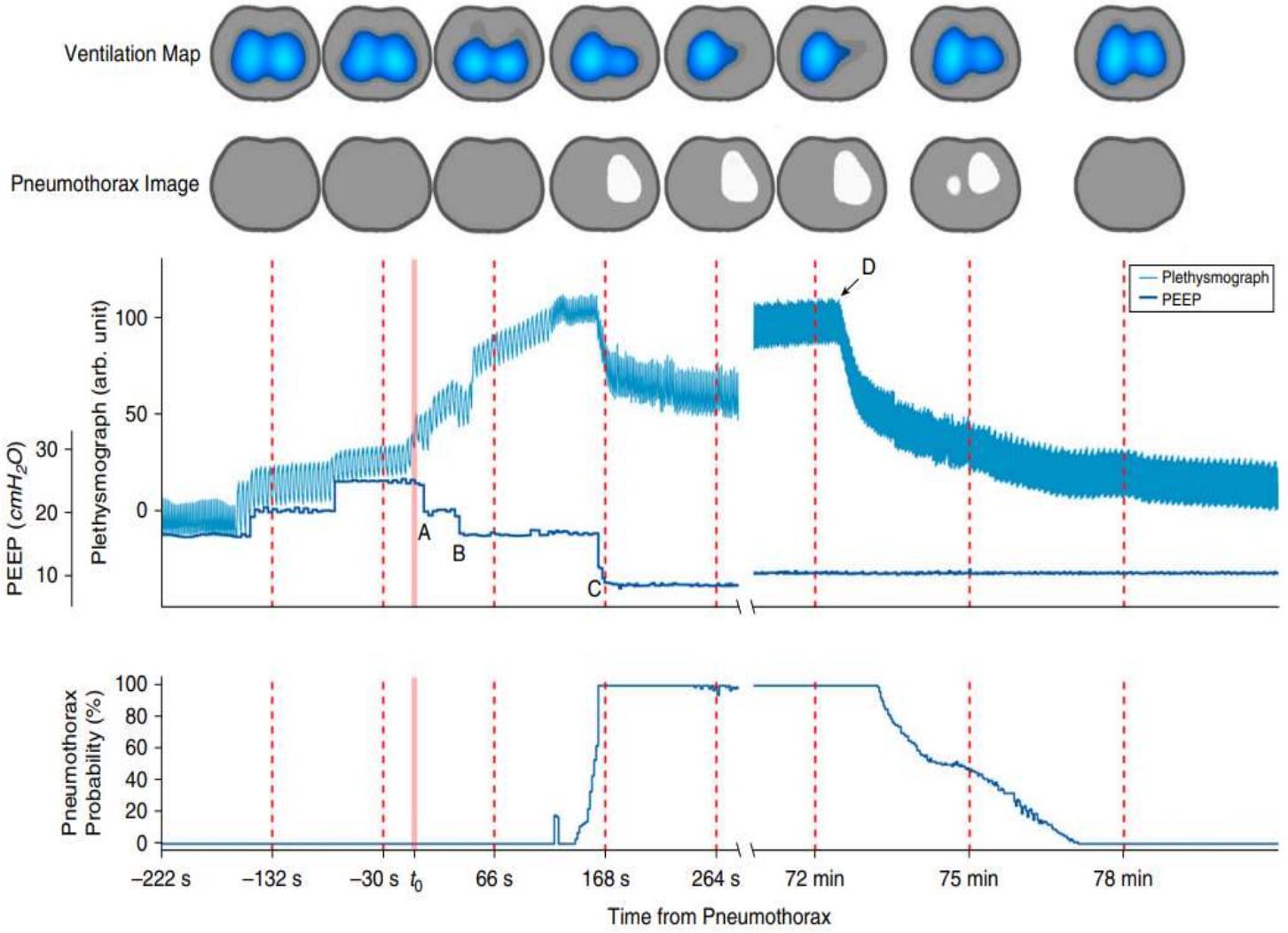


Zhiyong Yuan et al Resp Care 2020

Pneumothorax

- Occult pneumothorax is common in critical patients of RTA where cxr might not pick up on AP film
- Usg surpasses cxr in the detection of pneumothorax but has limitations – like interobserver variability, difficulty in quantifying
- CT is the IOC but risk of radiation exposure, shifting the patient for CT
- EIT can provide non-invasive, radiation-free, real-time monitoring for the detection of pneumothorax

Monitoring of Pneumothorax Appearance with Electrical Impedance Tomography during Recruitment Maneuvers



On the ventilation maps, dark to light shades of blue - increasing values of regional ventilation
Gray- indicates the total absence of ventilation

The pneumothorax images show the regions corresponding to the pneumothorax in white

Caio Morais et al .atsjournals 2017

Detection of Pneumothorax by EIT

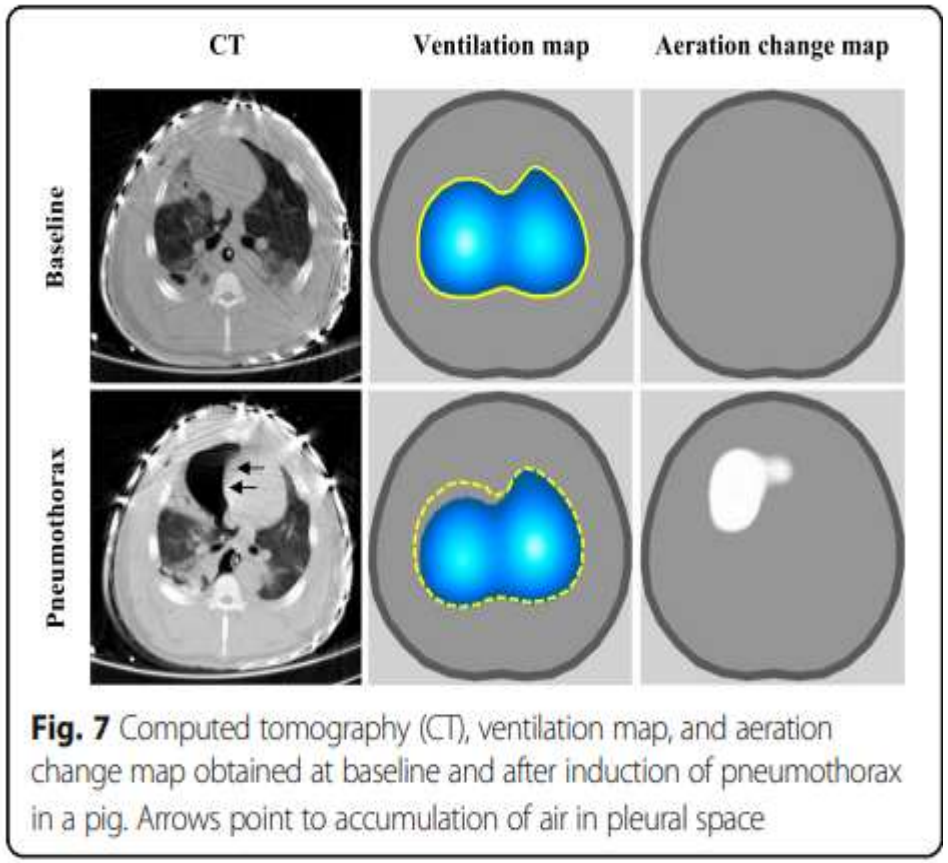
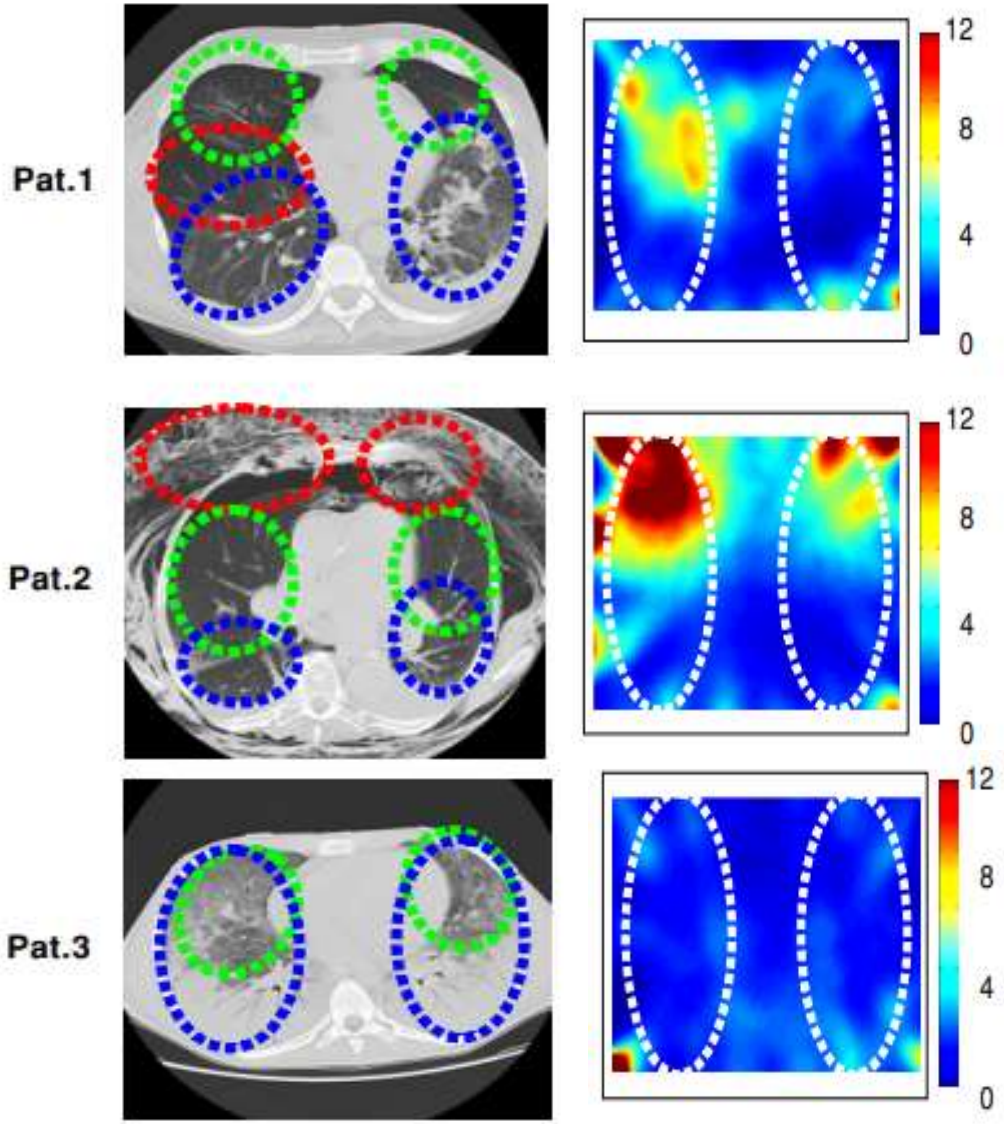


