Lung Recruitment and Electrical Impedance Tomography

David Grooms MSHS, RRT

Clinical Operations Director- Hamilton Medical Inc.

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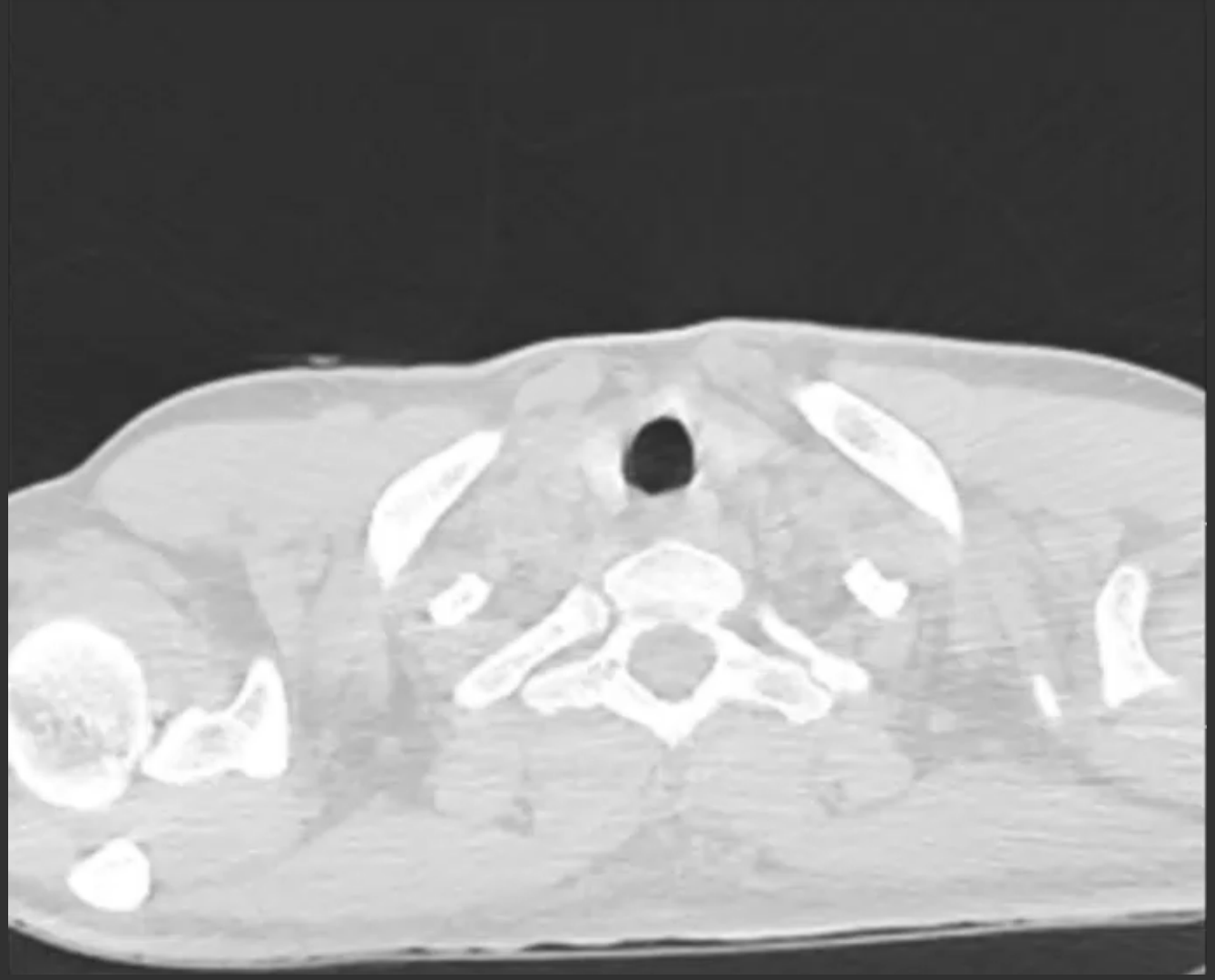
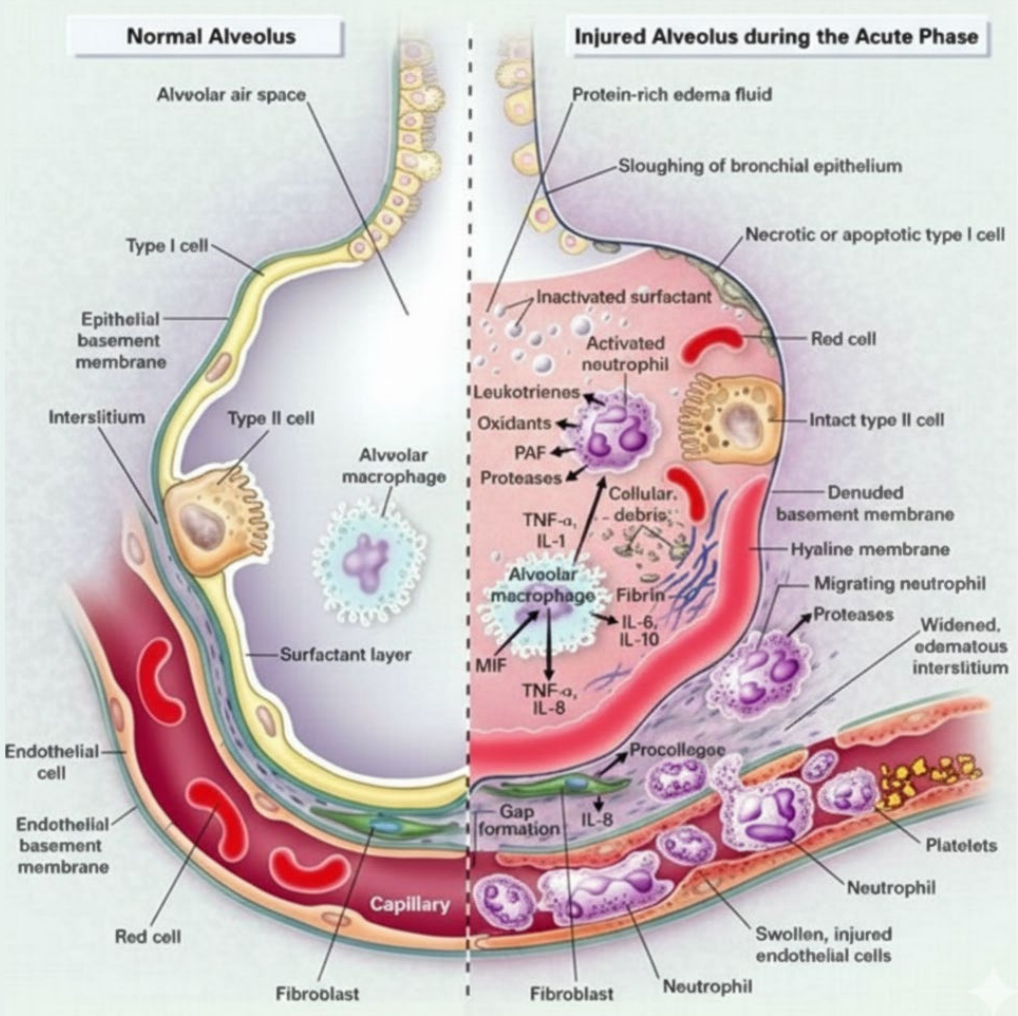
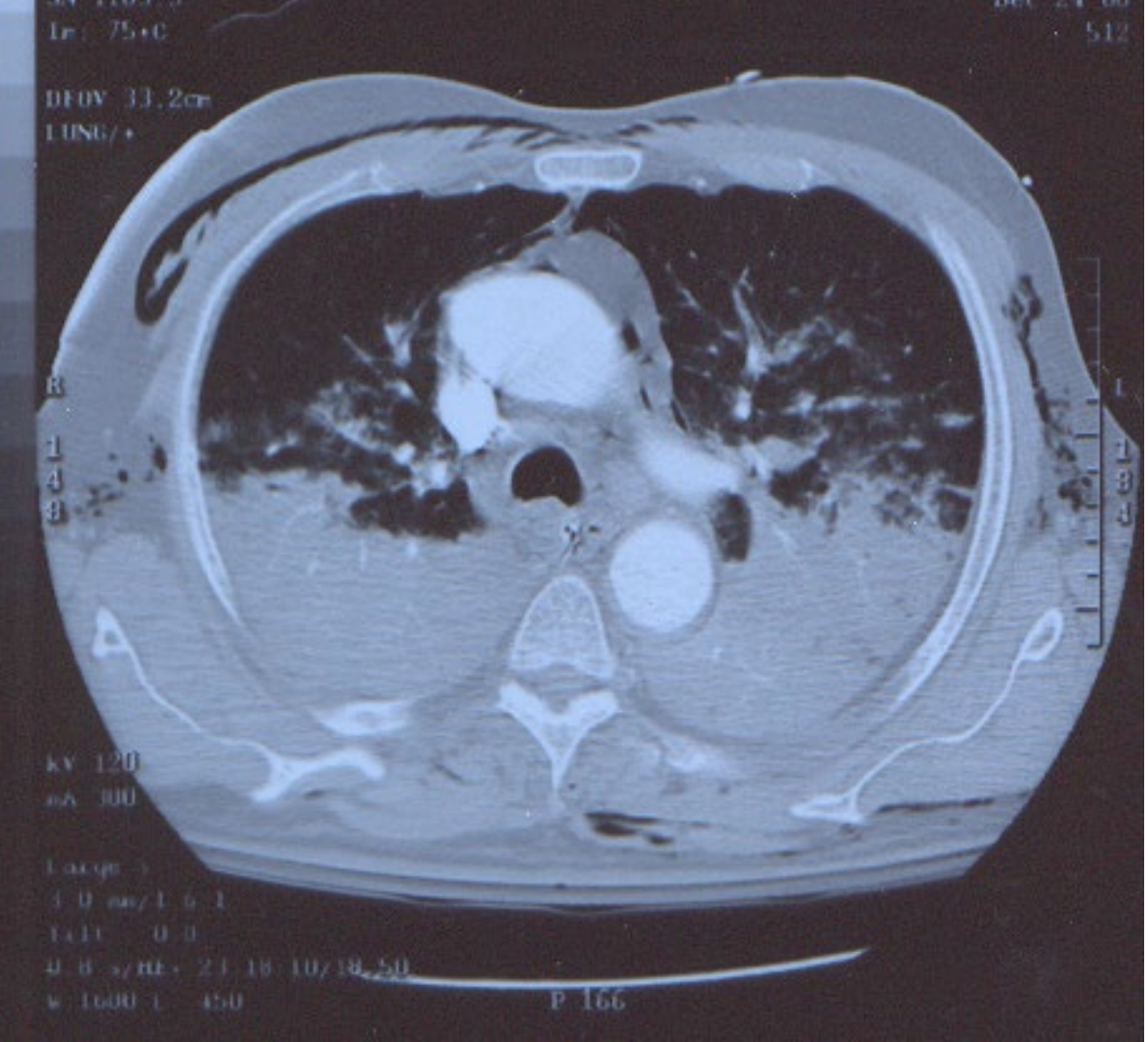
Disclaimer

- Clinical Operations Manager for Hamilton Medical Inc.
- And I love this F’ing conference!!!!!!




Normal Alveolus
Alveolar air space
Type I cell
Epithelial basement membrane
Interstitium
Type II cell
Alveolar macrophage
Surfactant layer
Endothelial cell
Endothelial basement membrane
Red cell
Capillary
Fibroblast
Injured Alveolus during the Acute Phase
Protein-rich edema fluid
Sloughing of bronchial epithelium
Necrotic or apoptotic type I cell
Inactivated surfactant
Activated neutrophil
Red cell
Leukotrienes
Oxidants
PAF
Proteases
Intact type II cell
Cellular debris
TNF-α, IL-1
Denuded basement membrane
Hyaline membrane
Alveolar macrophage
Fibrin
Migrating neutrophil
Proteases
IL-6, IL-10
MIF
TNF-α, IL-8
Widened, edematous interstitium
Procollagen
Gap formation
IL-8
Platelets
Neutrophil
Swollen, injured endothelial cells
Fibroblast
Neutrophil



“Baby lung” concept

An ARDS lung is characterized by:

- Lung collapse and consolidation
- Increased lung weight
- Lung heterogeneity
- Reduced size of the normal aerated lung

Gattinoni. Intensive Care Med. 2005

Mechanism of Ventilator-Induced Lung Injury (VILI)

Mechanical injury

Stress

“Baby lung”

Primarily responsible for the mechanical properties of the ARDS lung

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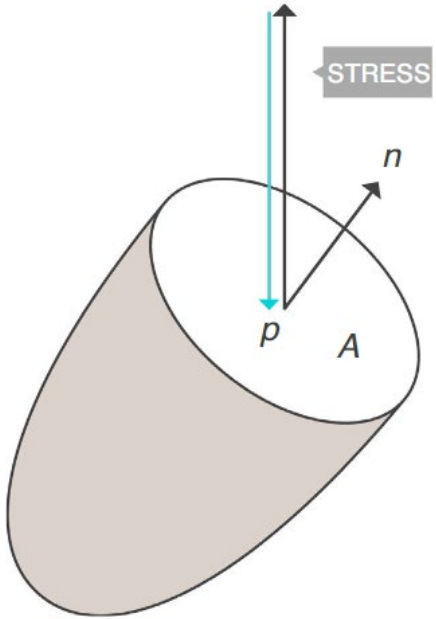
Lung Stress

- Internal pressure/forces applied to the lung tissue
  - Driving Pressure
    - Plateau-PEEP
  - Transpulmonary Pressure
    - Palv-Pchest



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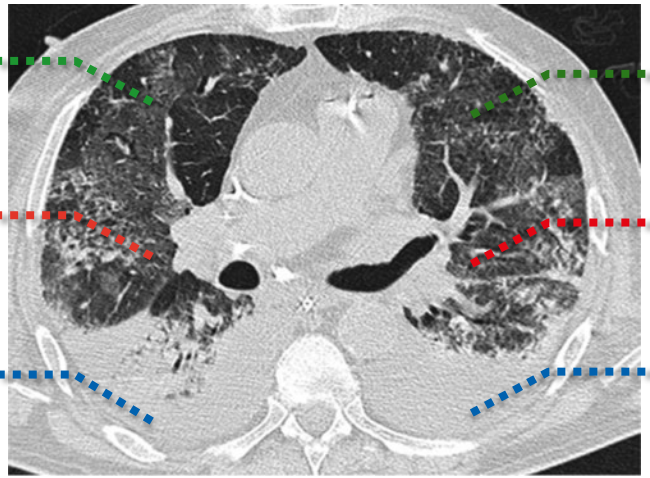
Mechanism of Ventilator-Induced Lung Injury (VILI)

Mechanical injury

Stress

Strain

Atelectrauma



“Baby lung”
Primarily responsible for the mechanical properties of the ARDS lung

Repetitive opening and closing
At points of micromechanical heterogeneity

Collapsed or consolidated lung
Gasless compartment primary responsible for the impairment of oxygenation

Inflammatory injury

Biotrauma

Alveolar inflammation

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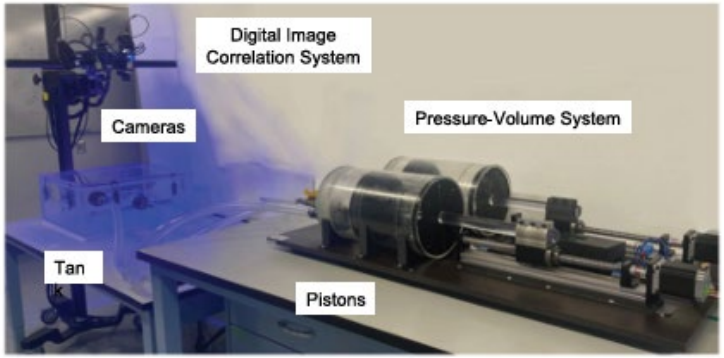
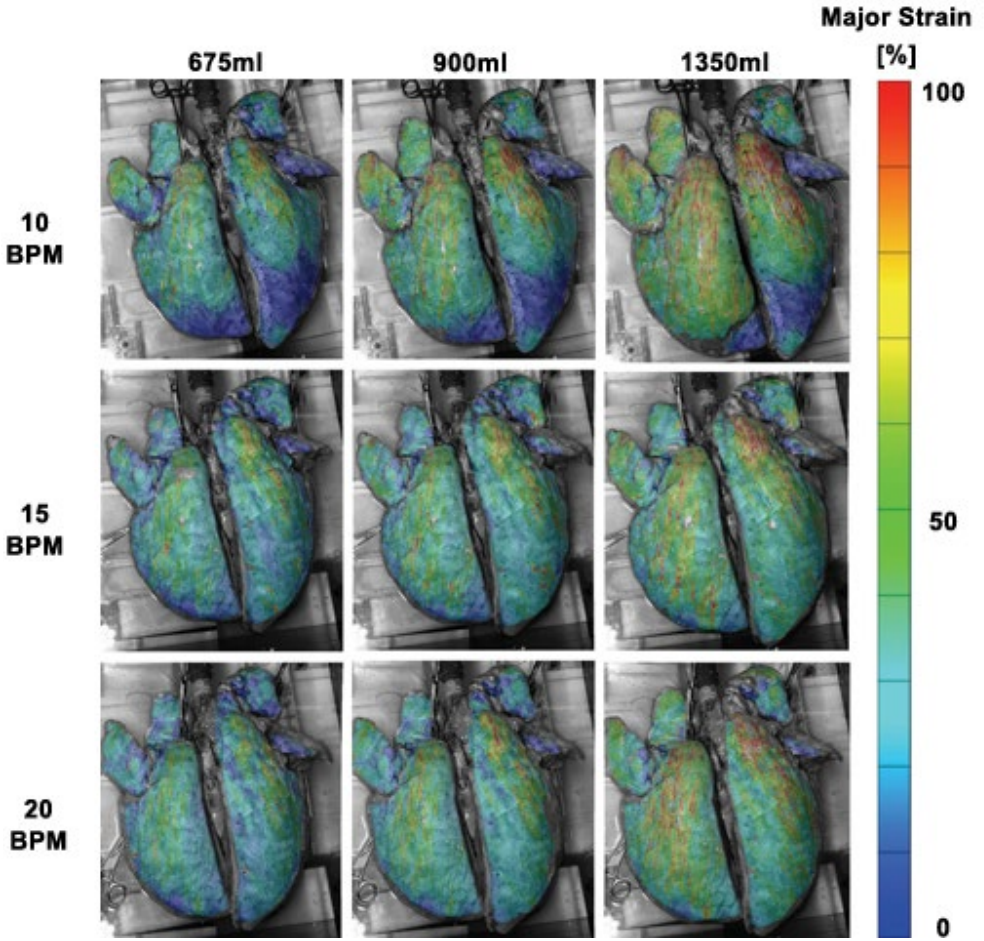
RESEARCH Open Access