Fig. 7 Computed tomography (CT), ventilation map, and aeration change map obtained at baseline and after induction of pneumothorax in a pig. Arrows point to accumulation of air in pleural space



G Hahn et al imaging pathologic pulmonary air and fluid by EIT

Monitor the effects of endotracheal aspiration on pulmonary volumes

- ET suctioning leads to significant lung de-recruitment
- Closed suctioning minimizes loss of lung volume compared with open suctioning
- After each suction, the CSC requires flushing with NS while suction is simultaneously applied to prevent built-up secretion within the CSC
- It was observed that during cleaning of the CSC, there was a marked loss of lung volume
- It was due to the absence of a valve between the CSC and the patient's airway

Amanda Corley RN et al RC Journal 2014

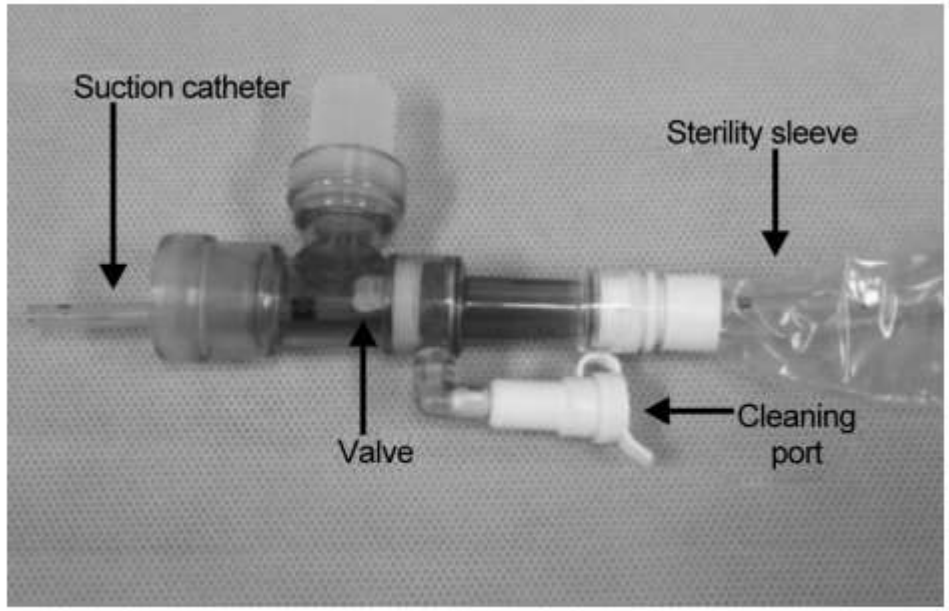
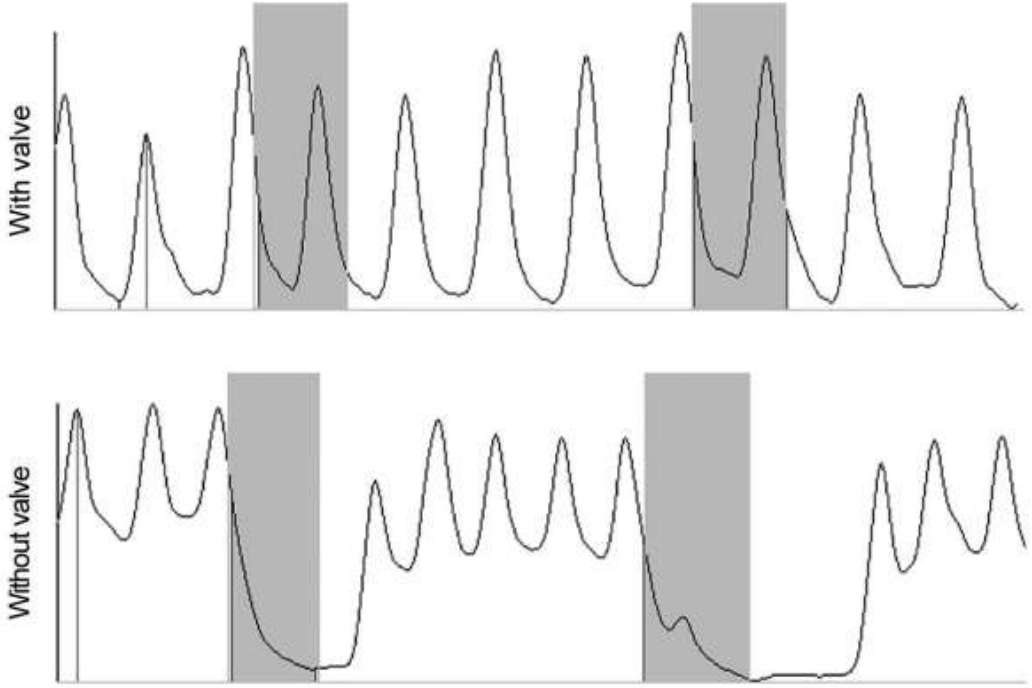


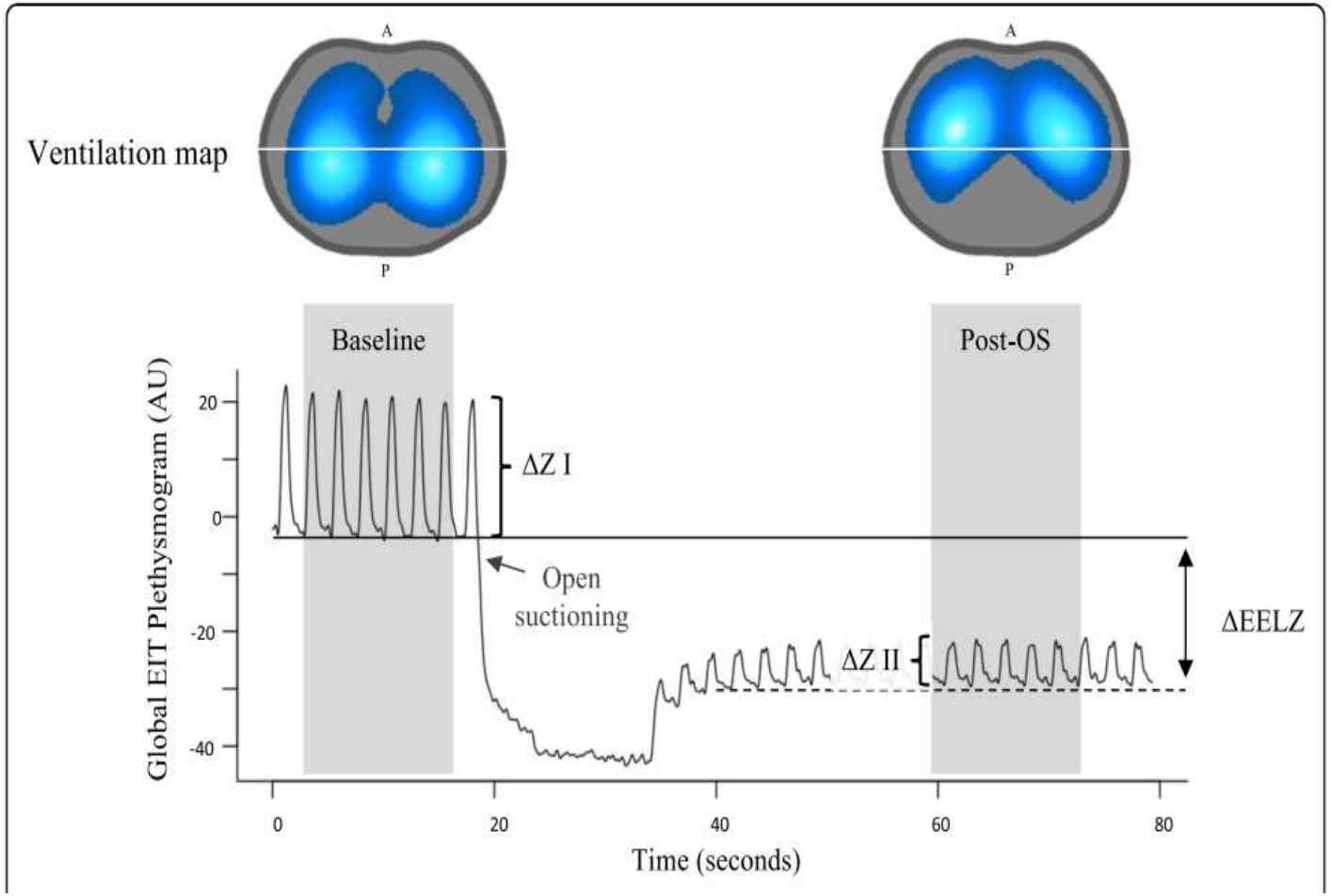
Fig. 1. The Ballard Trach Care 72 closed suction catheter.