Examining lung mechanical strains as influenced by breathing volumes and rates using experimental digital image correlation

C. A. Mariano[1], S. Sattari[1], K. A. M. Quiros[1], T. M. Nelson[1] and M. Eskandari[1,2,3*]





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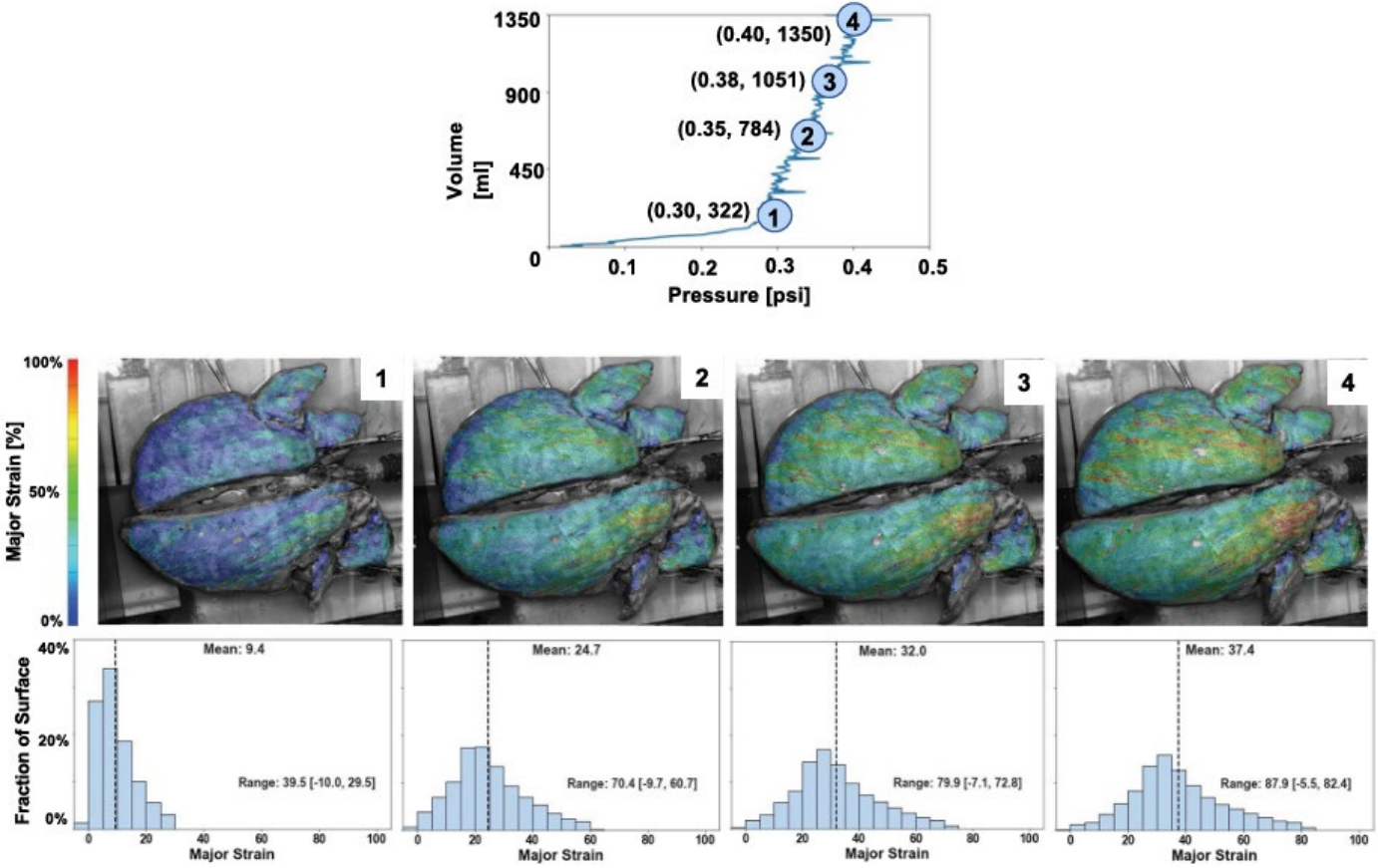

Mariano et al. Examining lung mechanical strains as influenced by breathing volumes and rates…https://doi.org/10.1186/s12931-022-01999-7

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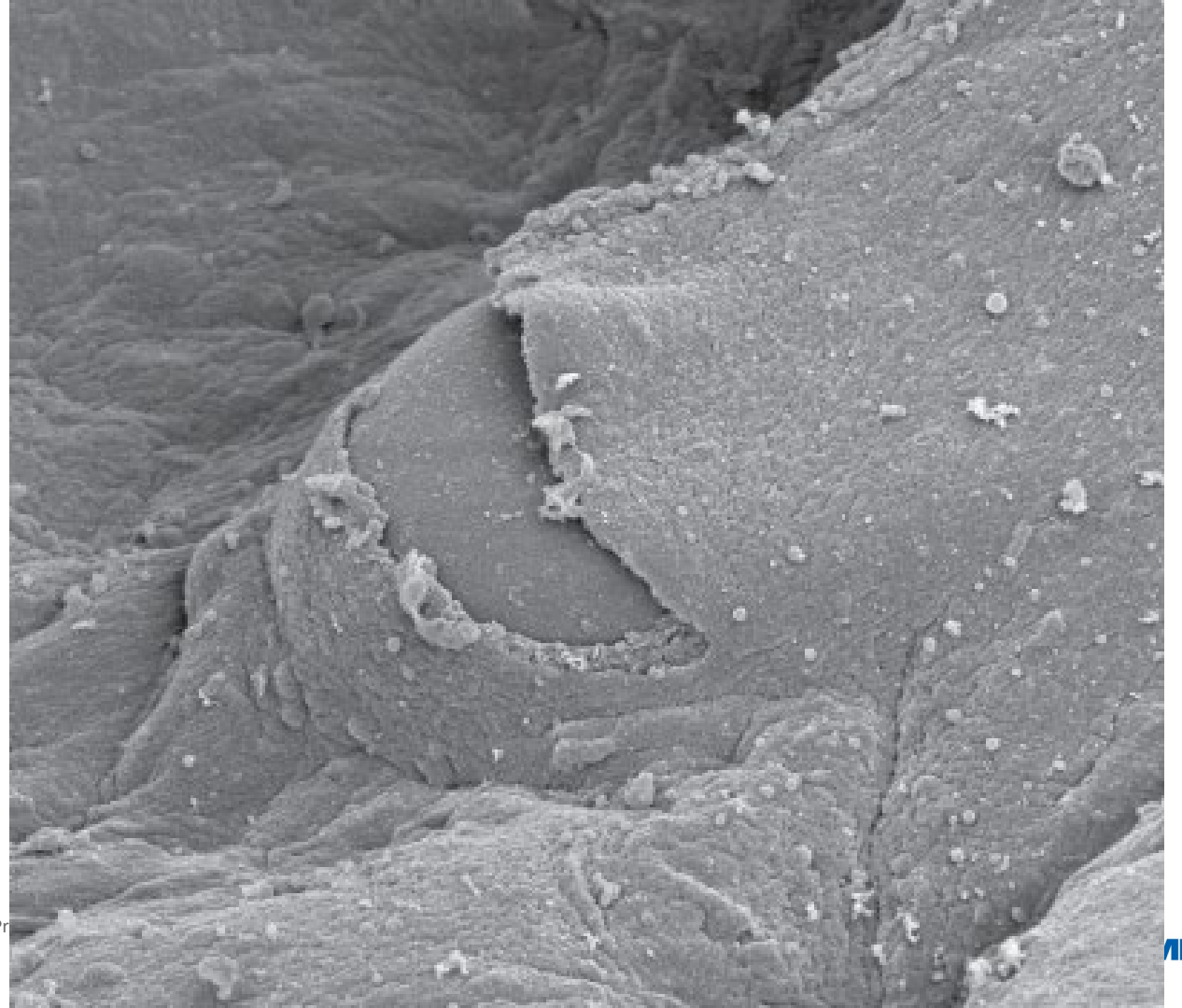

Tobin MJ. Principles and Pr

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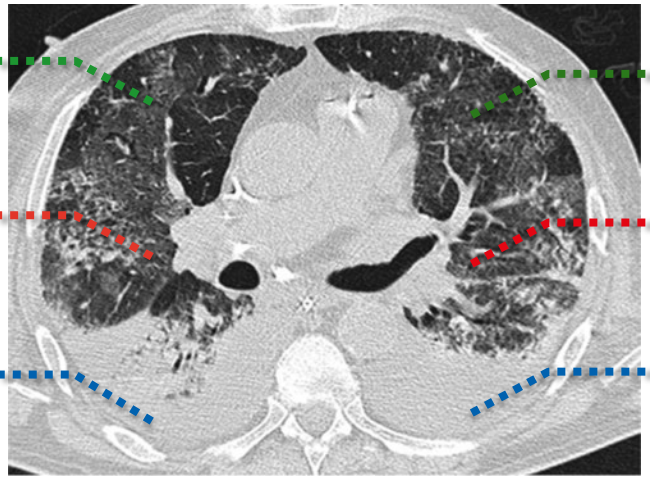
Mechanism of Ventilator-Induced Lung Injury (VILI)

Mechanical injury



“Baby lung”
Primarily responsible for the mechanical properties of the ARDS lung

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Collapsed or consolidated lung
Gasless compartment primary responsible for the impairment of oxygenation

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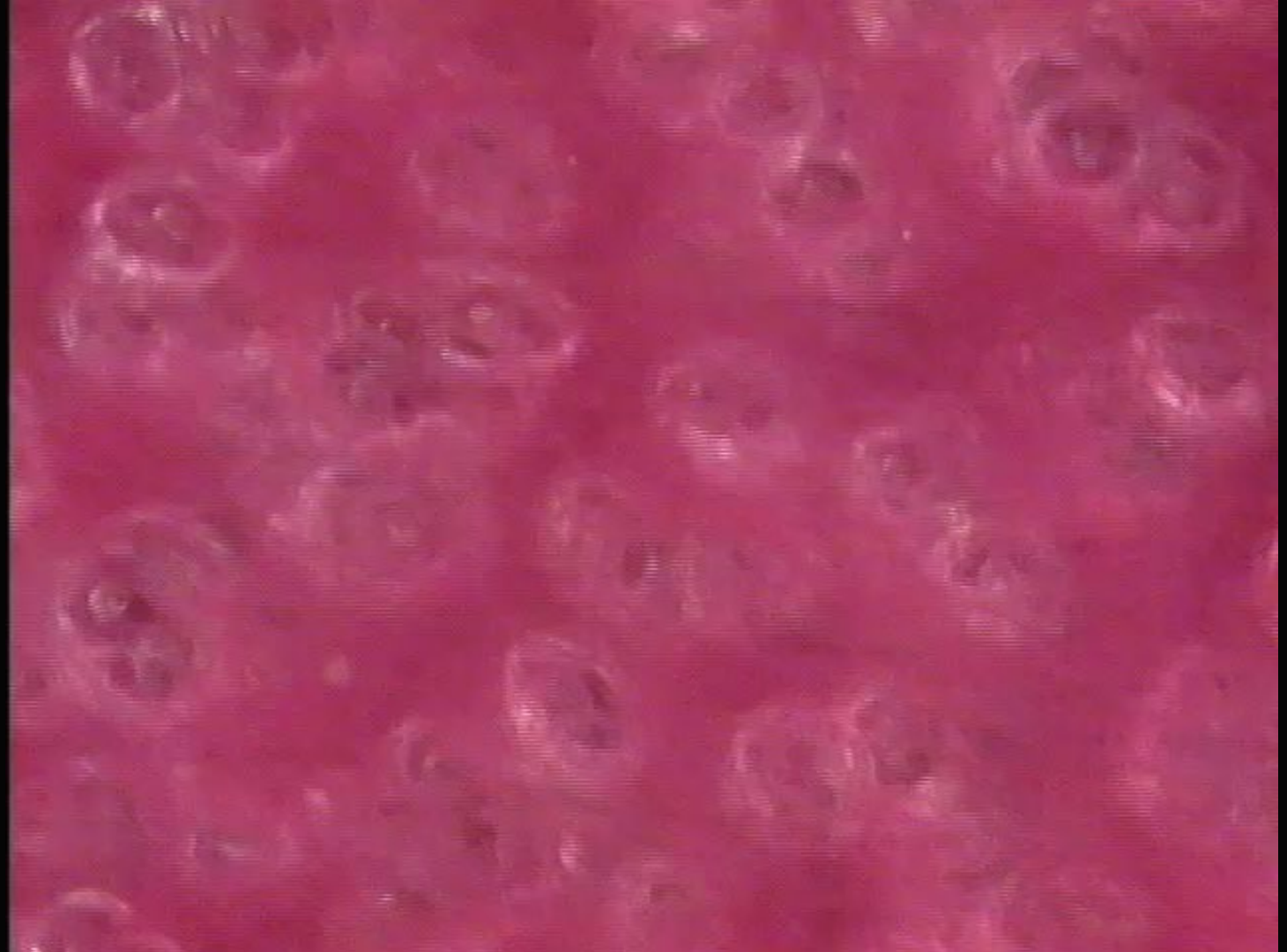


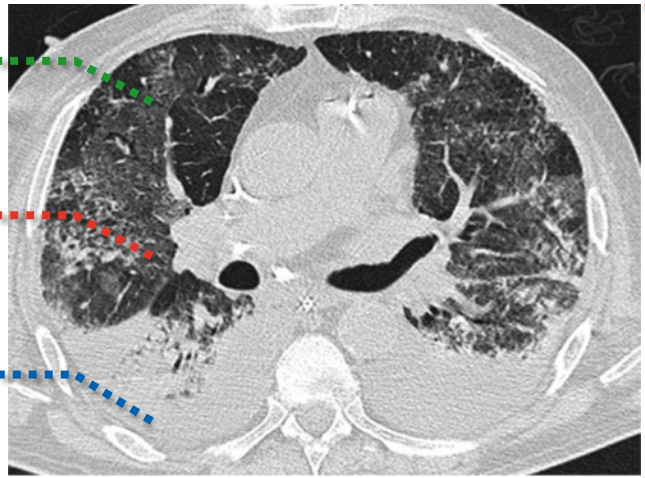
Mechanism of Ventilator-Induced Lung Injury (VILI)

Mechanical injury

Stress

Strain

Atelectrauma



Inflammatory injury

Biotrauma

Alveolar inflammation

Ergotrauma:

Vt, RR, ΔP, Flow, PEEP

$$MP\_dynamic = 0.098 \times RR \times TV \times (P_{peak} - (0.5 \times (P_{peak} - PEEP)))$$

$$MP\_static = 0.098 \times RR \times TV \times (P_{peak} - (0.5 \times (P_{plateau} - PEEP)))$$

Gattinoni. Intensive Care Med 2016 / Urner. Lancet Respir Med 2020

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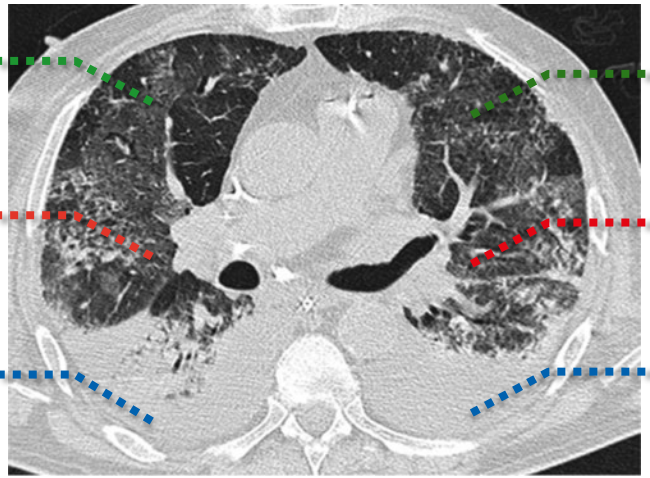
Prevention of Ventilator-Induced Lung Injury (VILI)

Mechanical injury

Stress

Strain

Atelectrauma



Limiting excessive Pplateau?

Limiting Vt @ ΔP?

Apply an open-lung strategy?

Recruitment maneuver and PEEP setting

$$MP\_dynamic = 0.098 \times RR \times TV \times (P_{peak} - (0.5 \times (P_{peak} - PEEP)))$$

$$MP\_static = 0.098 \times RR \times TV \times (P_{peak} - (0.5 \times (P_{plateau} - PEEP)))$$

Minimize the total energy load!