EIT ventilation waveforms during cleaning of CSC

It has a separate cleaning chamber that is isolated from the patient's airway and ventilator circuit by a valve

Amanda Corley RN et al RC Journal 2014



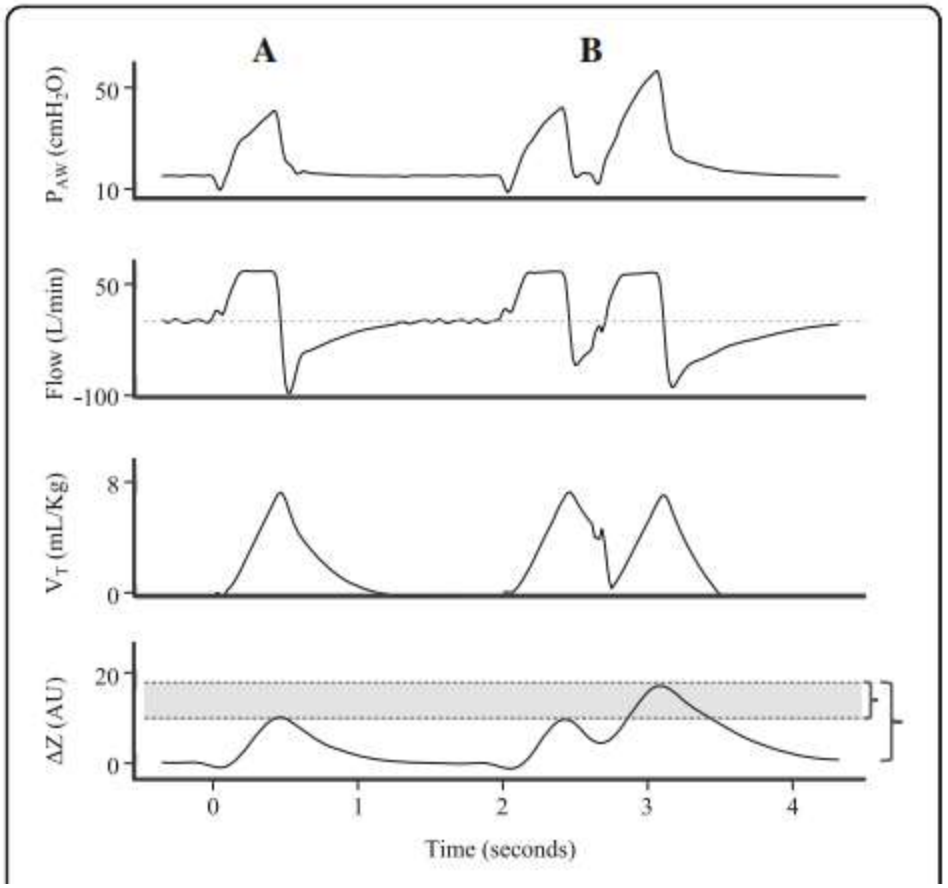
Reduction of pulmonary ventilation after OS

EELZ at baseline and post OS

- EELZ does not return to baseline values after OS

Ventilator Dyssynchrony by EIT

- Patient–ventilator dyssynchronies - weaning prolongation and increased mortality
- EIT plethysmogram may assist in the early identification of potentially harmful dyssynchronies, such as breath stacking and pendelluft
- Breath stacking - usually secondary to reverse triggering or double-triggering
- Where a second respiratory cycle is imposed by the ventilator on top of an incomplete exhalation

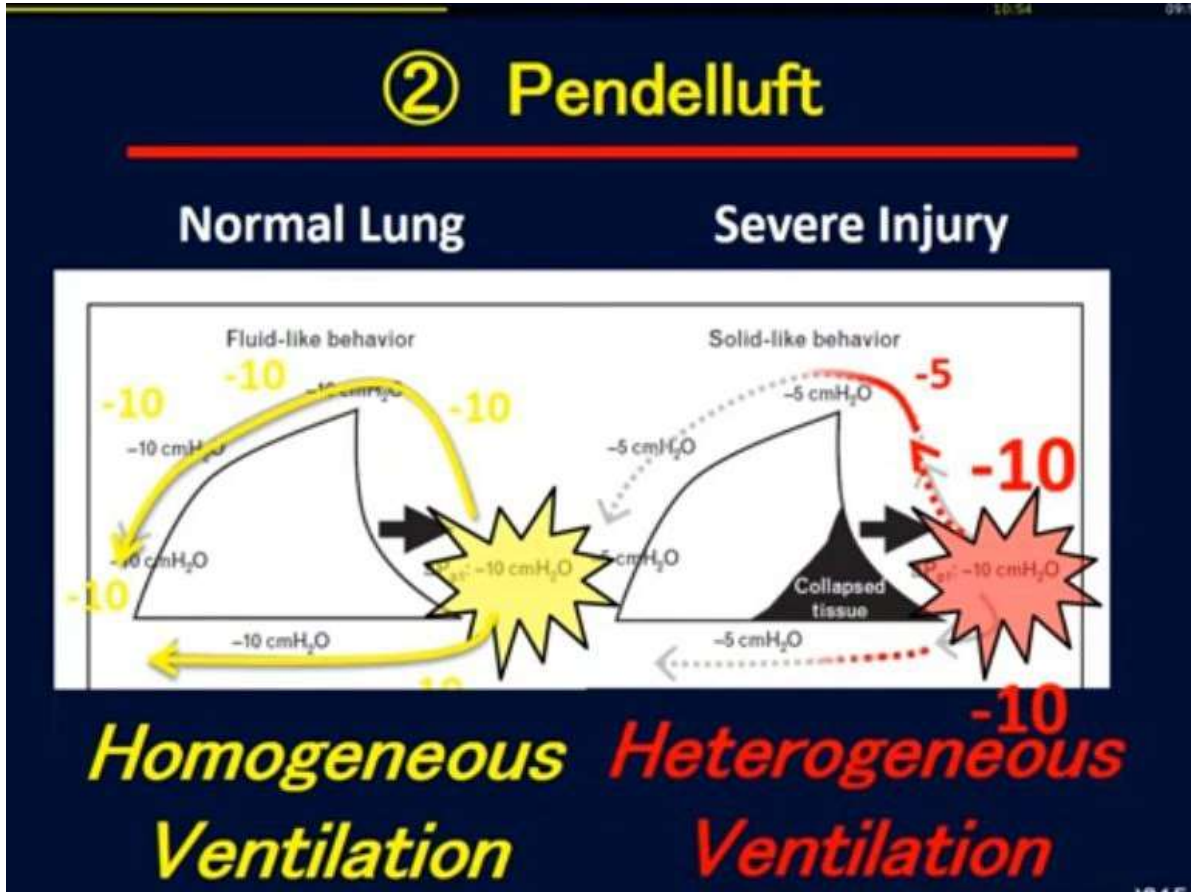


During breath stacking, the volume waveform shows an inspired volume of approximately 8 ml/kg of predicted weight

However, the inspired volume detected by EIT is nearly twice that of a regular cycle, which indicates injurious deformation of the lung