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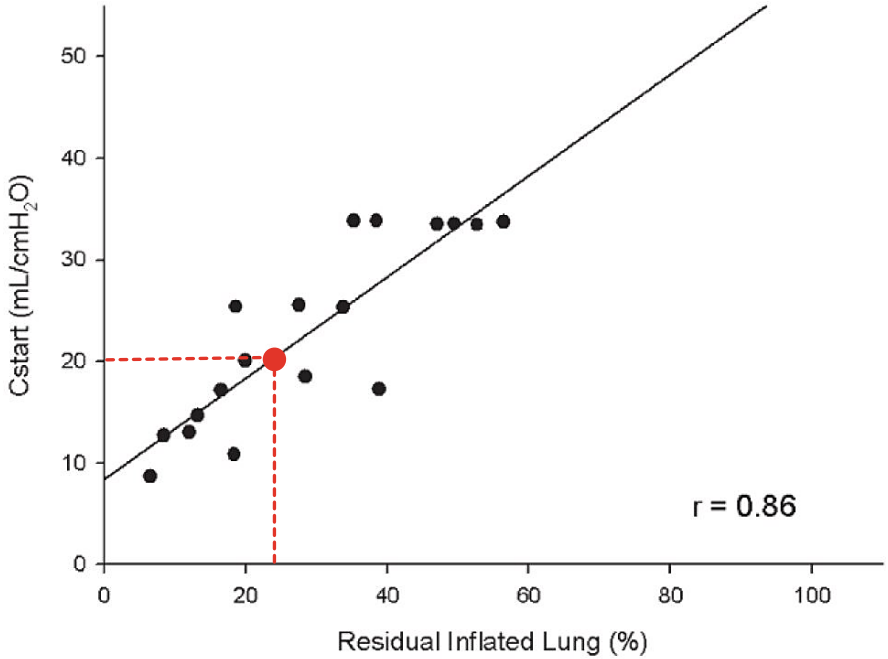
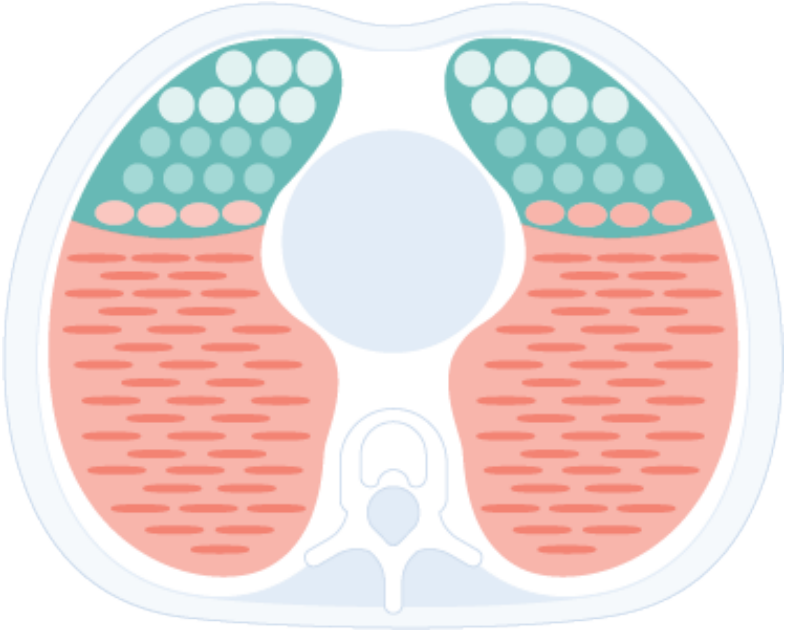
…the Baby lung is **small, NOT stiff!**





Gattinoni, L., Intensive Care Med. 2005

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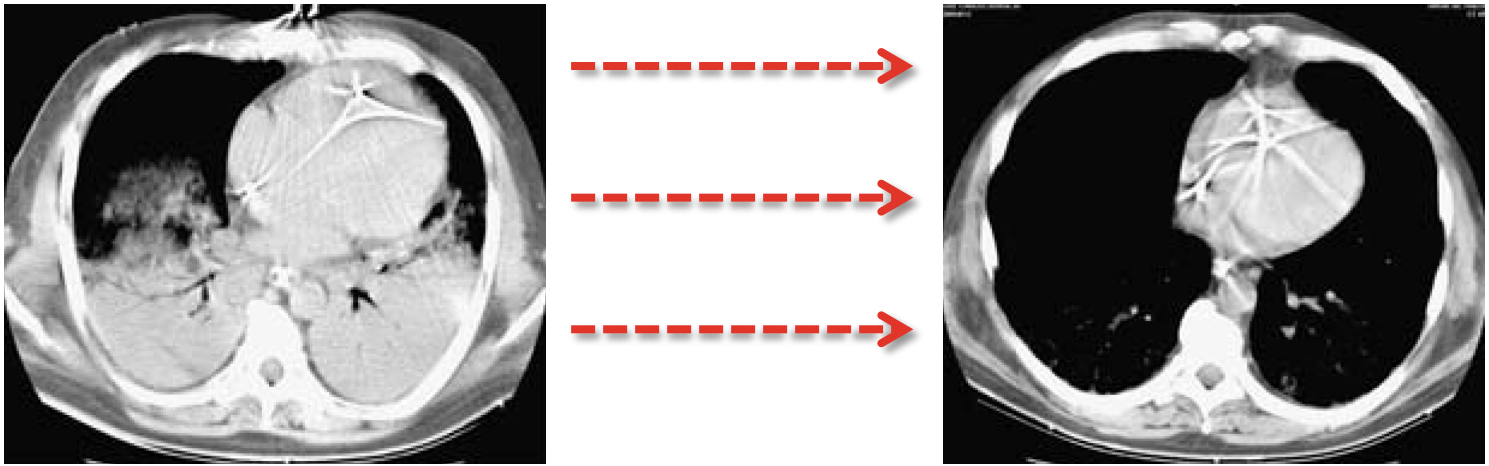
Open-lung strategy

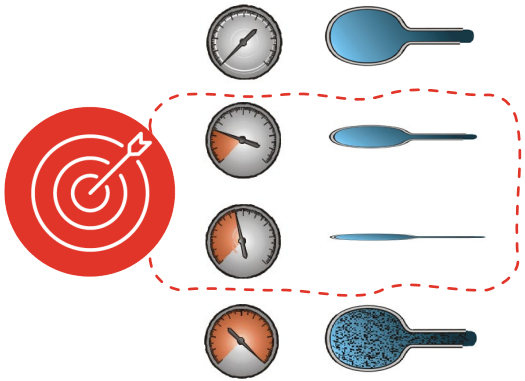


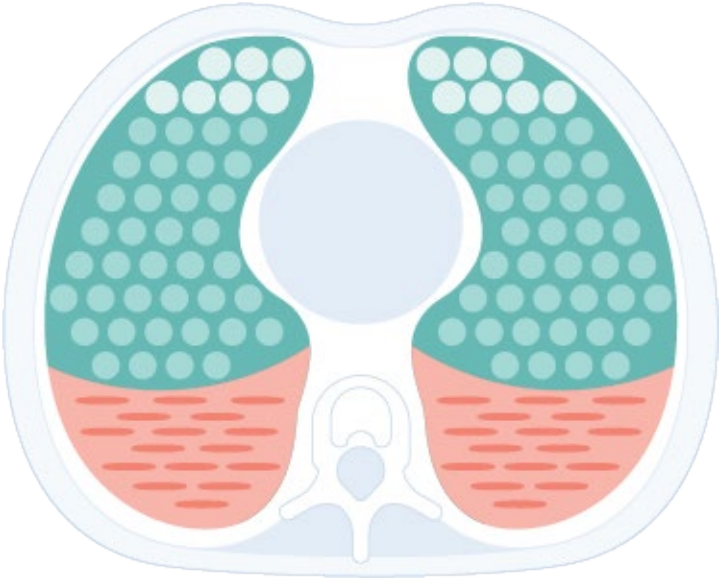
- **Re-aerate** collapsed lung
- **Improve:** lung homogeneity, compliance, and oxygenation
- **Decrease:** stress and strain applied to the lung, and atelectrauma

Borges. Am J Respir Crit Care Med 2006

Increase the size of the baby lung

- By applying a safe pressure threshold for a limited time





- Minimize overdistension
- Open small collapsed airways
- ∞

Borges. Am J Respir Crit Care Med 2006

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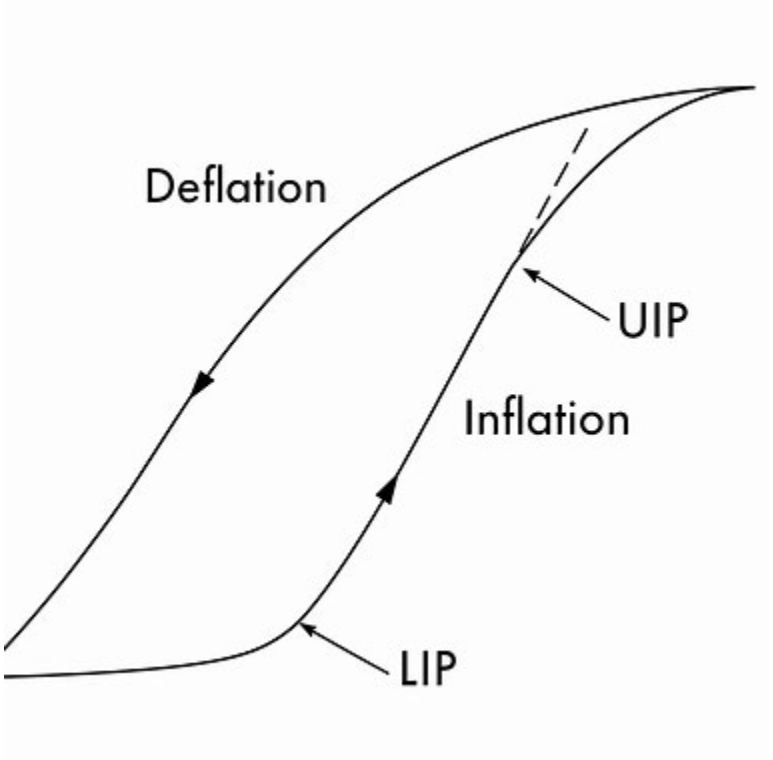
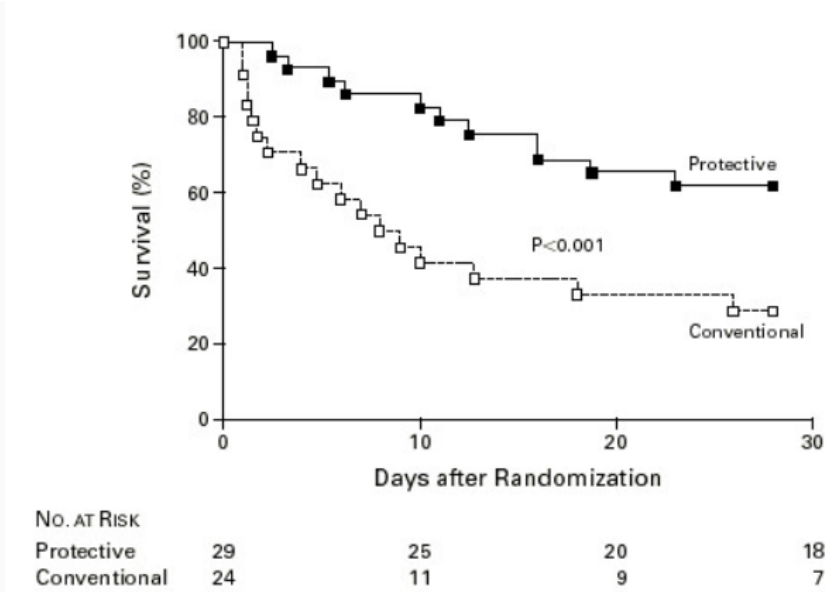
PEEP individualization story…





Amato et al. Effect of a protective- ventilation strategy on mortality in the acute respiratory distress syndrome. 1998. NEJM. Vol 338, 6, 347-354

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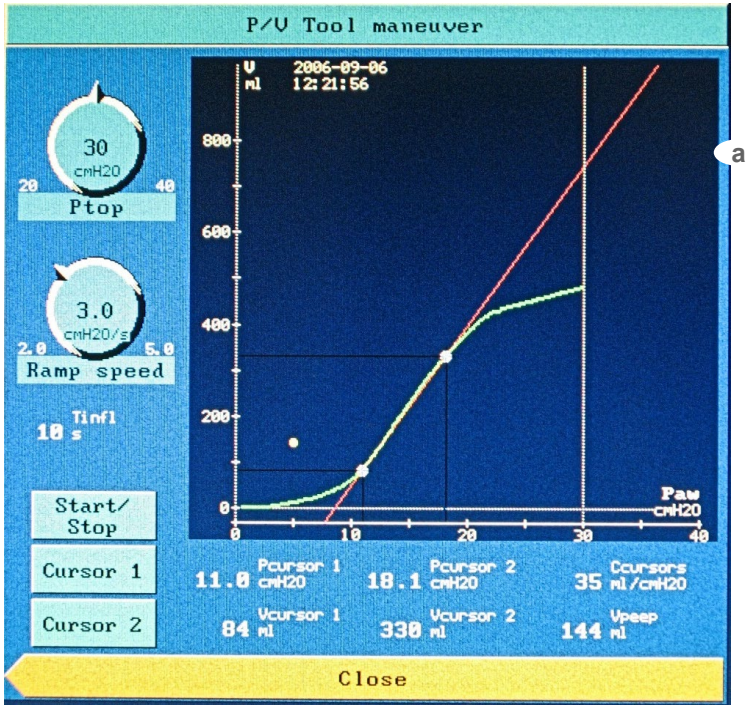
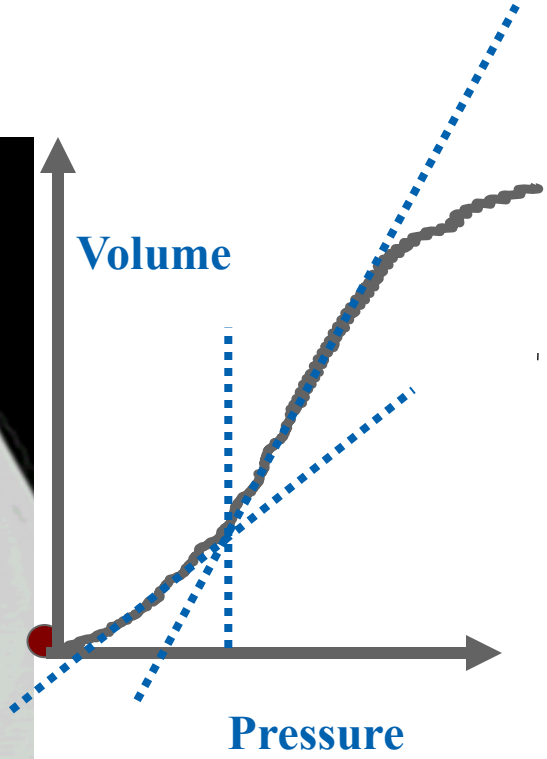
P/V Tool- “The OG”

- LIP- Reversal of alveolar collapse
- UIP- Beginning of hyperinflation



ARDS
CT and PV Curve (slow inflation)



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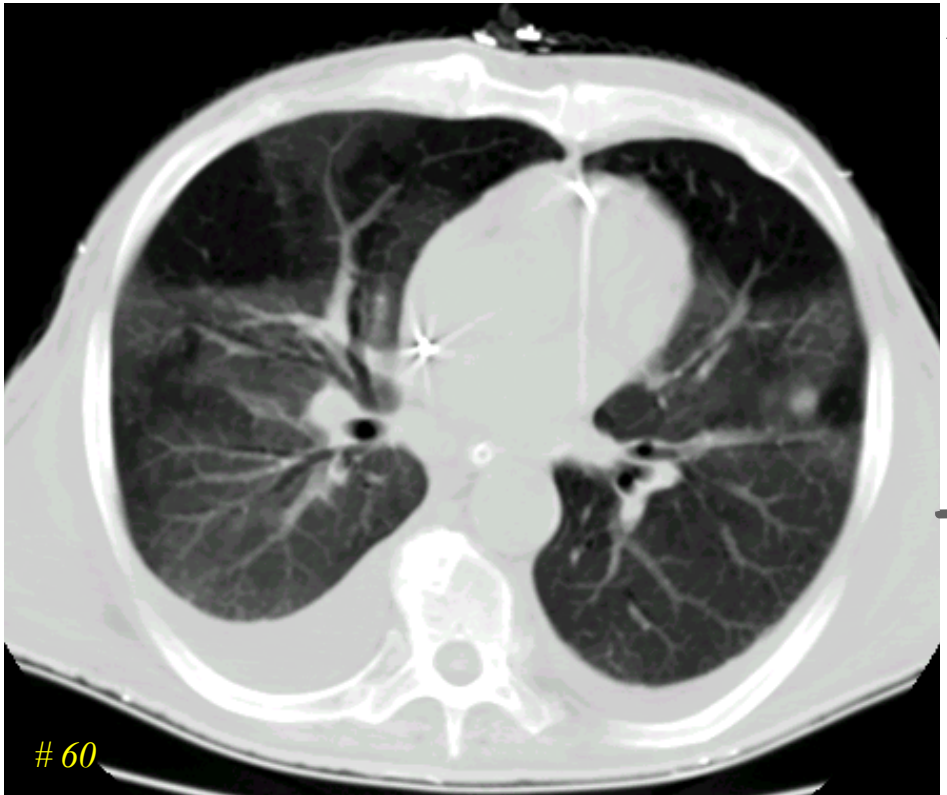

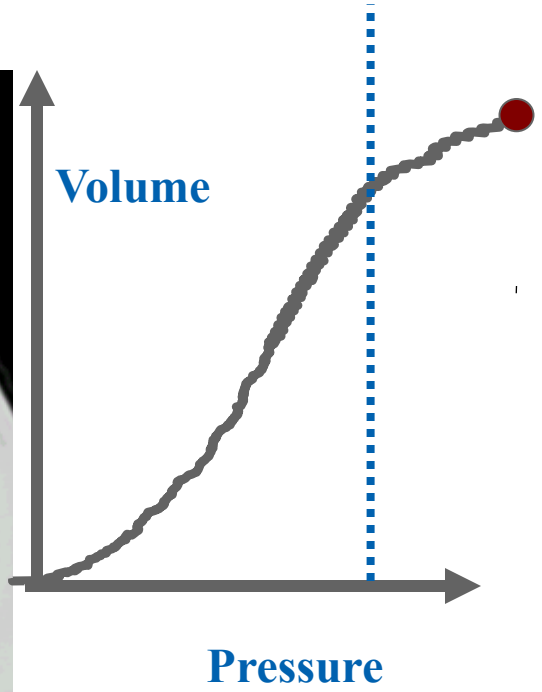

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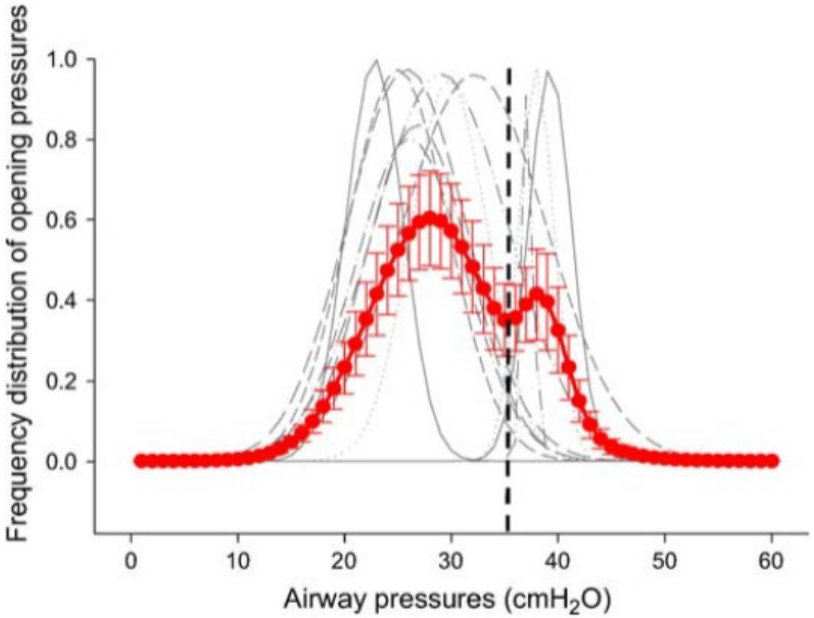
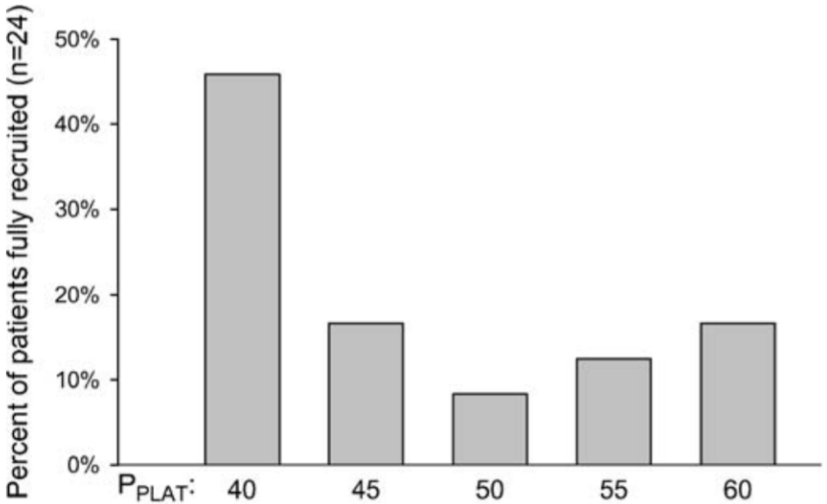
Recruitment at 40 cmH2O