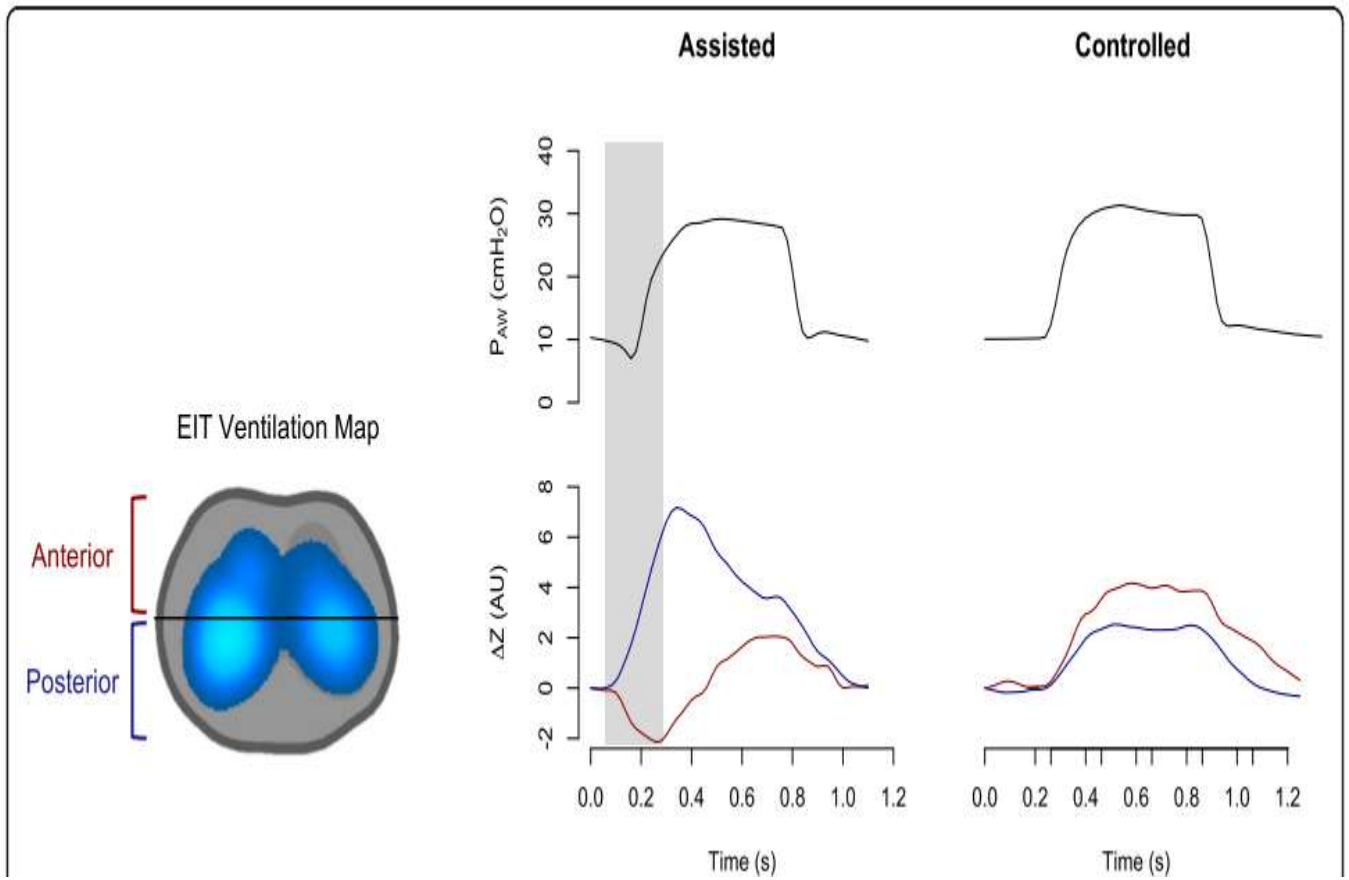
Spontaneous Effort Causes Occult Pendelluft during Mechanical Ventilation

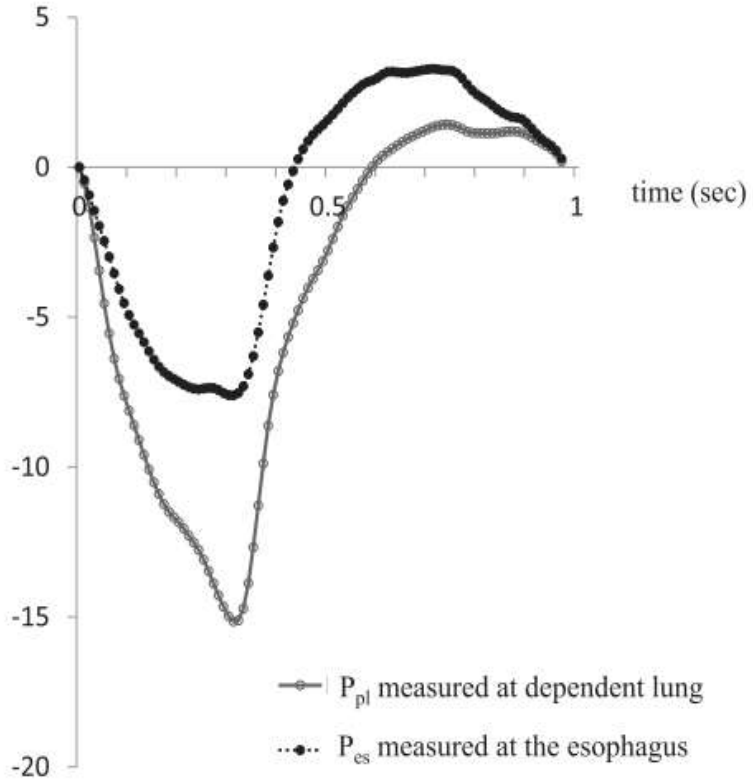
Takeshi Yoshida[1,2], Vinicius Torsani[1], Susimeire Gomes[1], Roberta R. De Santis[1], Marcelo A. Beraldo[1], L. V. Costa[1], Mauro R. Tucci[1], Walter A. Zin[3], Brian P. Kavanagh[4,5], and Marcelo B. P. Amato[1]



In normal lungs, local changes in pleural pressure (Ppl) are generalized over the whole pleural surface

In injured lungs, a pendelluft phenomenon (movement of air within the lung from nondependent to dependent regions without change in tidal volume) was caused by spontaneous breathing during MV



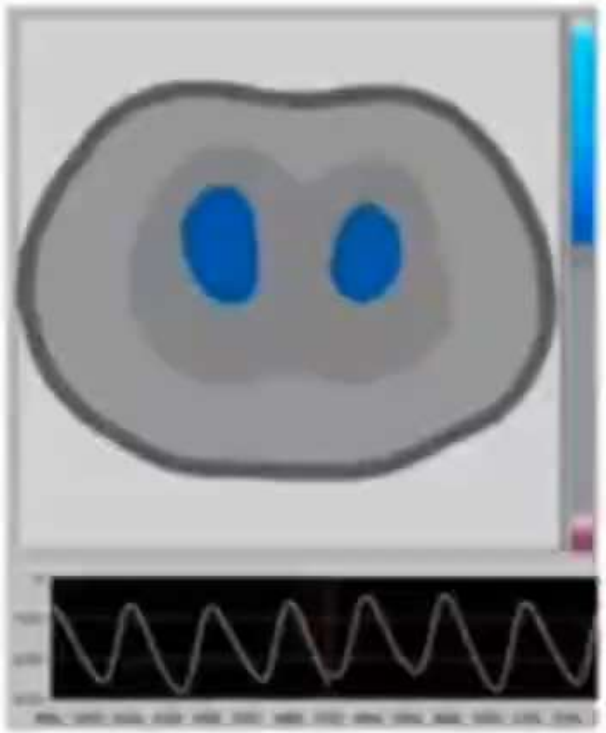


Takeshi Yoshida et al AJRCCM 2013

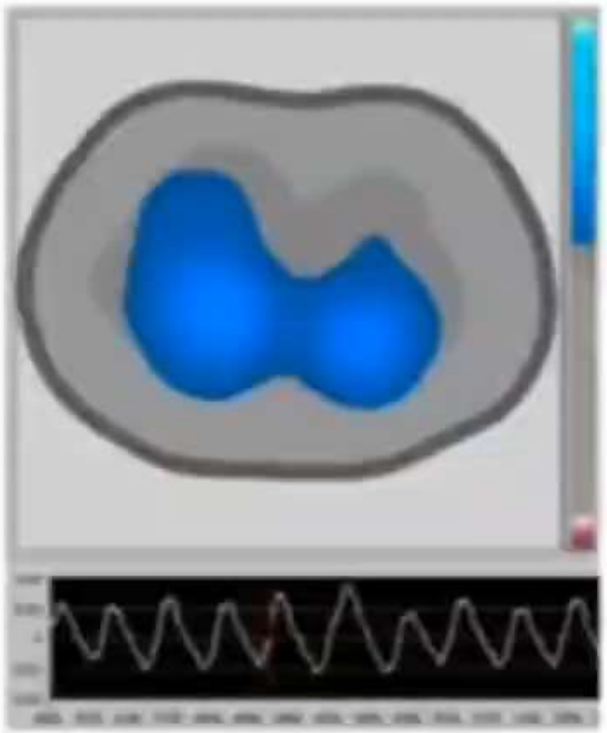
EIT Ventilation Image

Quantitative and Qualitative Interpretation

Controlled MV



Assisted MV



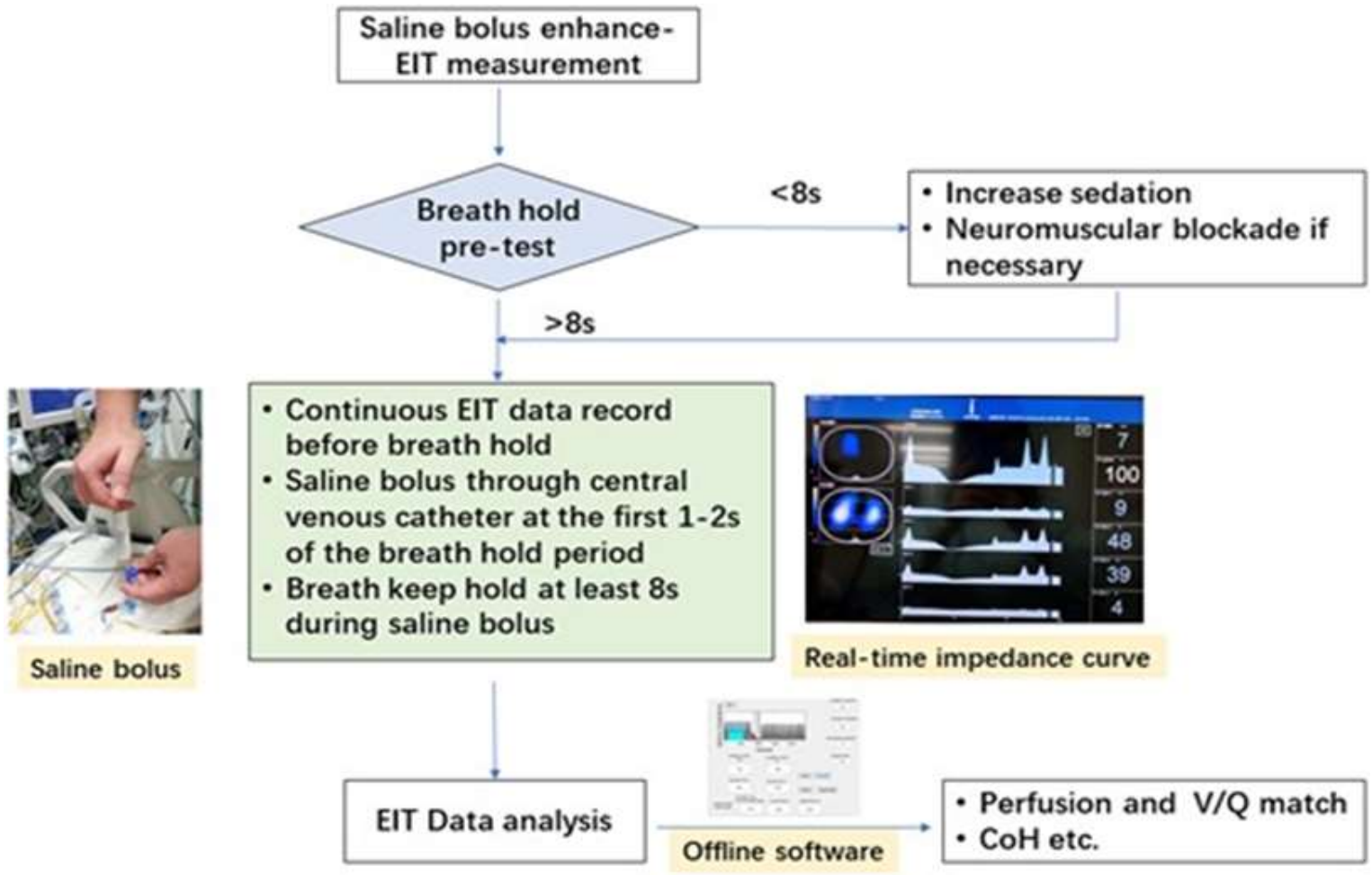
Takeshi Yoshida et al AJRCCM 2013

Pulmonary Perfusion

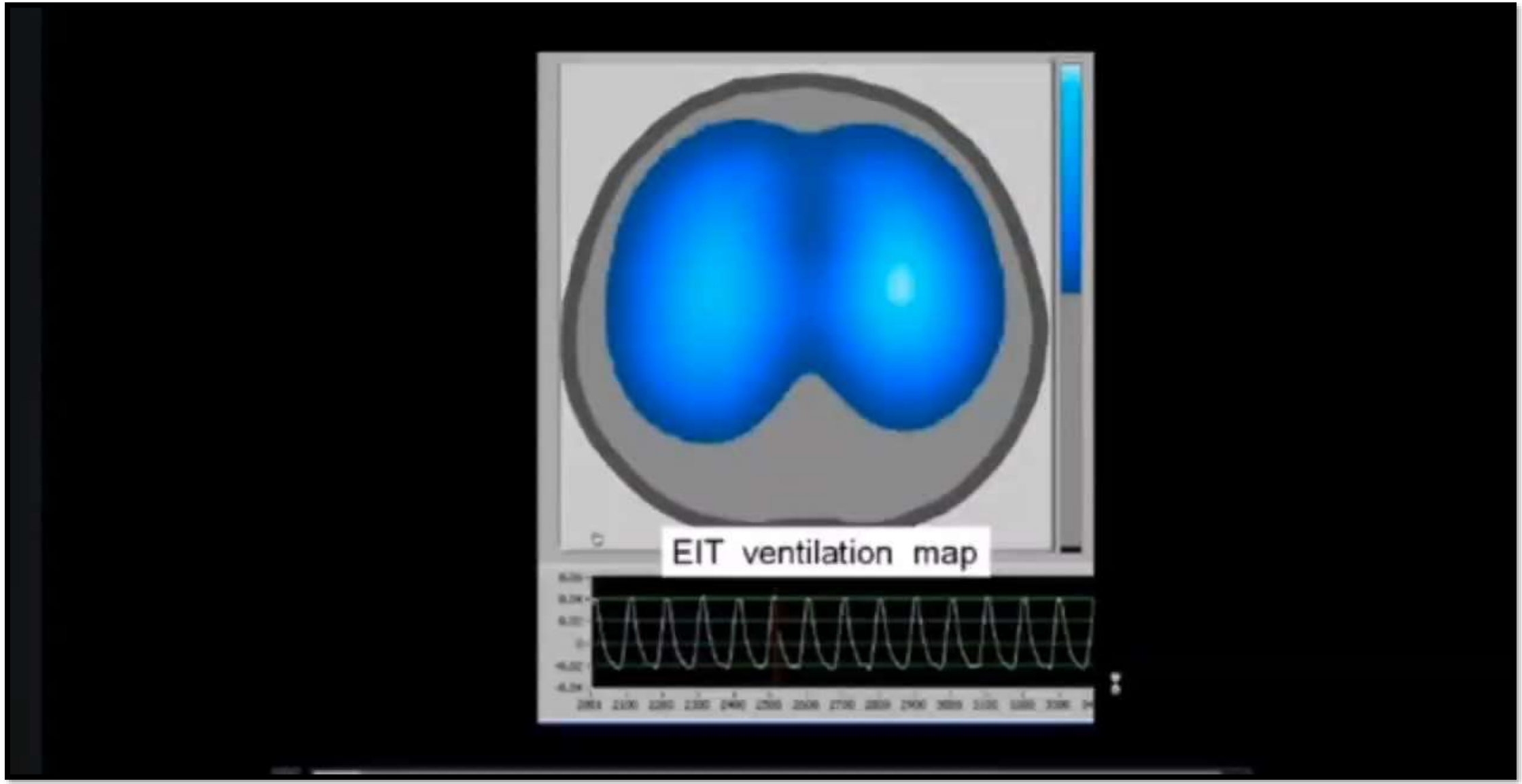
- One of the targets of MV is to promote adequate gas exchange, but the efficiency of this process depends not only on ventilation but also on adequate pulmonary perfusion
- EIT also estimates perfusion disturbances at the bedside
- 2 methods of lung perfusion assessment by EIT

1. First pass kinetics - performed by a brief respiratory pause, followed by a rapid iv bolus of hypertonic sodium chloride injected through a central venous line (the saline will act as an intravascular contrast due to its high conductivity)
2. Based on the separation of the cardiac signal to the ventilation signal by electrocardiography gating or by algorithms based on principal component analysis