Borges et al. Reversibility of Lung Collapse and Hypoxemia in Early Acute ARDS. 2006 https://www.atsjournals.org/doi/epdf/10.1164/rccm.200506-976OC?role=tab

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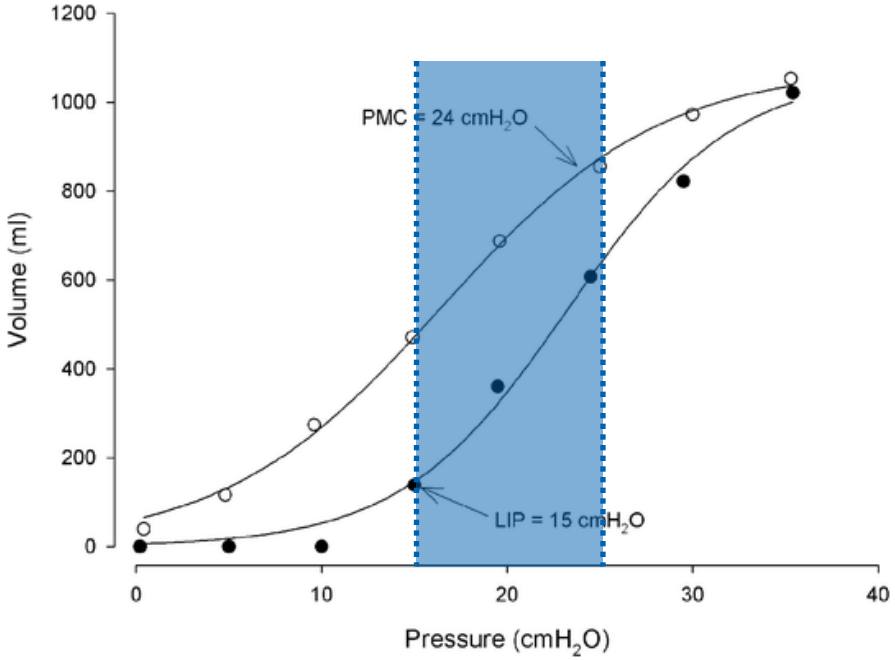
Expiratory P/V relationship



Yartsev, Al. Optimal PEEP for open lung ventilation in ARDS. 2016. Respiratory Intensive Care

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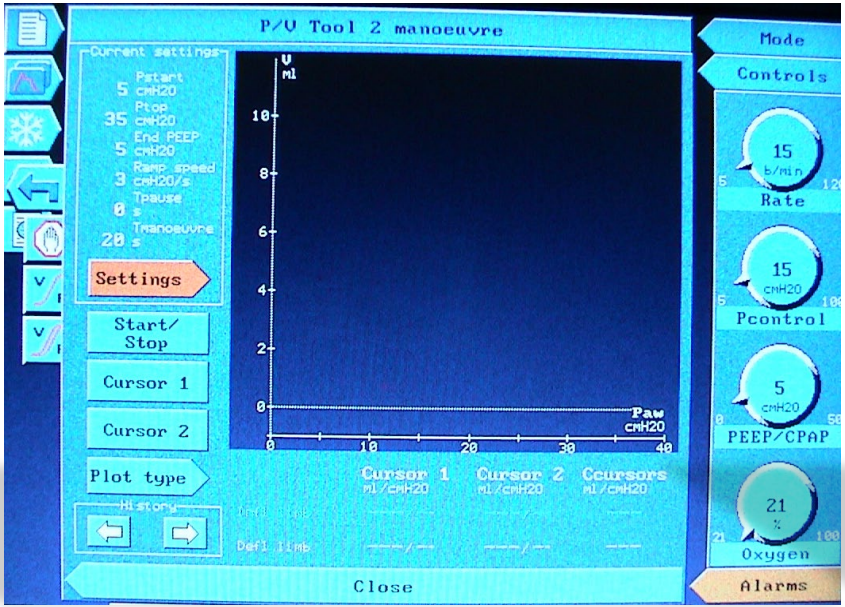
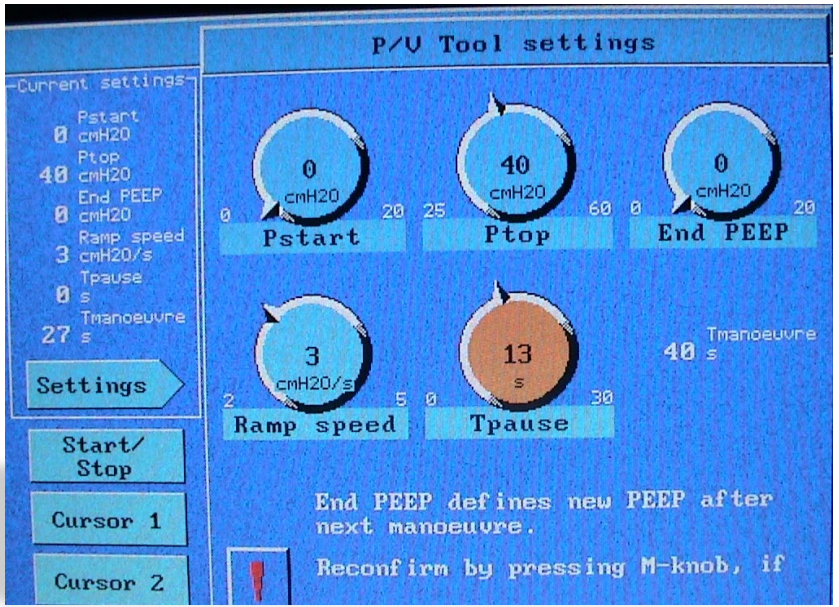
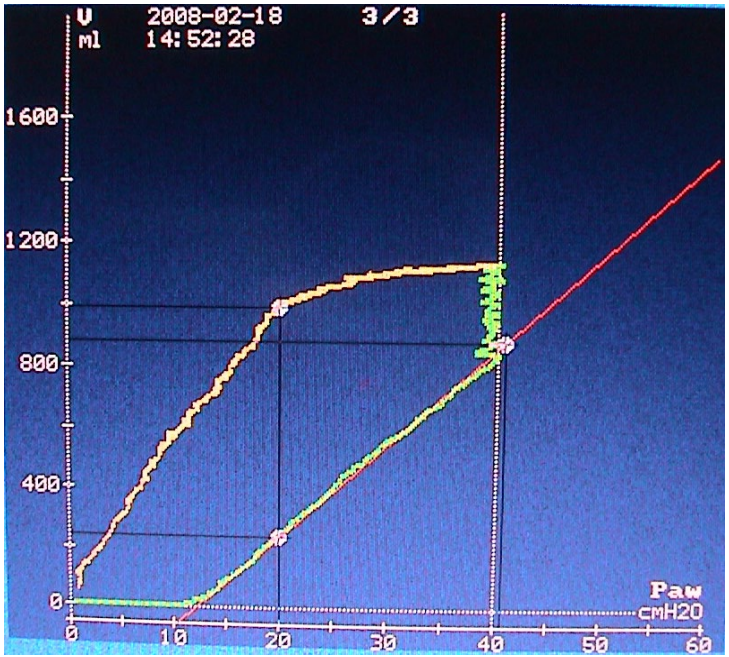
P/V Tool 2


P/V Tool 2 manoeuvre
Current settings
Pstart 5 cmH2O
Ptop 35 cmH2O
End PEEP 5 cmH2O
Ramp speed 3 cmH2O/s
Tpause 0 s
Tmanoeuvre 20 s
Settings
Start/ Stop
Cursor 1
Cursor 2
Plot type
History
Close
V ml
Paw cmH2O
Cursor 1 ml/cmH2O
Cursor 2 ml/cmH2O
Ccursors ml/cmH2O
Mode
Controls
15 b/min Rate
15 cmH2O Pcontrol
5 cmH2O PEEP/CPAP
21 % Oxygen
Alarms


P/V Tool settings
Current settings
Pstart 0 cmH2O
Ptop 40 cmH2O
End PEEP 0 cmH2O
Ramp speed 3 cmH2O/s
Tpause 0 s
Tmanoeuvre 27 s
Settings
Start/ Stop
Cursor 1
Cursor 2
0 cmH2O Pstart
40 cmH2O Ptop
0 cmH2O End PEEP
3 cmH2O/s Ramp speed
13 s Tpause
Tmanoeuvre 40 s
End PEEP defines new PEEP after next manoeuvre.
Reconfirm by pressing M-knob, if

P/V Tool 2



- Introduced:
  - Recruitment manuever ability
  - Expiratory curve
    - Manual assessment of Point of Maximum Curvature (PMC)
  - Manual measurement of Delta Volume

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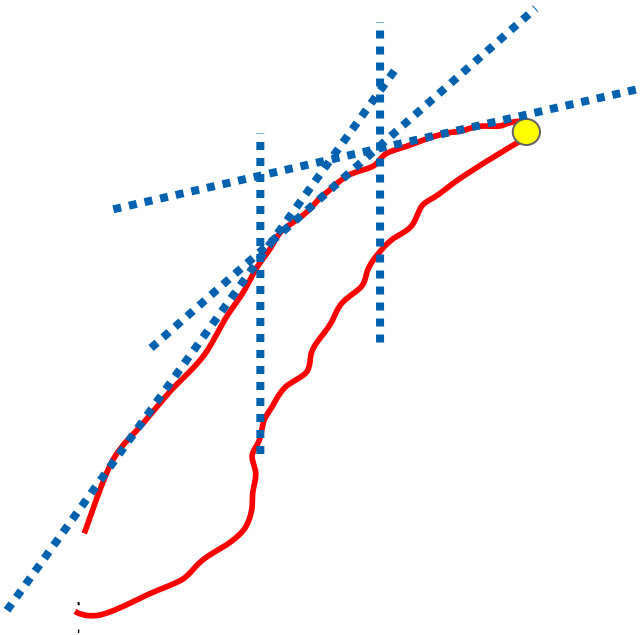

(Unpublished images)

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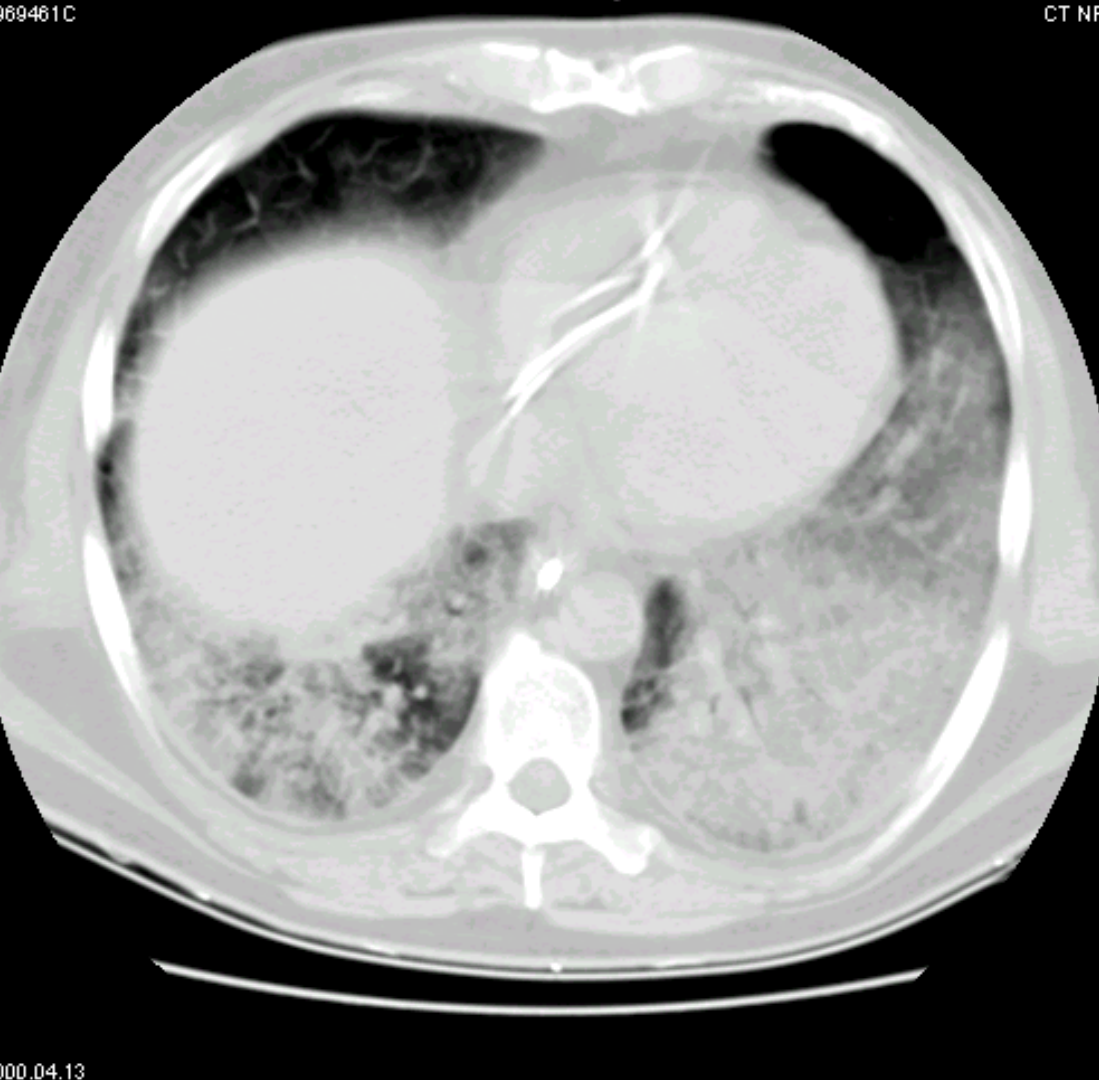

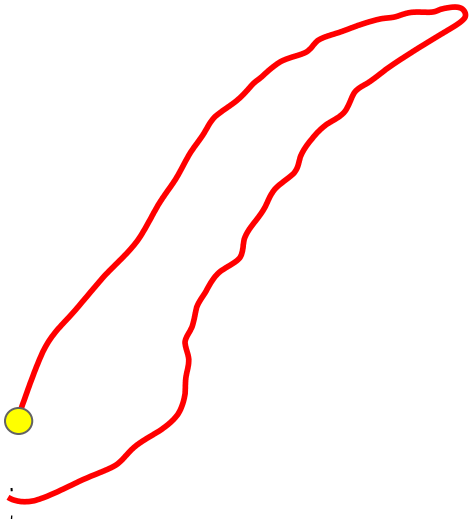

(Unpublished images)

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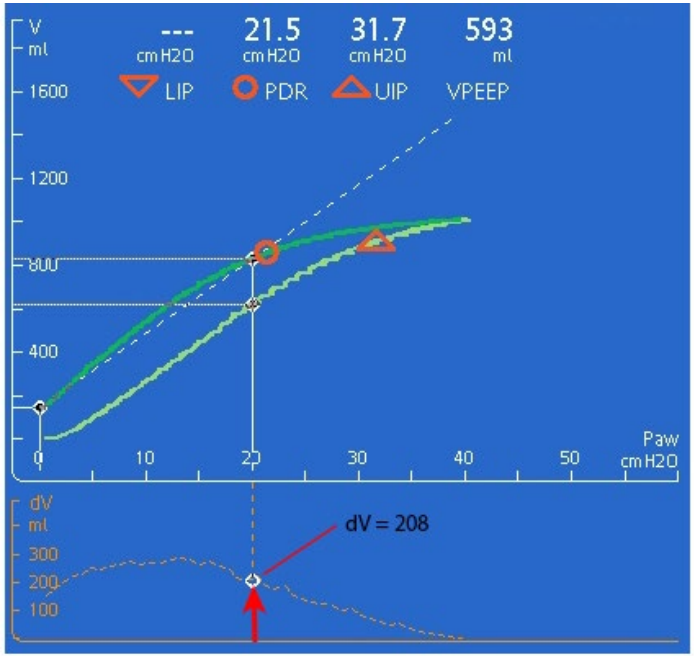
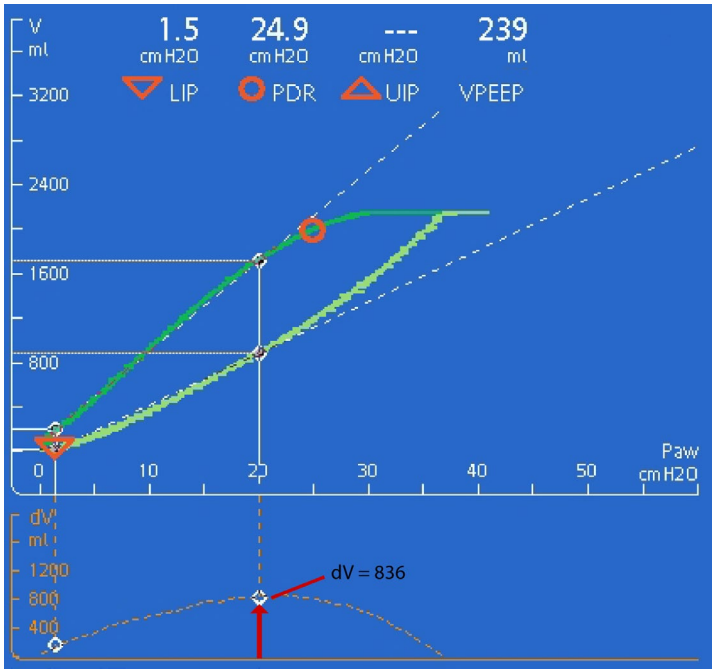
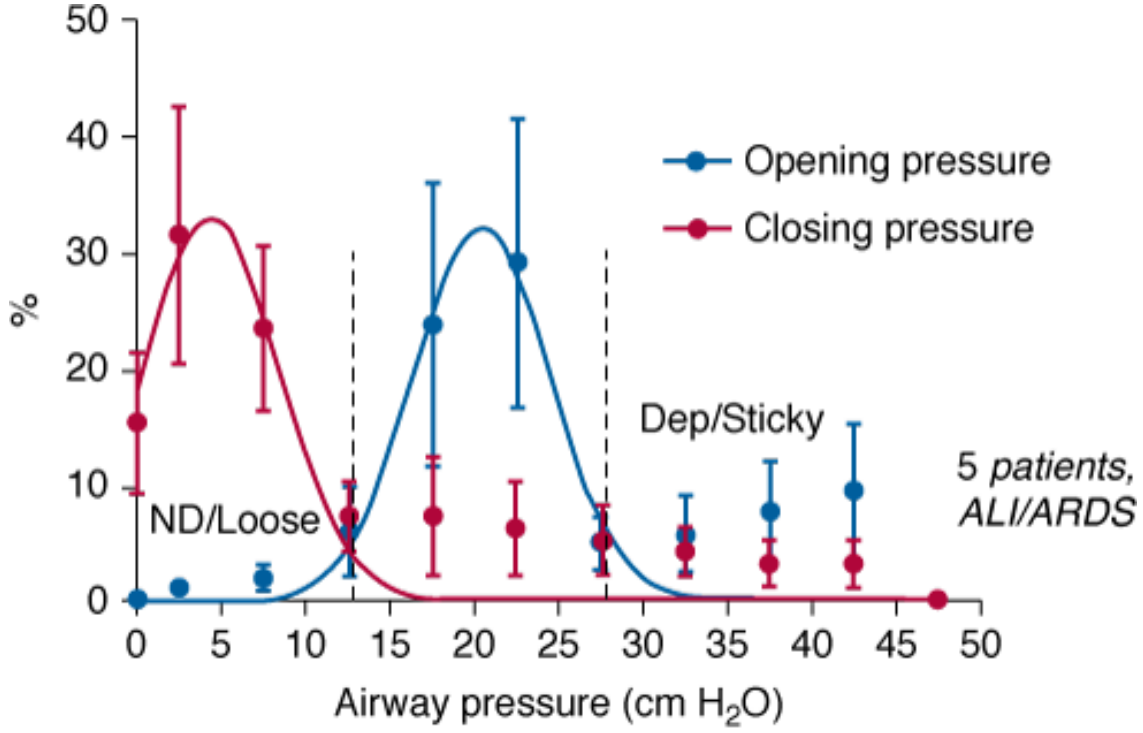
P/V Tool Pro (500 ml @20 cm H2O)






Patient
Additions
Modes
ET tube
Trend
60
2
29 Ppeak cmH2O
0.1
6.7 ExpMinVol l/min
1300
VTE
Paw
Ptrach
cmH2O
40
30
20
10
0
1 2 3 4 5 6 7 8 9 10
s
IntelliCuff
15 b/min
Rate
400 ml
Vt
5 cmH2O
PEEP/CPAP
100 %
Oxygen
Controls
Hold
P/V Tool
V ml
21.3 cmH2O LIP
24.0 cmH2O PDR
--- cmH2O UIP
182 ml Vpeep
2020-02-06 8
16:11:28
1600
1200
800
400
0 10 20 30 40 50
Paw cmH2O
dV ml
1200
800
400
End PEEP defines new PEEP after next maneuver.
Reconfirm if
- Ptop is greater than 40 cmH2O, or
- Tpause is greater than 5 s
5 cmH2O Pstart
40 cmH2O Ptop
20 cmH2O End PEEP
5 cmH2O/s Ramp speed
10 s Tpause
21 s Tmaneuver
Close

Opening and Closing Pressures



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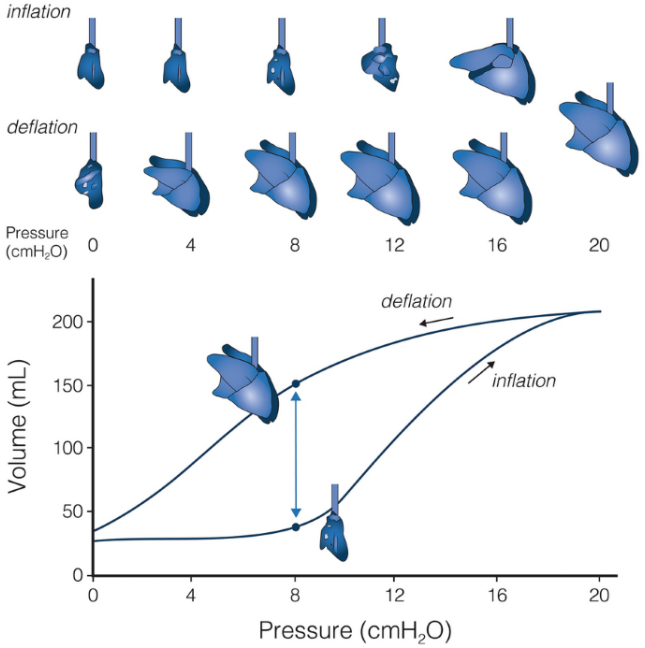
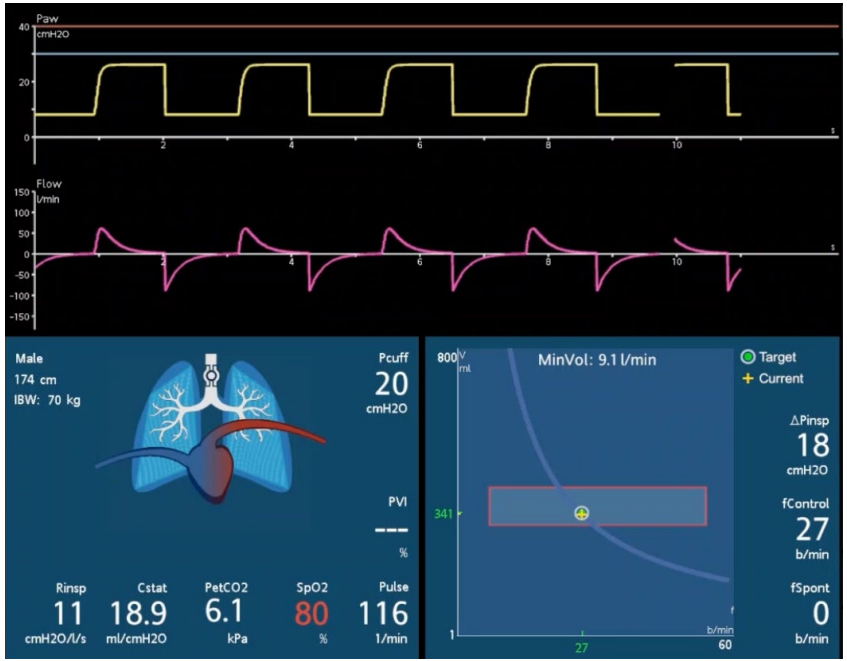
Sustaining Lung recruitment

- Process of re-inflating collapsed or poorly aerated alveoli
  - Temporarily by increasing airway pressure



Assessing Lung Recruitment Potential (P/V Tool)



Chiumello D, Arnal JM et al. Hysteresis and Lung Recruitment in Acute Respiratory Distress Syndrome Patients: A CT Scan Study. CCM Journal, 2020, 48:10

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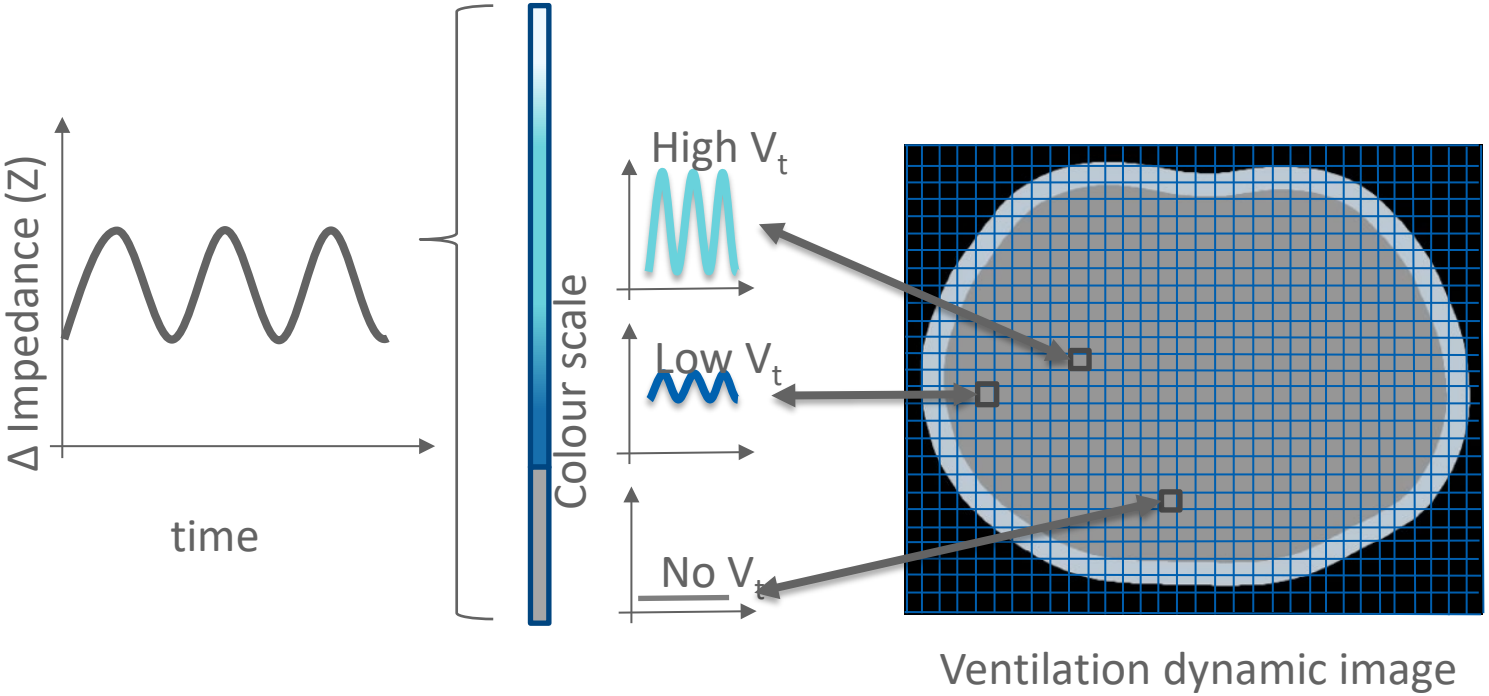
Electrical Impedance Tomography


Telemedicina - FMUSP

How can I interpret EIT signals



Ventilation dynamic image

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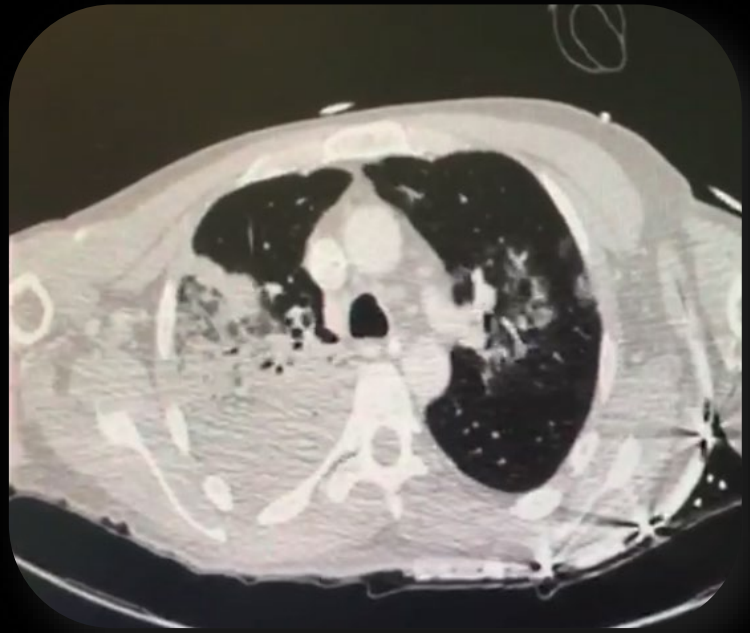
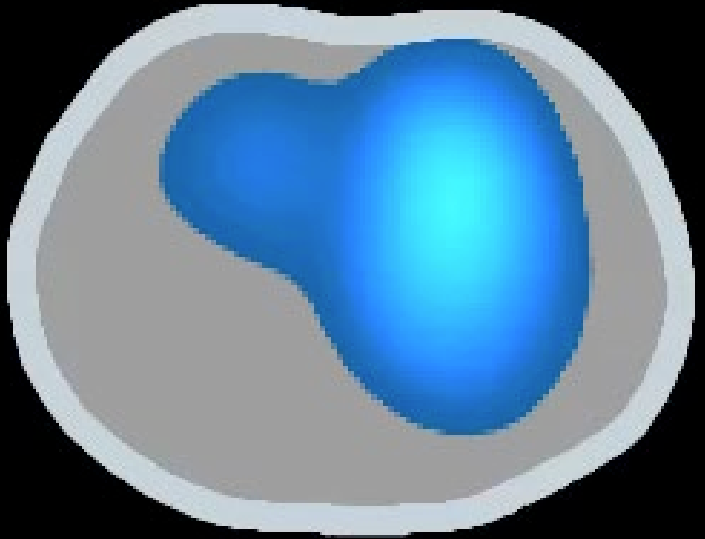
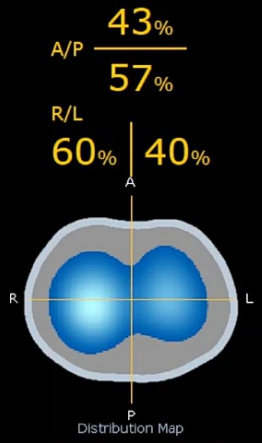
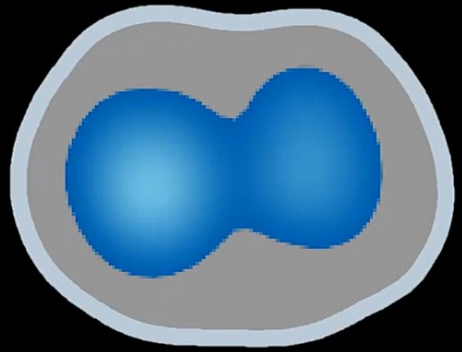