N Wang et al 2023



N Wang et al 2023


EIT ventilation map

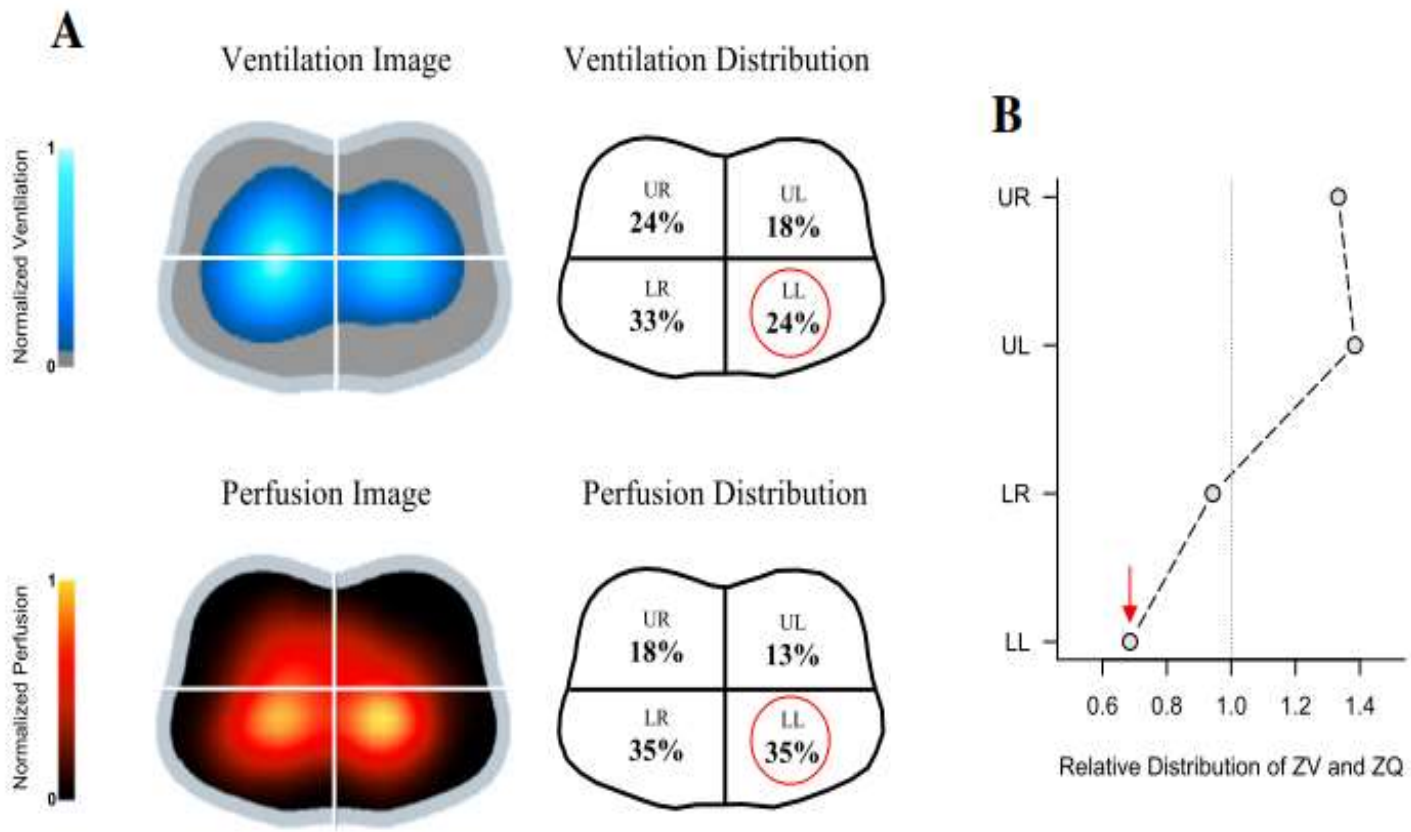
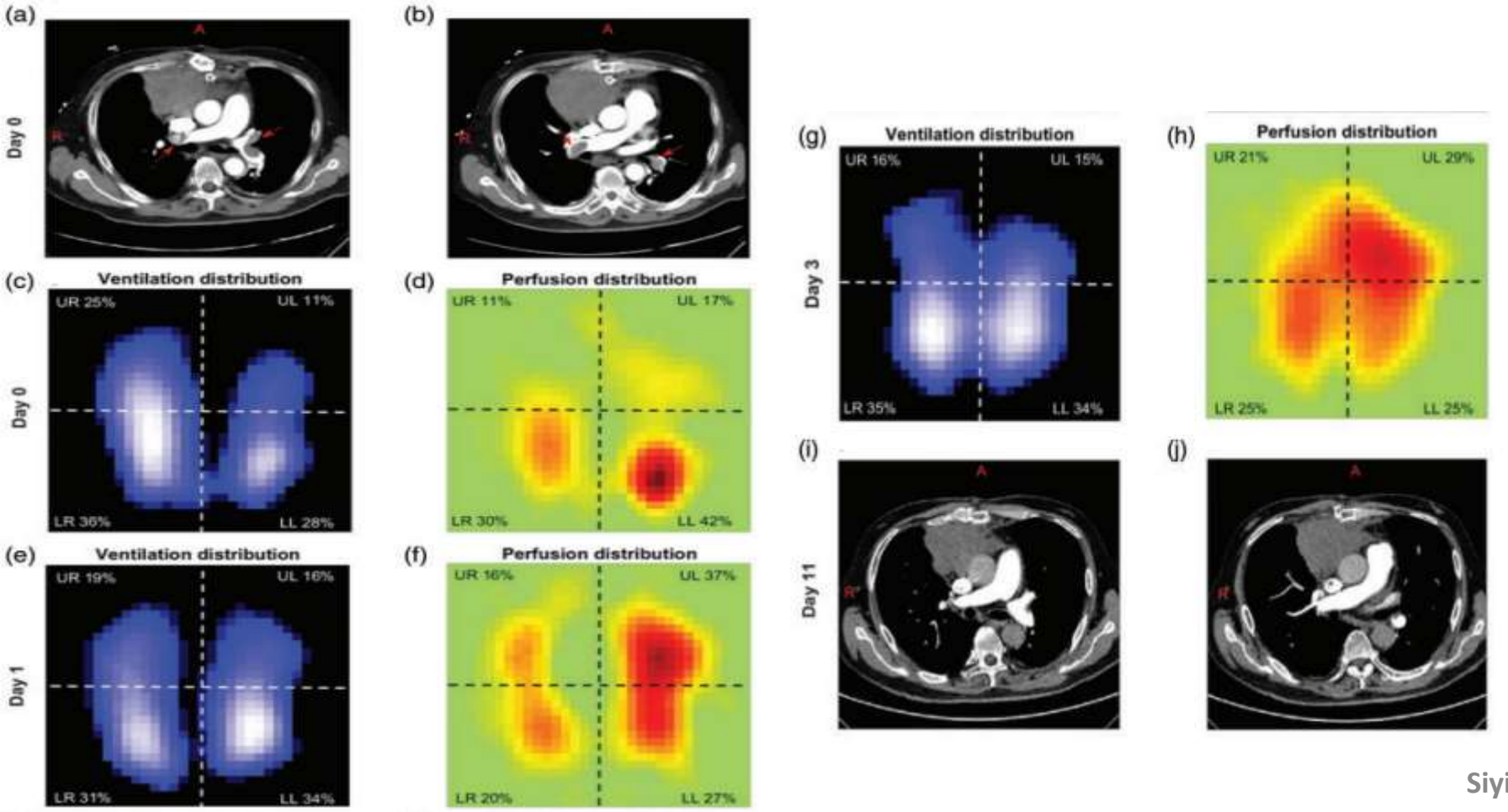


Fig. 11 Electrical impedance tomography (EIT) ventilation and perfusion images of patient with community-acquired pneumonia affecting left lower lobe. Color scale adjusted by linear normalization. **a** Ventilation reduction at lower left quadrant in comparison with lower right quadrant, without changes in perfusion distribution at the lower quadrants. **b** Ventilation and perfusion decoupling in left lower quadrant represented by low distribution ratio. LL lower left, LR lower right, UL upper left, UR upper right, ZV ventilation estimated by EIT, ZQ perfusion estimated by EIT. Image provided by Fernando Suarez-Sipmann. Red arrow indicates ventilation/perfusion ratio in the LL quadrant

Bedside assessment of pulmonary perfusion by EIT in a patient of acute PTE



Siyi Yuan et al 2021

Bedside Evaluation of Pulmonary Embolism by Saline Contrast Electrical Impedance Tomography Method: A Prospective Observational Study

AJRCCM 2020

- Included patients who were sequentially admitted to the ICU with ARF or who had a new onset of ARF in ICU
- PaO2 /FIO2 <300 mm Hg, and/or peripheral oxygen saturation as measured by pulse oximetry <94%
- EIT measurements were obtained with PulmoVista500 (Drager ¨ Medical)
- Functional ventilation and perfusion maps were derived