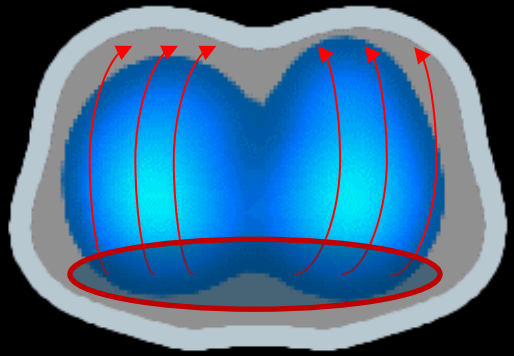


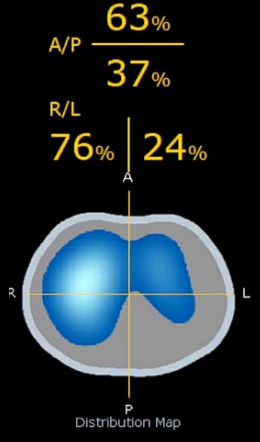


Distribution Map

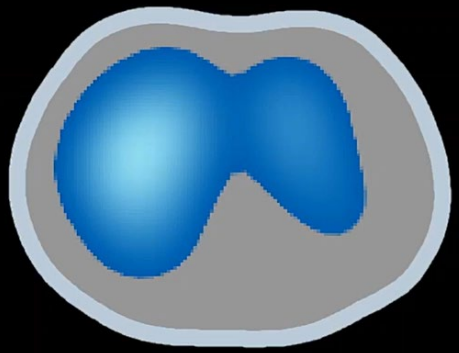


Dynamic Image

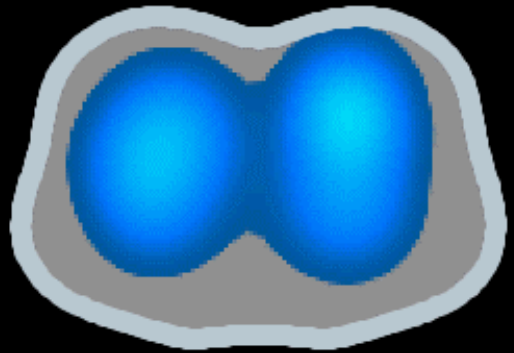


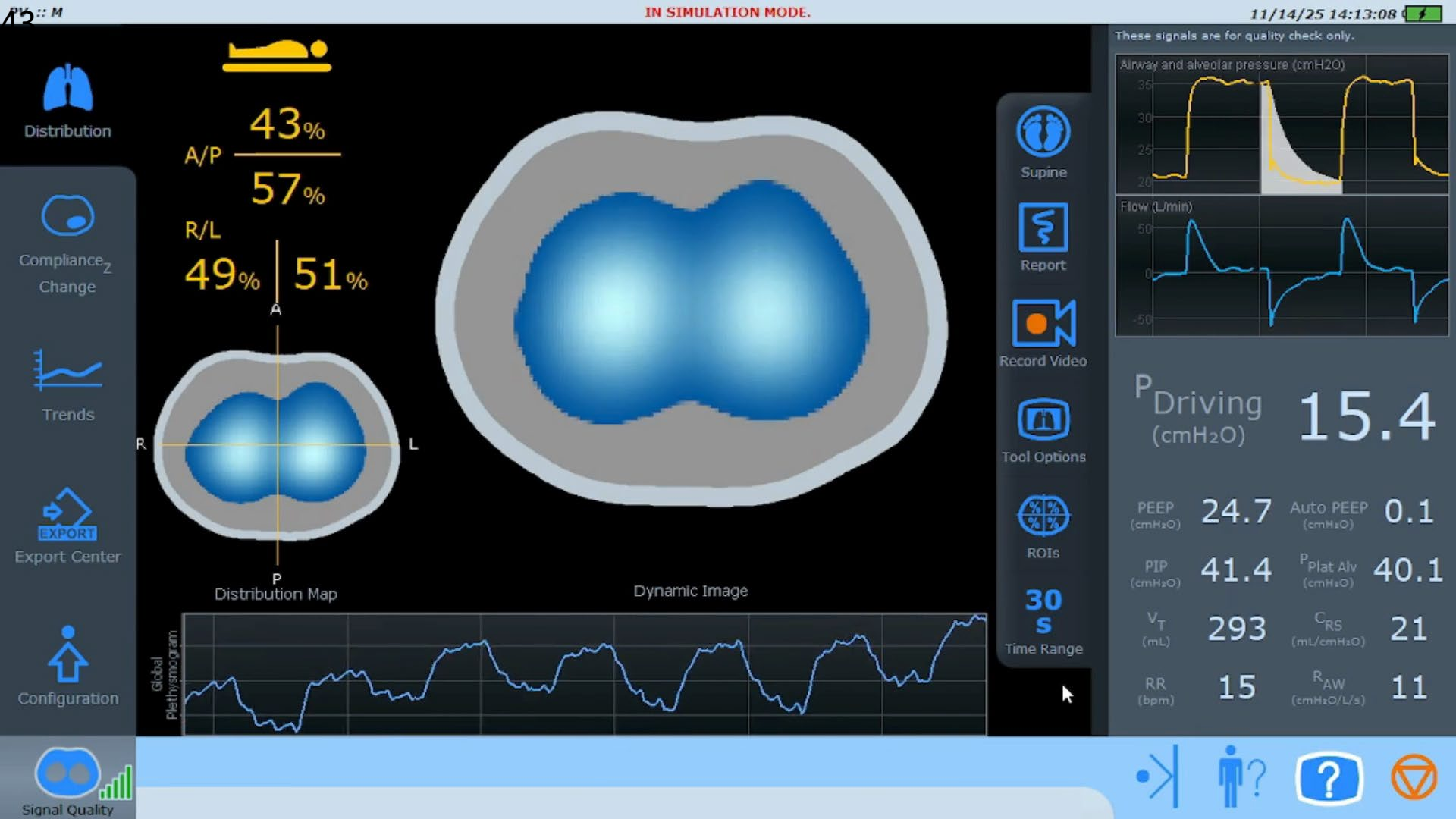


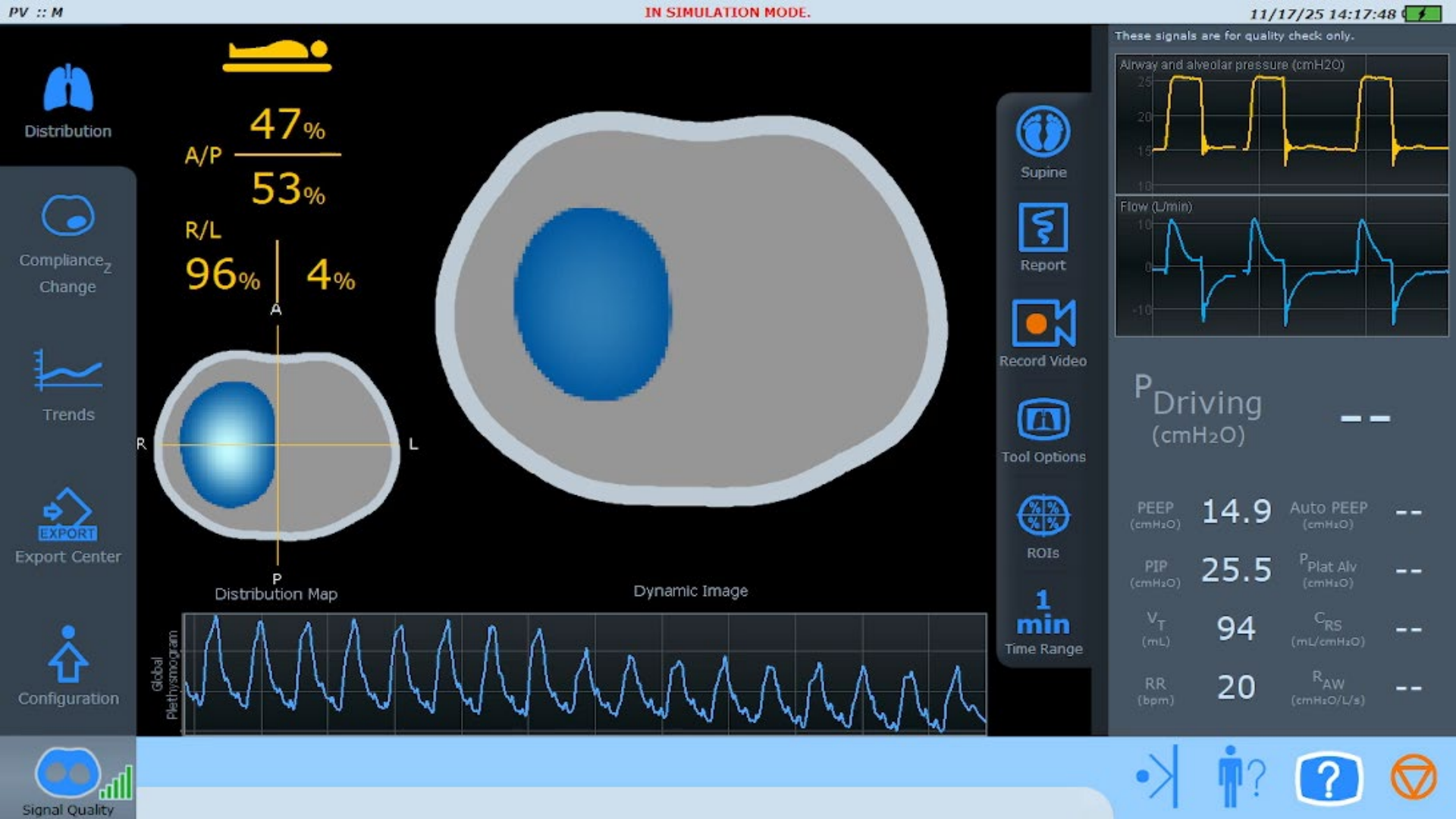
Distribution Map

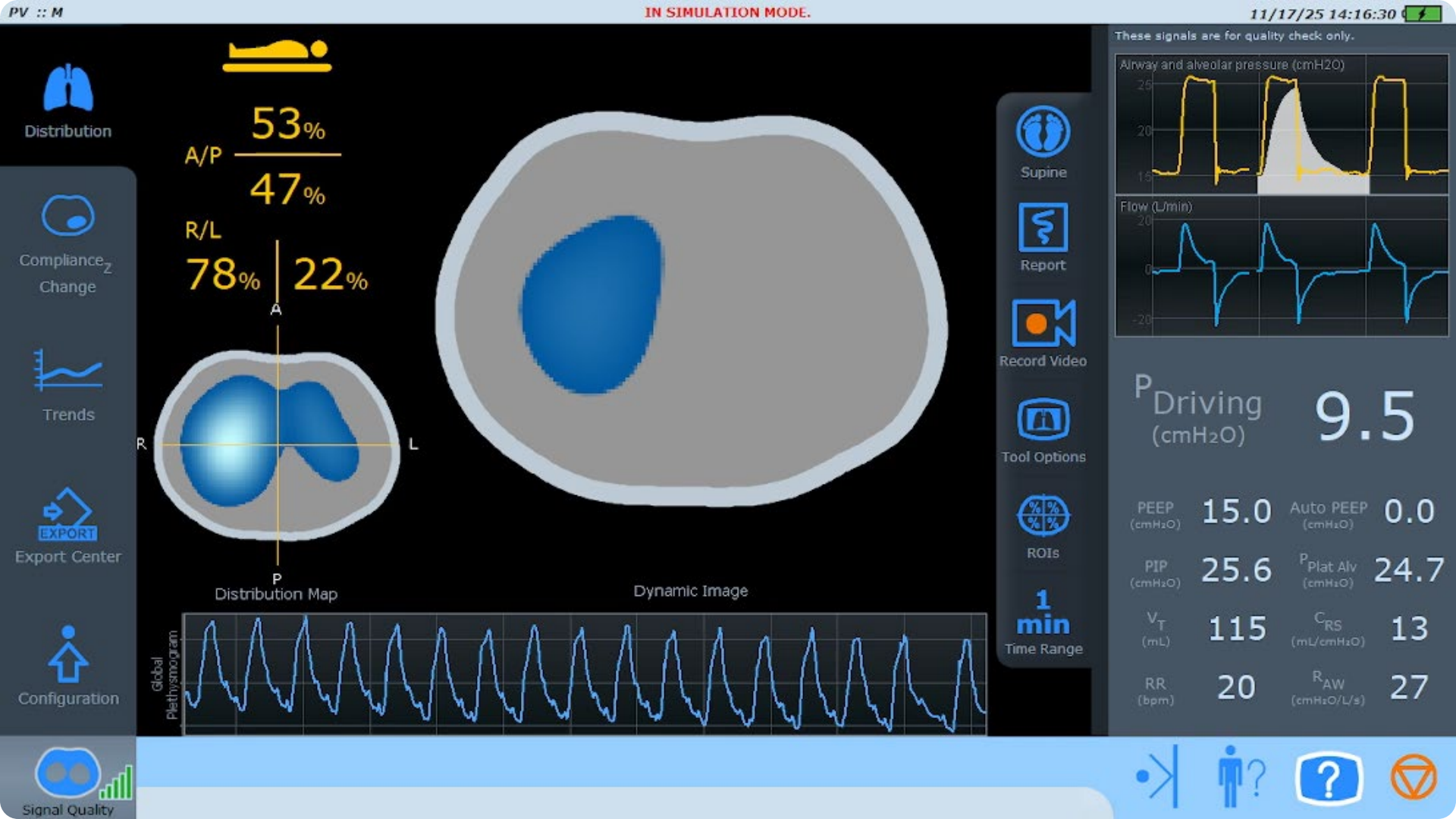


Dynamic Image



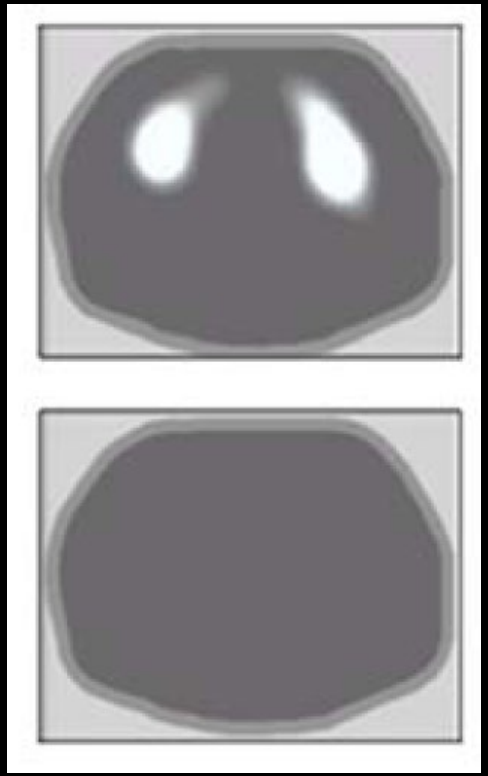

Distribution
A/P
43%
57%
R/L
49%
51%
A
R
L
P
Distribution Map
Dynamic Image
Global Plethysmogram
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
Supine
Report
Record Video
Tool Options
ROIs
30 s
Time Range
These signals are for quality check only.
Airway and alveolar pressure (cmH2O)
35
30
25
20
Flow (L/min)
50
0
-50
P Driving (cmH2O) 15.4
PEEP (cmH2O) 24.7
Auto PEEP (cmH2O) 0.1
PIP (cmH2O) 41.4
P Plat Alv (cmH2O) 40.1
V T (mL) 293
C RS (mL/cmH2O) 21
RR (bpm) 15
R AW (cmH2O/L/s) 11

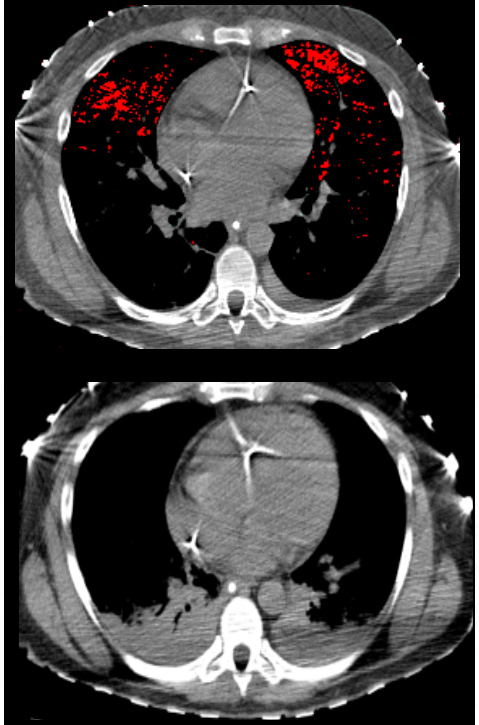

PV :: M
IN SIMULATION MODE.
11/17/25 14:17:48
Distribution
Compliance Change
Trends
Export Center
Configuration
Signal Quality
47%
A/P
53%
R/L
96%
4%
A
R
L
P
Distribution Map
Dynamic Image
Global Plethysmogram
Supine
Report
Record Video
Tool Options
ROIs
1 min
Time Range
These signals are for quality check only.
Airway and alveolar pressure (cmH2O)
Flow (L/min)
P Driving (cmH2O) --
PEEP (cmH2O) 14.9
Auto PEEP (cmH2O) --
PIP (cmH2O) 25.5
P Plat Alv (cmH2O) --
VT (mL) 94
CRS (mL/cmH2O) --
RR (bpm) 20
RAW (cmH2O/L/s) --

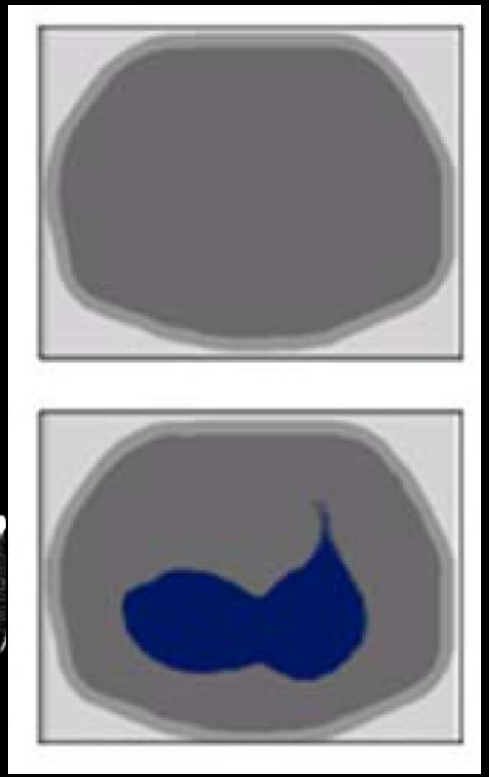

PV :: M
IN SIMULATION MODE.
11/17/25 14:16:30
Distribution
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
53%
A/P
47%
R/L
78%
22%
A
R
L
P
Distribution Map
Dynamic Image
Global Plethysmogram
Supine
Report
Record Video
Tool Options
ROIs
1 min
Time Range
These signals are for quality check only.
Airway and alveolar pressure (cmH2O)
Flow (L/min)
P Driving (cmH2O) 9.5
PEEP (cmH2O) 15.0
Auto PEEP (cmH2O) 0.0
PIP (cmH2O) 25.6
P Plat Alv (cmH2O) 24.7
V T (mL) 115
C RS (mL/cmH2O) 13
RR (bpm) 20
R AW (cmH2O/L/s) 27

Hyperdistension image

Cum. Collapse image

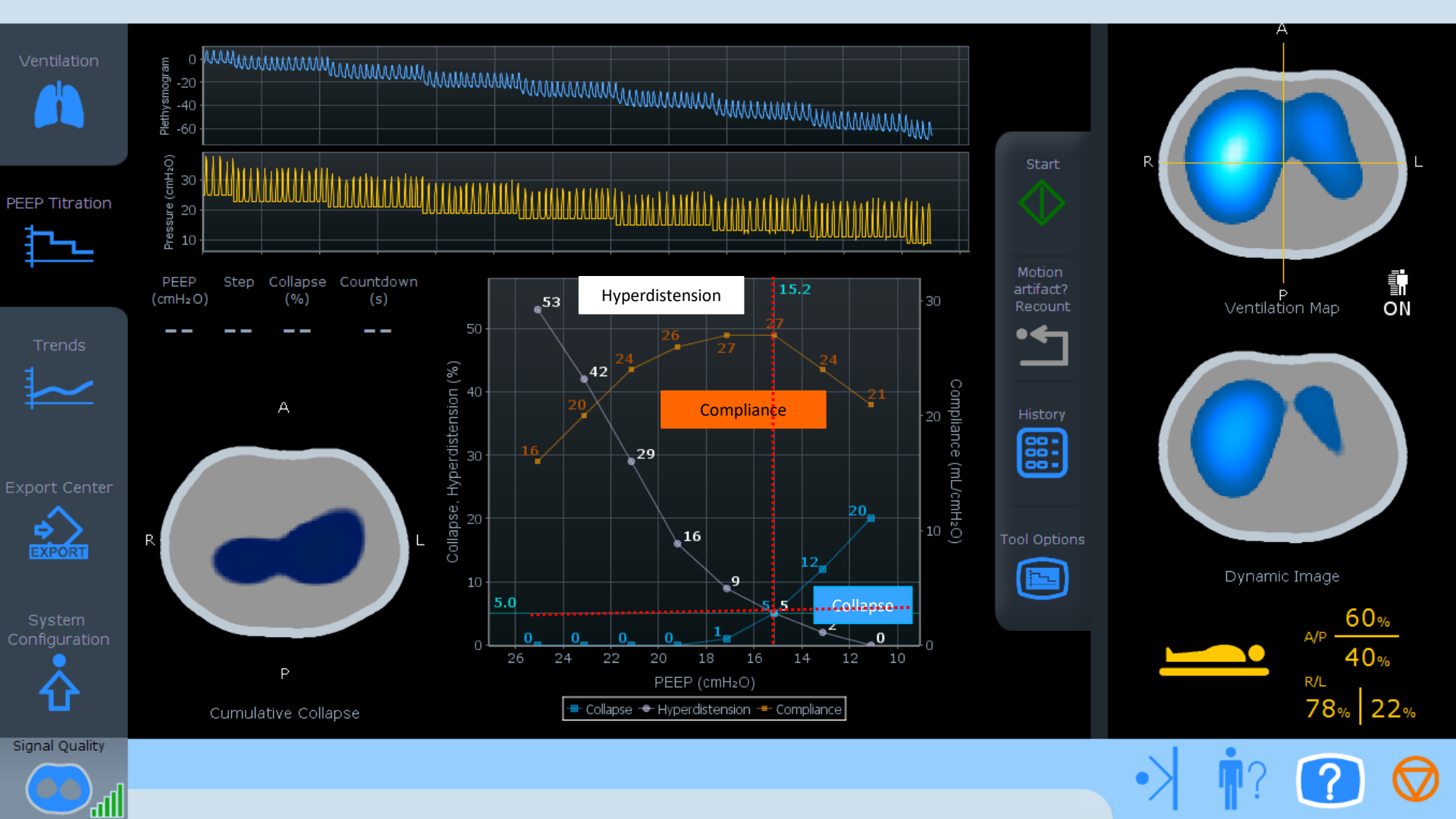






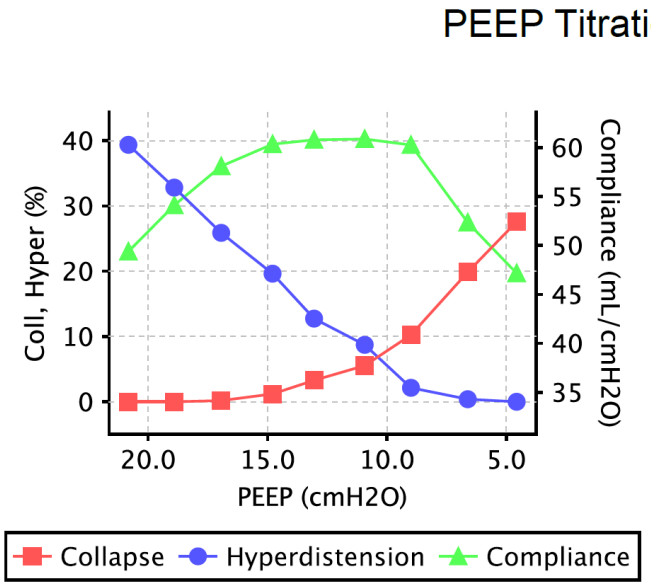
EIT

EIT


Ventilation
PEEP Titration
Trends
Export Center
EXPORT
System Configuration
Signal Quality
Plethysmogram
0
-20
-40
-60
Pressure (cmH₂O)
30
20
10
PEEP (cmH₂O)
Step
Collapse (%)
Countdown (s)
A
R
L
P
Cumulative Collapse
Hyperdistension
Compliance
Collapse
15.2
5.0
53
42
29
16
9
5
2
0
16
20
24
26
27
27
24
21
20
12
1
0
0
0
0
0
Collapse, Hyperdistension (%)
Compliance (mL/cmH₂O)
PEEP (cmH₂O)
Collapse
Hyperdistension
Compliance
Start
Motion artifact? Recount
History
Tool Options
A
R
L
P
Ventilation Map
ON
Dynamic Image
A/P
60%
40%
R/L
78%
22%

PEET Titration BMI

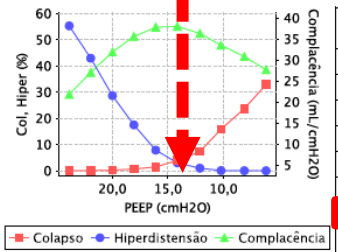
BMI = 25



PEEP (cmH_2O)	Compliance (mL/cmH_2O)	Hyper-distension	Collapse (%)
20.8	49.4	39.4	0.0
18.9	54.1	32.8	0.0
16.9	58.1	25.9	0.2
14.8	60.3	19.6	1.2
13.1	60.8	12.7	3.3
10.9	60.9	8.7	5.5
9.0	60.3	2.1	10.2
6.6	52.3	0.4	19.9
4.6	47.2	0.0	27.6

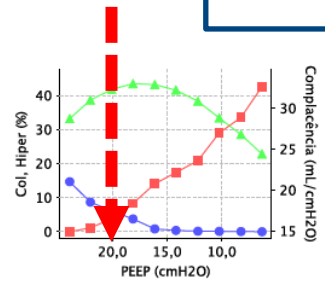
Change in body position

Supine



PEEP (cmH_2O)	Complacência (mL/cmH_2O)	Hiperdist. (%)	Colapso (%)
23,9	22	55	0
22,0	27	43	0
20,0	32	29	0
18,1	36	17	1
16,1	38	8	1
14,1	38	3	4
12,1	36	1	7
10,2	34	0	16
8,1	31	0	24
6,2	28	0	33

Prone



PEEP (cmH_2O)	Complacência (mL/cmH_2O)	Hiperdist. (%)	Colapso (%)
23,9	29	15	0
22,0	31	9	1
20,1	32	6	4
18,1	33	4	8
16,1	33	1	14
14,2	32	0	17
12,2	31	0	21
10,2	29	0	29
8,2	27	0	34
6,3	24	0	43

ORIGINAL ARTICLE

Limiting Overdistention or Collapse When Mechanically Ventilating Injured Lungs

A Randomized Study in a Porcine Model

Mayson L. A. Sousa[1,2,4], Bhushan H. Katira[4,7], Sheena Bouch[4], Vanessa Hsing[4], Doreen Engelberts[4], Marcelo B. P. Amato[5,6], Martin Post[3,4], and Laurent J. Brochard[1,2]

[1]Keenan Centre for Biomedical Research, Critical Care Department, St. Michael's Hospital, Unity Health Toronto, Toronto, Ontario, Canada; [2]Interdepartmental Division of Critical Care Medicine and [3]Department of Physiology, University of Toronto, Toronto, Ontario, Canada; [4]Translational Medicine Program, Research Institute, Hospital for Sick Children, Toronto, Ontario, Canada; [5]Divisão de Pneumologia, Faculdade de Medicina da Universidade de São Paulo, Sao Paulo, Brazil; [6]Instituto do Coração - InCor, Hospital das Clinicas, Faculade de Medicina da Universidade de São Paulo, São Paulo, Brazil; and [7]Pediatric Critical Care Medicine, Washington University in St. Louis, St. Louis, Missouri

ORCID IDs: 0000-0003-4236-5107 (M.L.A.S.); 0000-0002-4504-7094 (B.H.K.).

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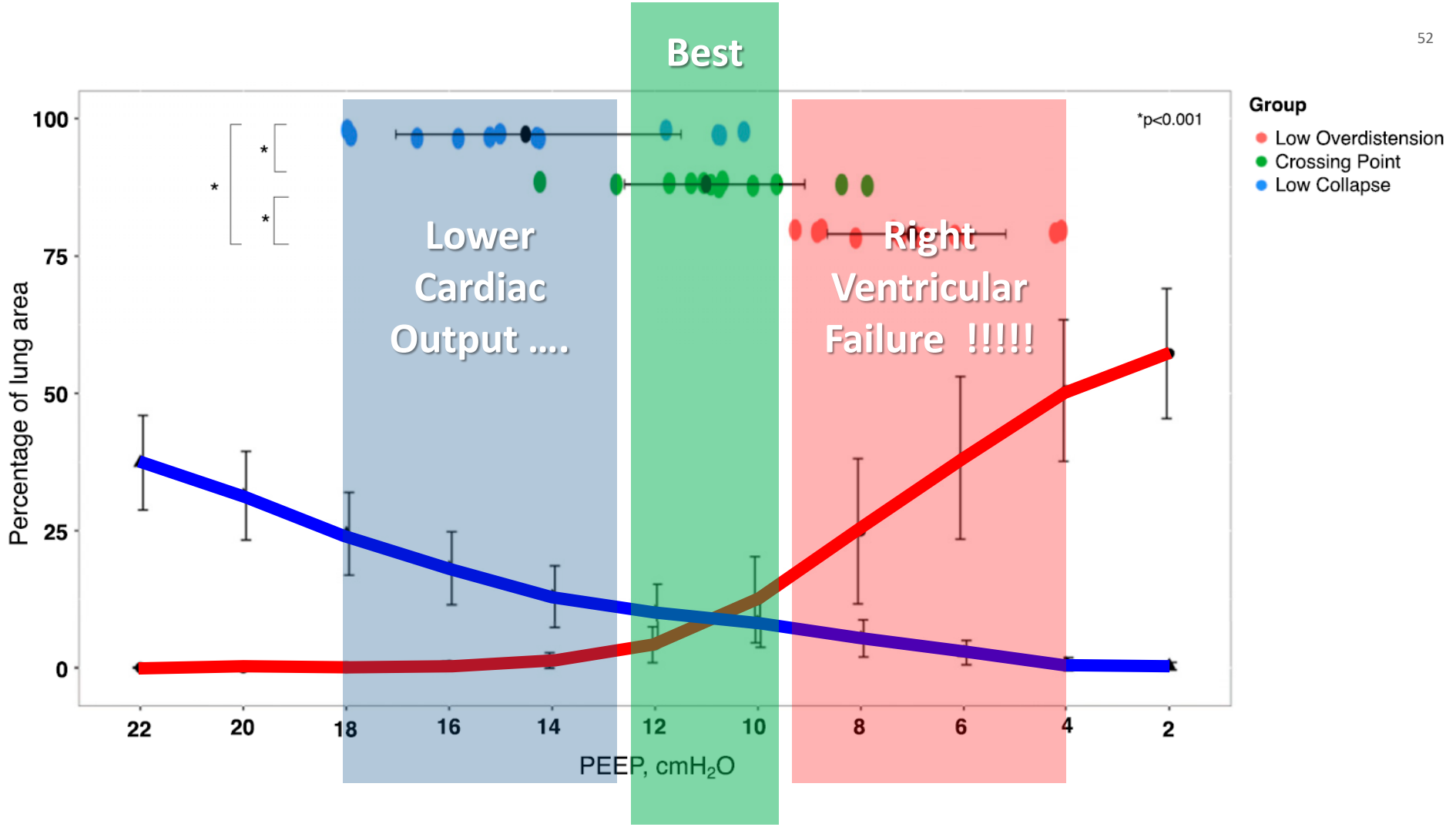
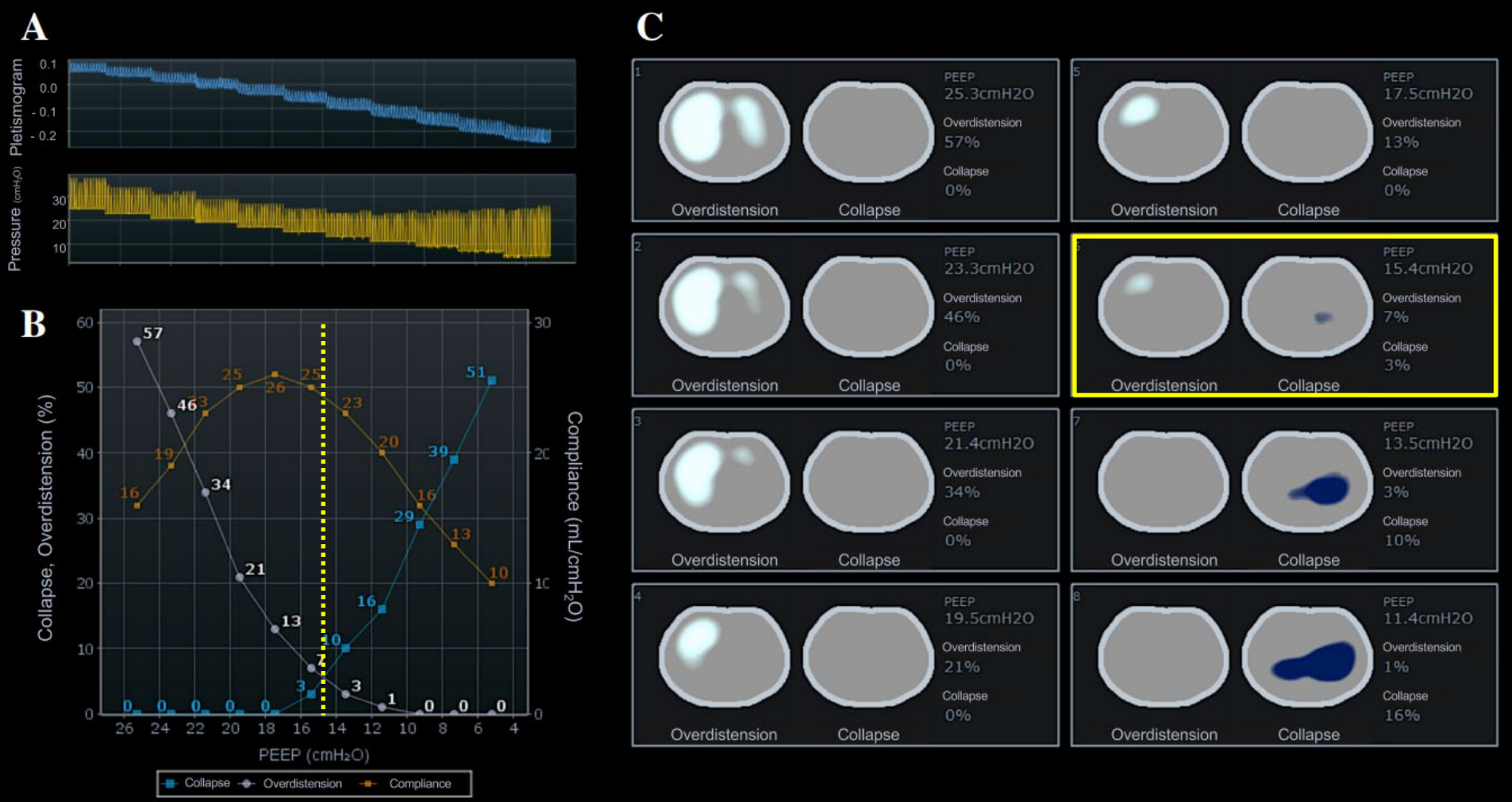
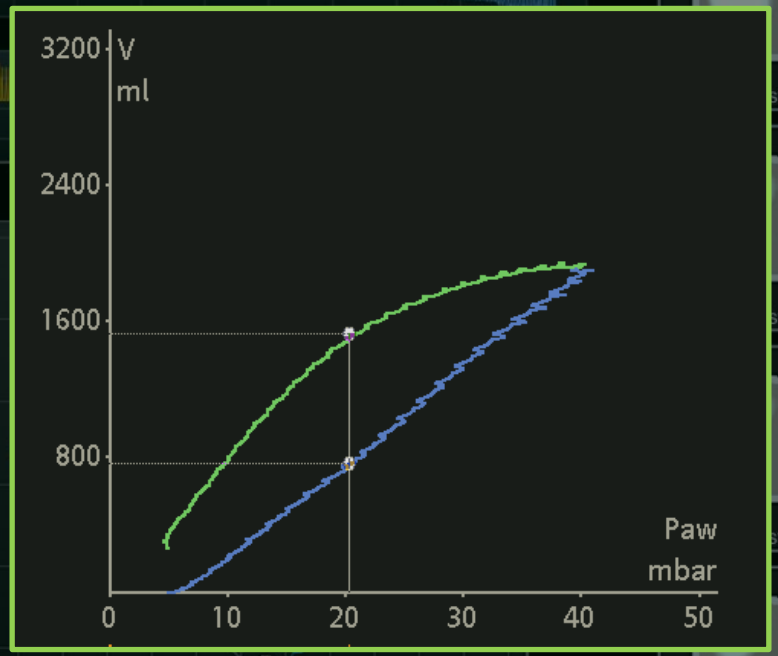

Best
Lower Cardiac Output ....
Right Ventricular Failure !!!!!
*p<0.001
Group
Low Overdistension
Crossing Point
Low Collapse
Percentage of lung area
100
75
50
25
0
22
20
18
16
14
12
10
8
6
4
2
PEEP, cmH2O


A
Pletismogram
0.1
0.0
- 0.1
- 0.2
Pressure (cmH2O)
30
20
10
B
Collapse, Overdistension (%)
Compliance (mL/cmH2O)
PEEP (cmH2O)
26 24 22 20 18 16 14 12 10 8 6 4
Collapse
Overdistension
Compliance
C
1
PEEP
25.3cmH2O
Overdistension
57%
Collapse
0%
Overdistension
Collapse
5
PEEP
17.5cmH2O
Overdistension
13%
Collapse
0%
Overdistension
Collapse
2
PEEP
23.3cmH2O
Overdistension
46%
Collapse
0%
Overdistension
Collapse
6
PEEP
15.4cmH2O
Overdistension
7%
Collapse
3%
Overdistension
Collapse
3
PEEP
21.4cmH2O
Overdistension
34%
Collapse
0%
Overdistension
Collapse
7
PEEP
13.5cmH2O
Overdistension
3%
Collapse
10%
Overdistension
Collapse
4
PEEP
19.5cmH2O
Overdistension
21%
Collapse
0%
Overdistension
Collapse
8
PEEP
11.4cmH2O
Overdistension
1%
Collapse
16%
Overdistension
Collapse


3200
V
ml
2400
1600
800
Paw
mbar
0
10
20
30
40
50

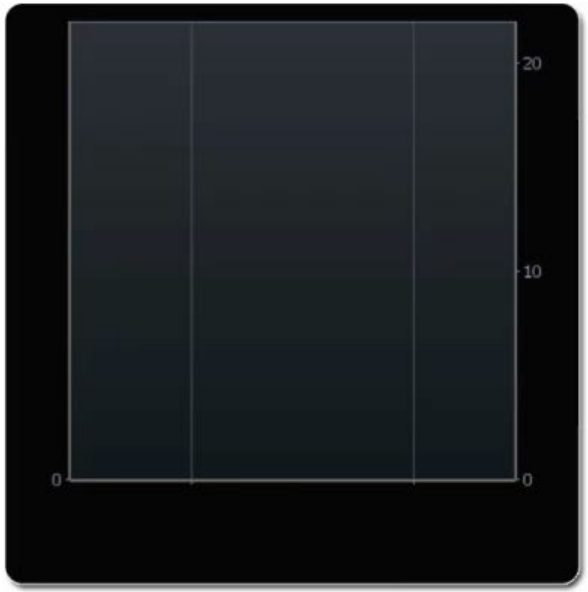
A
Pletismogram
Pressure (cmH2O)
0.1
0.0
- 0.1
- 0.2
30
20
10