Huaiwu He et al AJRCCM 2020

- EIT derived parameters

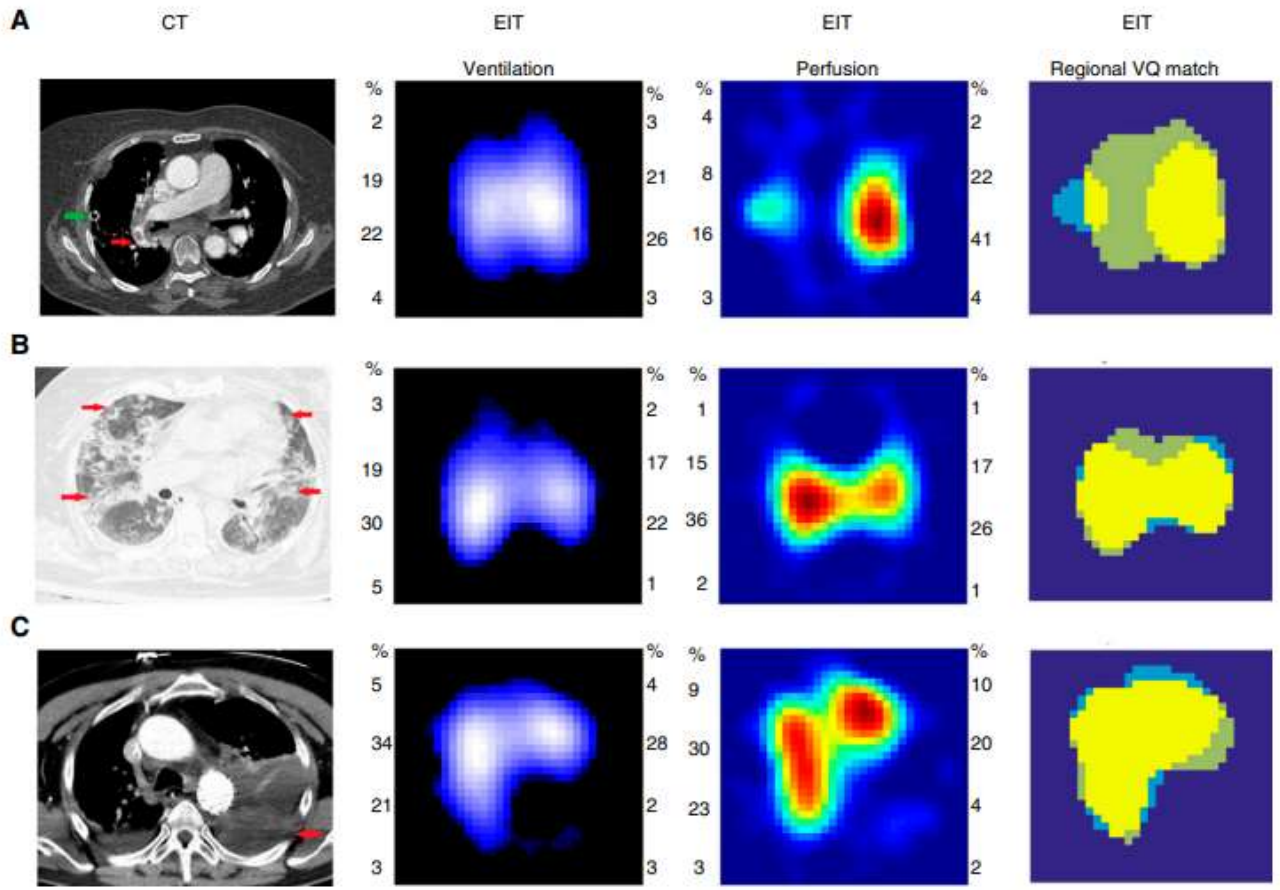
$$\text{Dead space \%} = R_V/(R_V + R_P + R_{V+P}) \times 100\%$$

$$\text{Intrapulmonary shunt \%} = R_P/(R_V + R_P + R_{V+P}) \times 100\%$$

$$\dot{V}/\dot{Q}\ \text{match \%} = R_{V+P}/(R_V + R_P + R_{V+P}) \times 100\%$$

- 68 patients with ARF were enrolled to the study, including 11 patients with PE
- 57 patients without PE (ARF caused by other reasons such as diffuse lung interstitial disease, lung edema/pneumonia, or pleural effusion)

Huaiwu He et al AJRCCM 2020

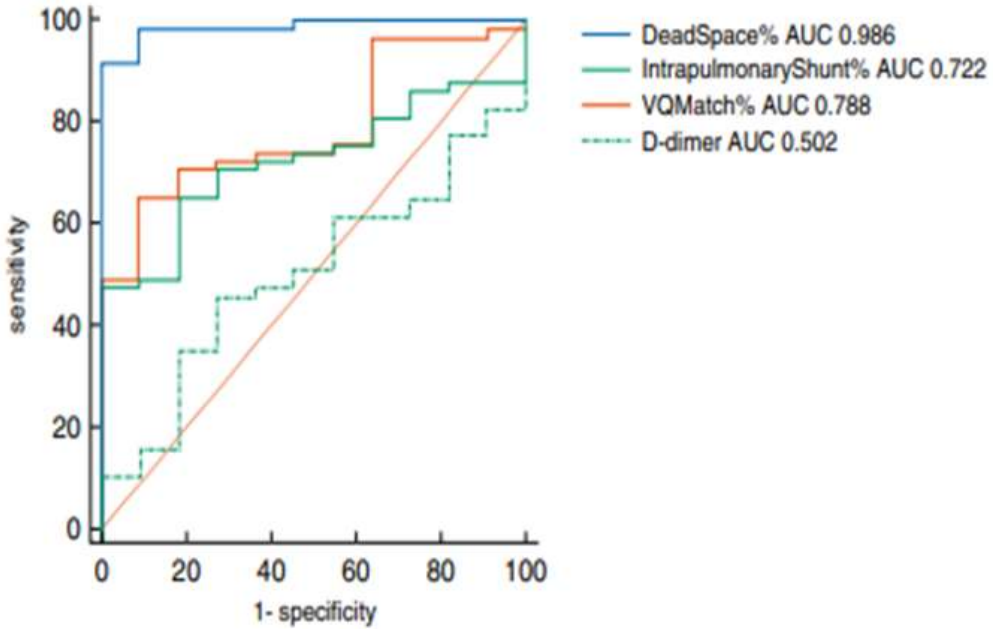


Defect in regional perfusion with normal ventilation was observed in the PE patient

No recognizable defects in regional ventilation and perfusion were observed in the patient with diffuse lung disease

Defects in both regional ventilation and perfusion were found in a patient with hemothorax

Huaiwu He et al AJRCCM 2020



(AUC) comparing the ability of dead space %, V -Q match %, intrapulmonary shunt %, and D-dimer to discriminate pulmonary embolism in the 68 patients. The AUC of dead space % was significantly higher than the AUC of the other parameters (P , 0.05)

Huaiwu He et al AJRCCM 2020

Electrical impedance tomography as a bedside assessment tool for COPD treatment during hospitalization

- EIT measurements - at the time of admission and before the discharge simultaneously when the FVC maneuver was conducted
- EIT data is usually illustrated as -

- Global impedance-time curve (sum of ΔZ from all pixels against time) and
- Regional impedance-time curves (sum of ΔZ from regions of interest against time)

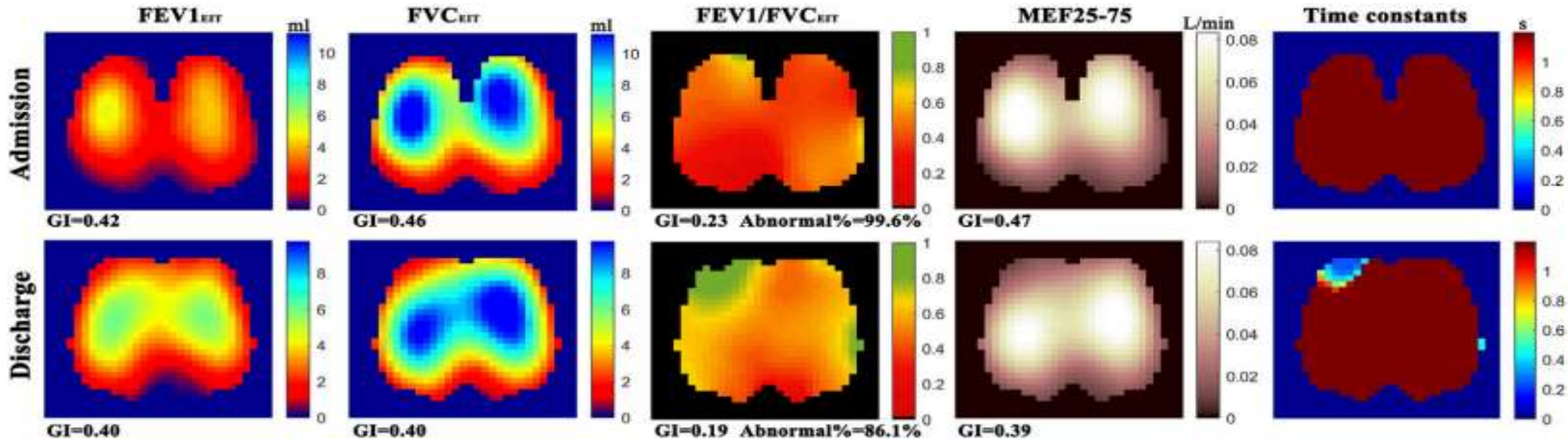
Yang L et al Front Physiol. 2024

- Spatial ventilation distribution was achieved by calculating the global inhomogeneity (GI) index
- A high GI index implies large variations among pixel tidal impedance values, indicating heterogeneous ventilation

Yang L et al Front Physiol. 2024

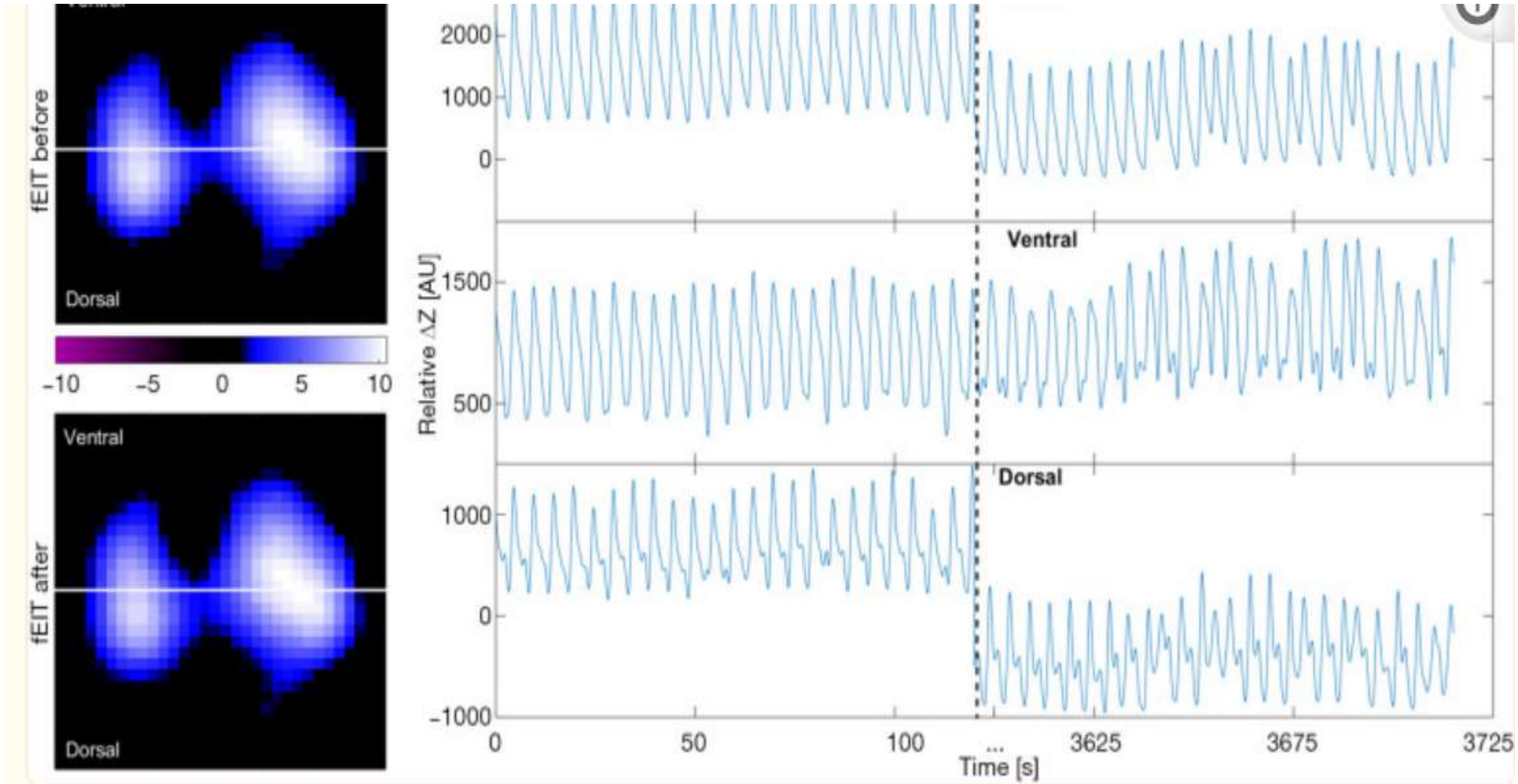
- ($FEV1_{EIT}$), - difference between the rel. ΔZ values after 1 s of forced full expiration and the value at residual lung volume at the beginning of the expiration limb of the maneuver in the lung pixels
- The global time points of 25% and 75% of FVC were identified (MEF25 and MEF75). The mean flow was calculated in the pixel level and denoted as MEF25-75EIT
- To characterize the dispersion of the fEIT images, i.e., the heterogeneity of their spatial distribution, the global inhomogeneity (GI) index was calculated for each type of fEIT

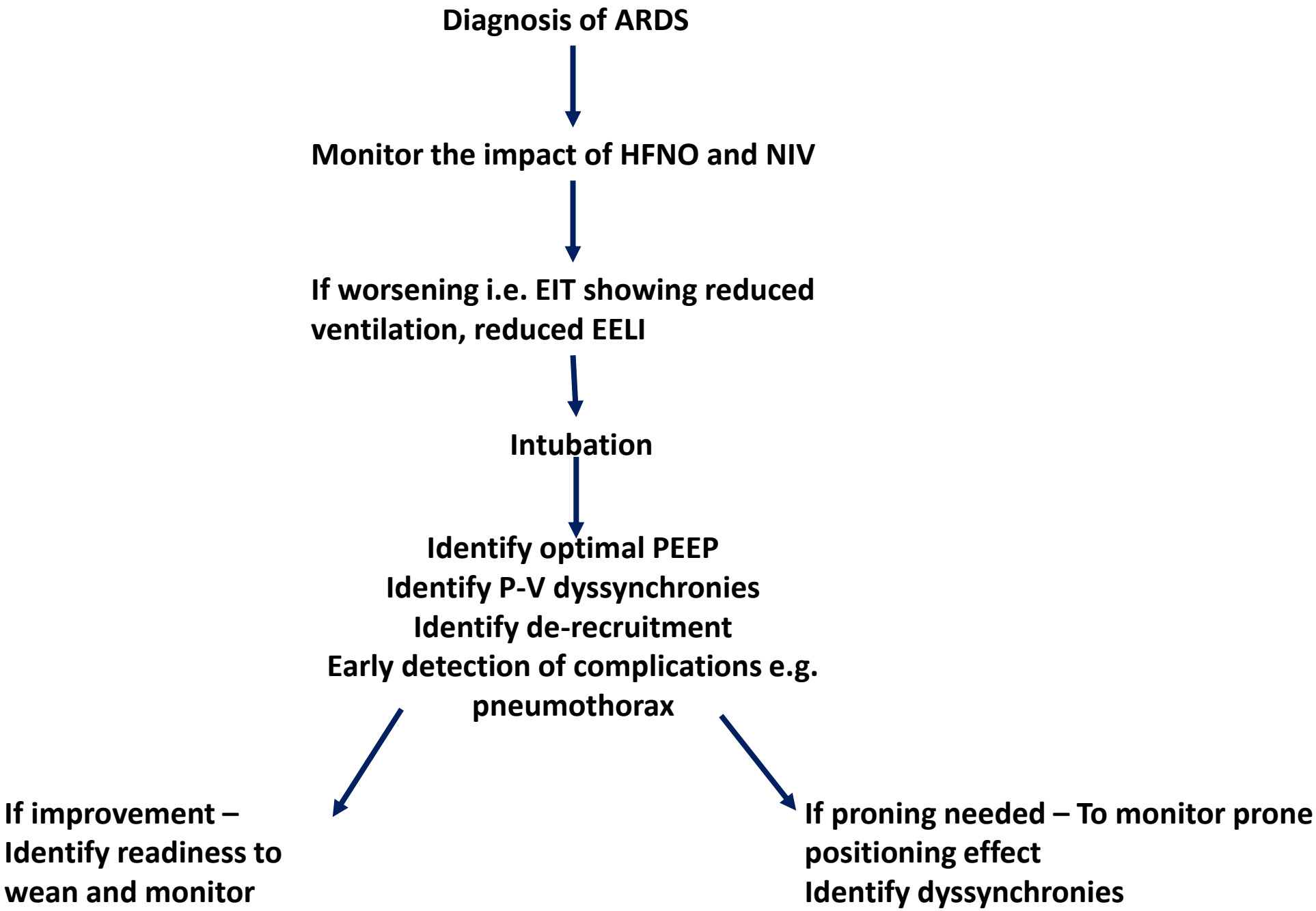
Yang L et al Front Physiol. 2024



Parameter	Admission	Discharge	p
GI_{FEV1}	0.46 ± 0.08	0.41 ± 0.03	0.002*
GI_{FVC}	0.43 ± 0.05	0.40 ± 0.03	0.01*
$GI_{FEV1/FVC}$	0.22 ± 0.12	0.13 ± 0.05	<0.001**
$GI_{MEF25-75}$	0.45 ± 0.06	0.41 ± 0.03	<0.001**

Yang L et al Front Physiol. 2024


fEIT before
Dorsal
-10
-5
0
5
10
Ventral
fEIT after
Dorsal
2000
1000
0
Ventral
Relative ΔZ [AU]
1500
500
Dorsal
1000
0
-1000
0
50
100
...
3625
3675
3725
Time [s]


Diagnosis of ARDS
Monitor the impact of HFNO and NIV
If worsening i.e. EIT showing reduced ventilation, reduced EELI
Intubation
Identify optimal PEEP
Identify P-V dyssynchronies
Identify de-recruitment
Early detection of complications e.g. pneumothorax
If improvement – Identify readiness to wean and monitor
If proning needed – To monitor prone positioning effect
Identify dyssynchronies

Main Advantages	Main Limitations
• Real-time monitoring of lung ventilation	• Low spatial resolution
• Evaluation of regional compliance before and after therapeutic procedures (e.g., recruitment)	• Most sensitive to detect electrical impedance changes occurring in plane of electrode belt
• Visualization and quantification of overdistension and collapse • Identification of pathological situations (inhomogeneity, Pendelluft effect)	• Performance, relevance, and reference values of EIT indices still lacking
• EIT can be coupled with ventilator for further physiological analysis	• Lung perfusion assessment insufficiently developed
• Noninvasive continuous bedside monitoring	• Unknown clinical benefit of daily EIT-guided mechanical ventilation strategy

Summary

- Electrical impedance tomography has huge potential as a non-invasive and real-time, radiation-free method
- Promising role in ARDS – optimization of peep, detection of complications such as pneumothorax, ventilator dyssynchronies, ETT dislodgement, and assessment of perfusion can also be done by EIT
- Potential role in other areas such as COPD, weaning, detection of PTE
- Further studies are needed to demonstrate its clinical outcome

Thank you!