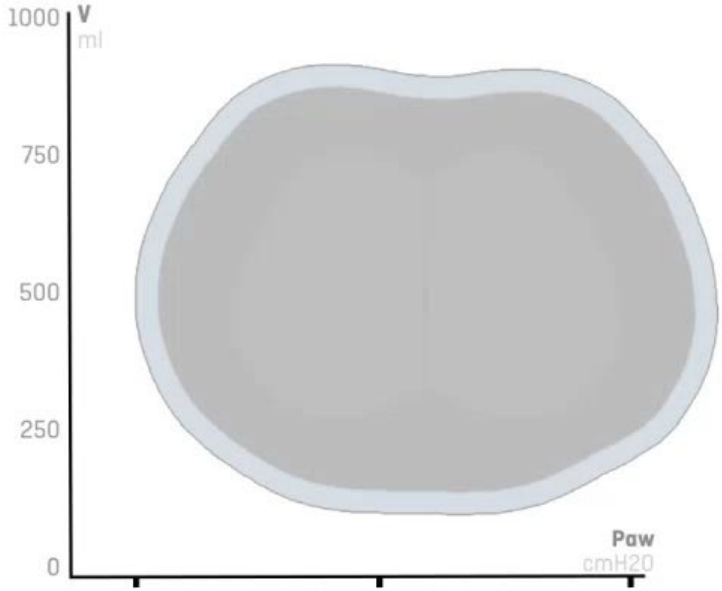
B
Collapse, Overdistension (%)
60
50
40
30
20
10
0
26 24 22 20 18 16 14 12 10 8 6 4
PEEP (cmH2O)
Collapse
Overdistension
Compliance

C
PEEP
25.3cmH2O
Overdistension
21%
Collapse
0%
Overdistension
Collapse
PEEP
17.5cmH2O
Overdistension
1%
Collapse
16%
Overdistension
Collapse

<60 seconds

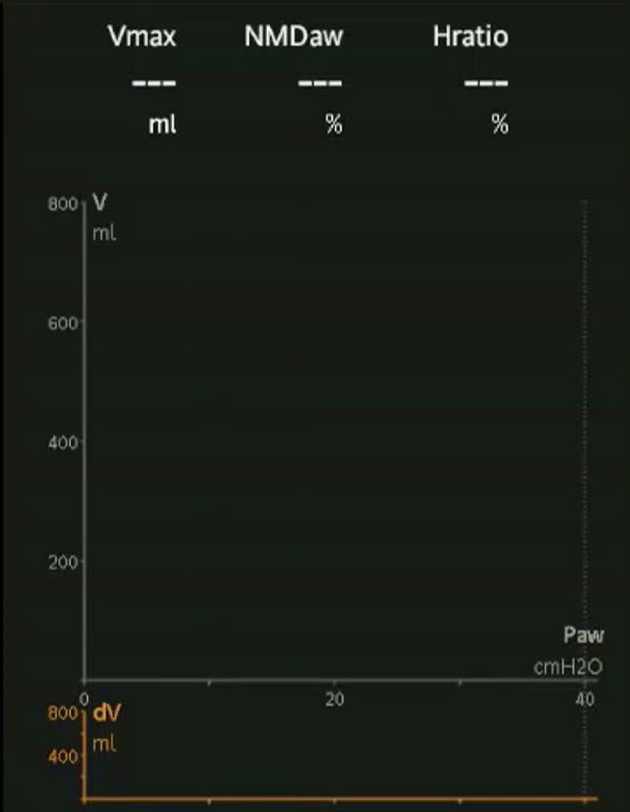
P/V Map



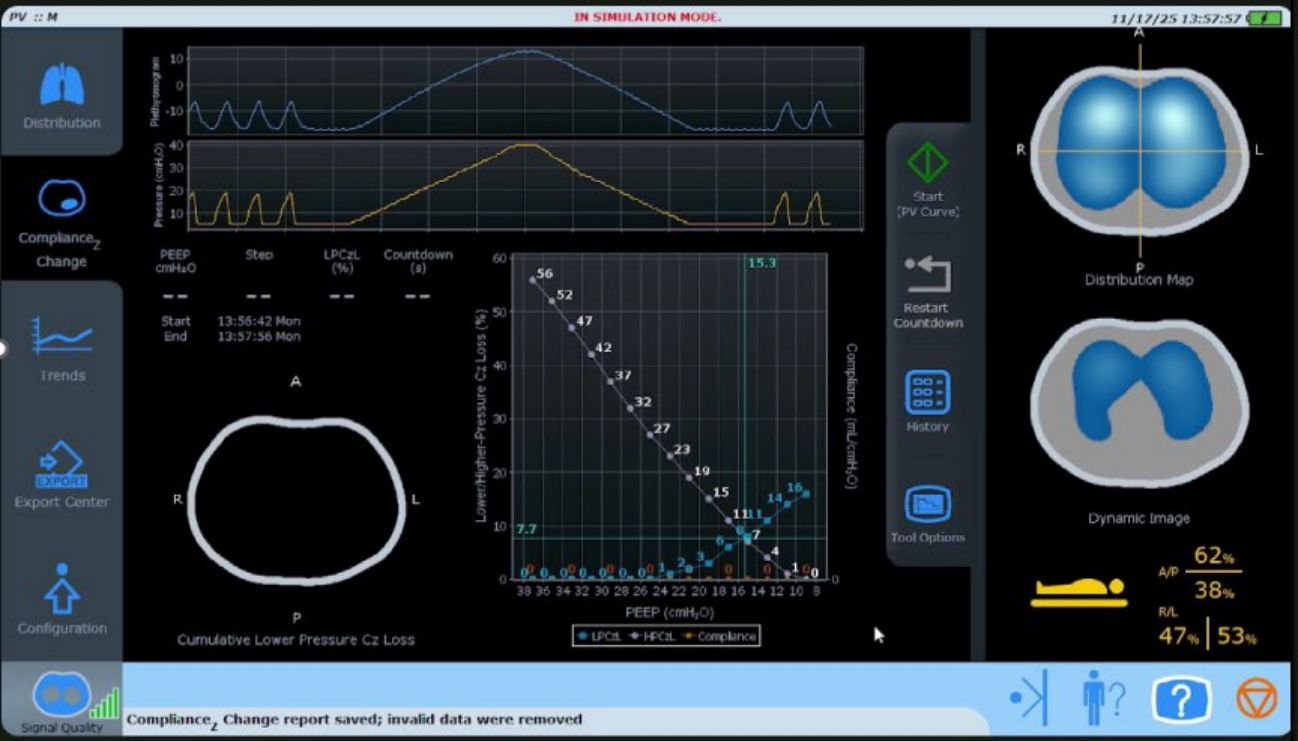


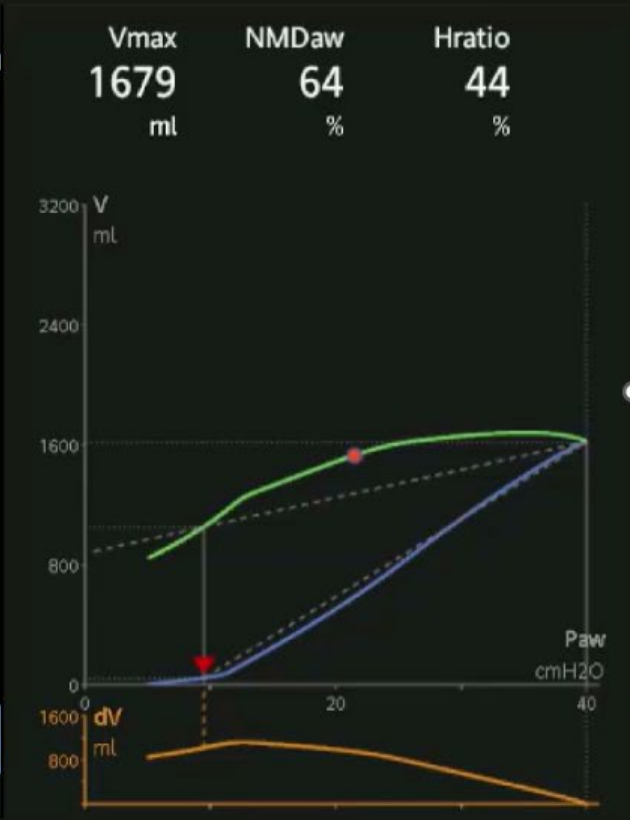
Individualized PEEP for all Patients!!!!!


PV :: M
IN SIMULATION MODE.
11/17/25 13:56:48
Distribution
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
Plethysmogram
Pressure (cmH2O)
PEEP cmH2O
Step
LPCzL (%)
Countdown (s)
5
Start
End
13:56:42 Mon
A
R
L
P
Cumulative Lower Pressure Cz Loss
Lower/Higher-Pressure Cz Loss (%)
Compliance (mL/cmH2O)
PEEP (cmH2O)
LPCzL
HPCzL
Compliance
Stop (PV Curve)
Restart Countdown
History
Tool Options
Distribution Map
Dynamic Image
A/P
R/L

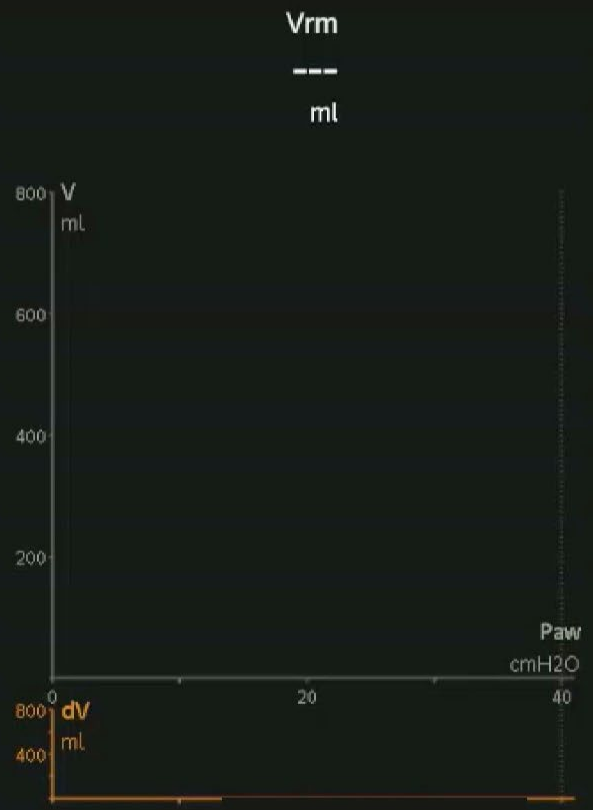

Vmax
NMDaw
Hratio

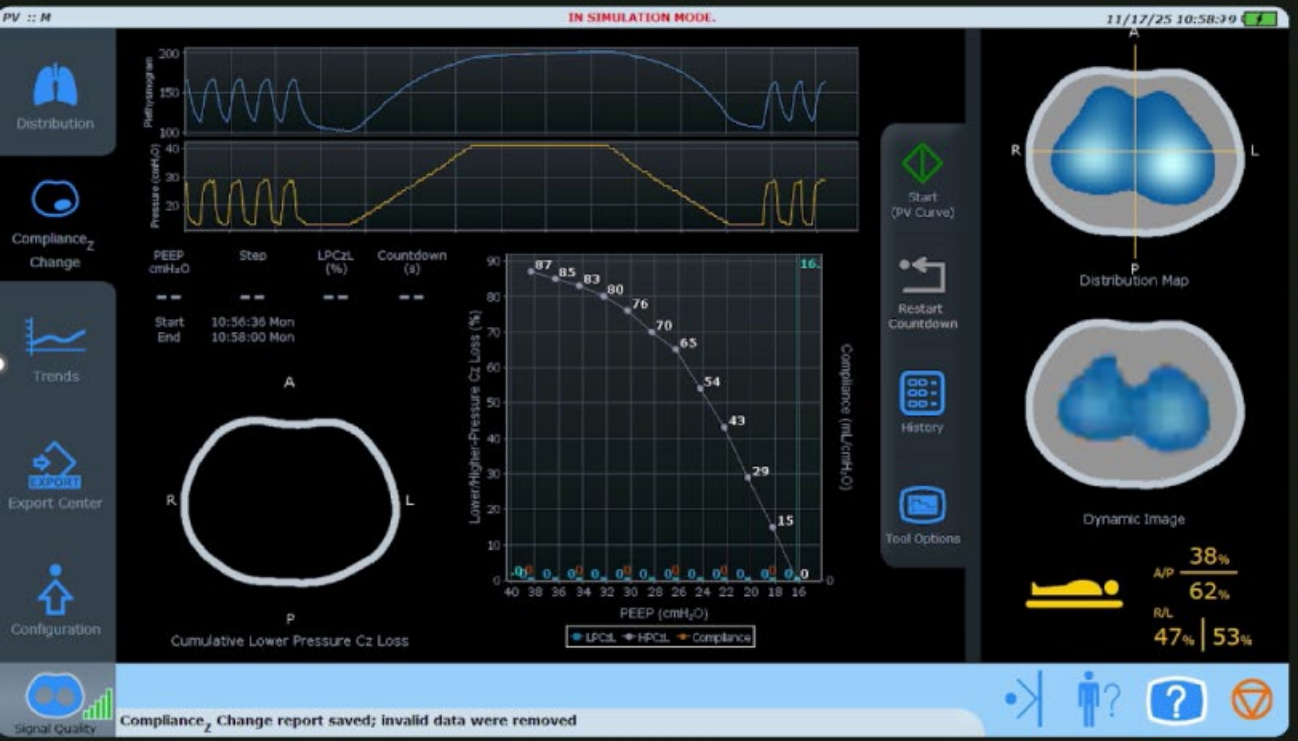
---
ml
%
%
V
ml
800
600
400
200
Paw
cmH2O
0
20
40
dV
ml
800
400

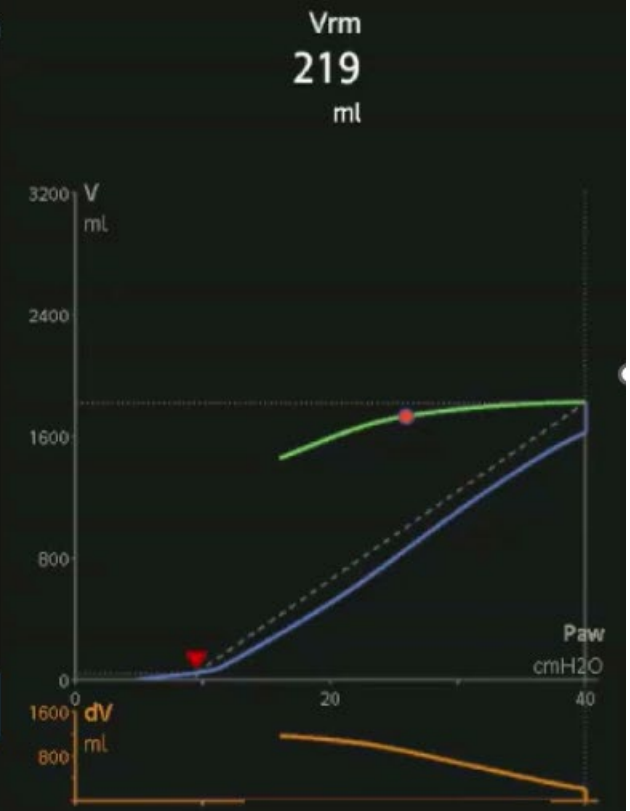

PV :: M
IN SIMULATION MODE.
11/17/25 13:57:57
Distribution
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
Plethysmogram
Pressure (cmH2O)
PEEP cmH2O
Step
LPCzL (%)
Countdown (s)
Start 13:56:42 Mon
End 13:57:56 Mon
A
R
L
P
Cumulative Lower Pressure Cz Loss
Lower/Higher-Pressure Cz Loss (%)
Compliance (mL/cmH2O)
15.3
7.7
PEEP (cmH2O)
LPCzL
HPCzL
Compliance
Start (PV Curve)
Restart Countdown
History
Tool Options
Distribution Map
Dynamic Image
A/P 62% 38%
R/L 47% 53%
Compliance Z Change report saved; invalid data were removed


Vmax
1679
ml
NMDaw
64
%
Hratio
44
%
3200
2400
1600
800
0
V
ml
Paw
cmH2O
20
40
dV
ml


PV :: M
IN SIMULATION MODE.
11/17/25 10:56:56
Distribution
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
Plethysmogram
Pressure (cmH2O)
PEEP cmH2O
Step
LPCzL (%)
Countdown (s)
13
Start
End
10:56:36 Mon
Cumulative Lower Pressure Cz Loss
Lower/Higher-Pressure Cz Loss (%)
Compliance (mL/cmH2O)
PEEP (cmH2O)
LPCzL
HPCzL
Compliance
Stop (PV Curve)
Restart Countdown
History
Tool Options
Distribution Map
Dynamic Image
A/P
64%
36%
R/L
32%
68%


Vrm
---
ml
V
ml
800
600
400
200
Paw
cmH2O
0
20
40
dV
ml
800
400


PV :: M
IN SIMULATION MODE.
11/17/25 10:58:39
Distribution
Compliance Z Change
Trends
Export Center
Configuration
Signal Quality
Pressure (cmH2O)
PEEP cmH2O
Step
LPCzL (%)
Countdown (s)
Start 10:56:36 Mon
End 10:58:00 Mon
A
R
L
P
Cumulative Lower Pressure Cz Loss
Lower/Higher-Pressure Cz Loss (%)
Compliance (mL/cmH2O)
PEEP (cmH2O)
LPCzL
HPCzL
Compliance
Start (PV Curve)
Restart Countdown
History
Tool Options
Distribution Map
Dynamic Image
A/P
38%
62%
R/L
47%
53%
Compliance Z Change report saved; invalid data were removed


Vrm
219
ml
V
ml
3200
2400
1600
800
0
Paw
cmH2O
20
40
dV
ml
1600
800

Thank you for your attention

David Grooms RRT, MSHS

Clinical Operations Director

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