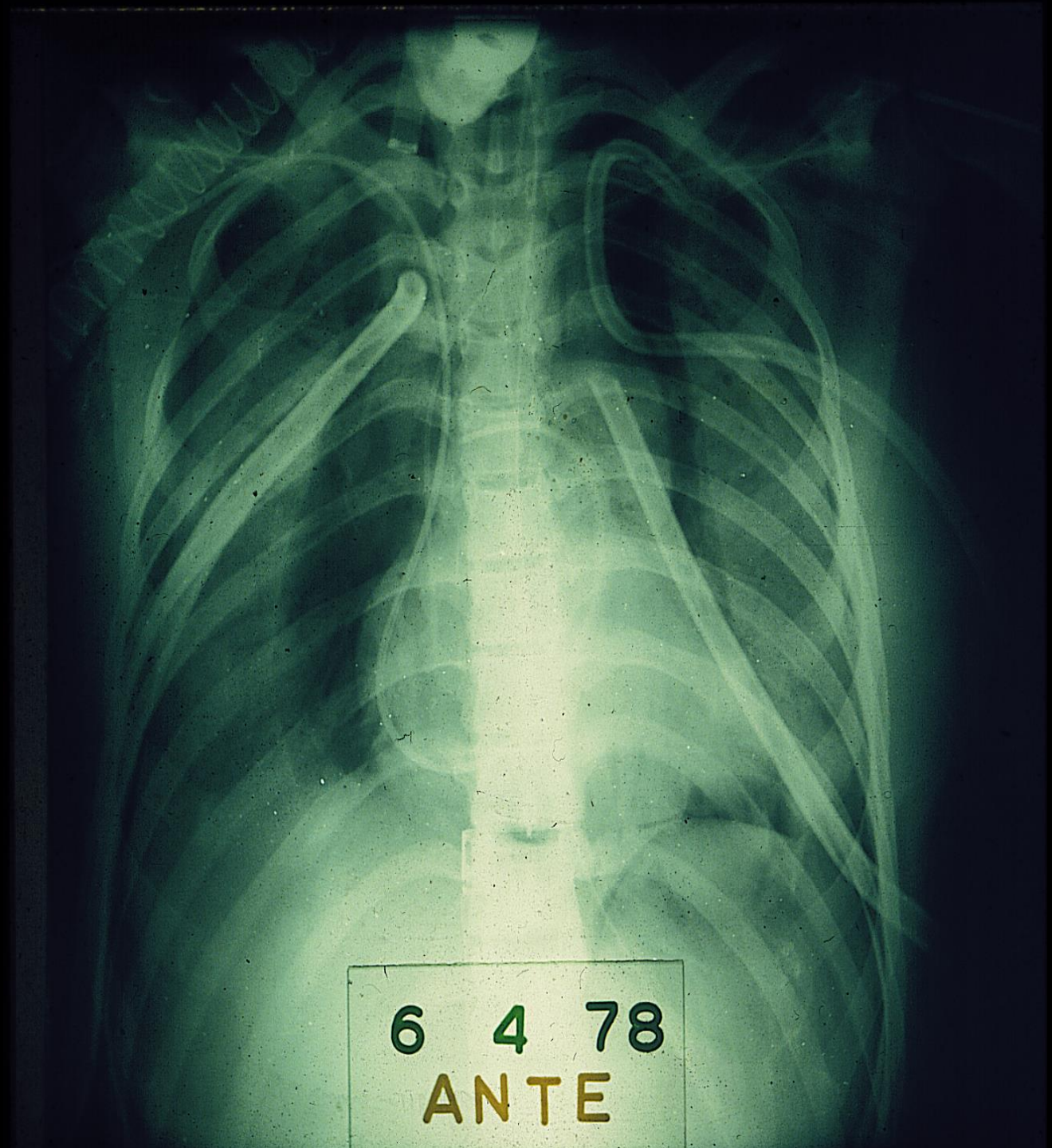
ARDS and VILI

CEEA 2015, Kosice

Luciano Gattinoni, MD, FRCP
Università di Milano
Fondazione IRCCS Ca' Granda
Ospedale Maggiore Policlinico
Milan, Italy


Stress and Strain
F
b
a
S=a*b
l_0
ΔL
σ=F/S
Transpulmonary pressure
ε=ΔL/L_0
V_TEELV


6 4 78
ANTE

VILI

What is due to the ventilator/ventilation:

- Tidal Volume
- Pressure change
- Flow rate
- Respiratory rate

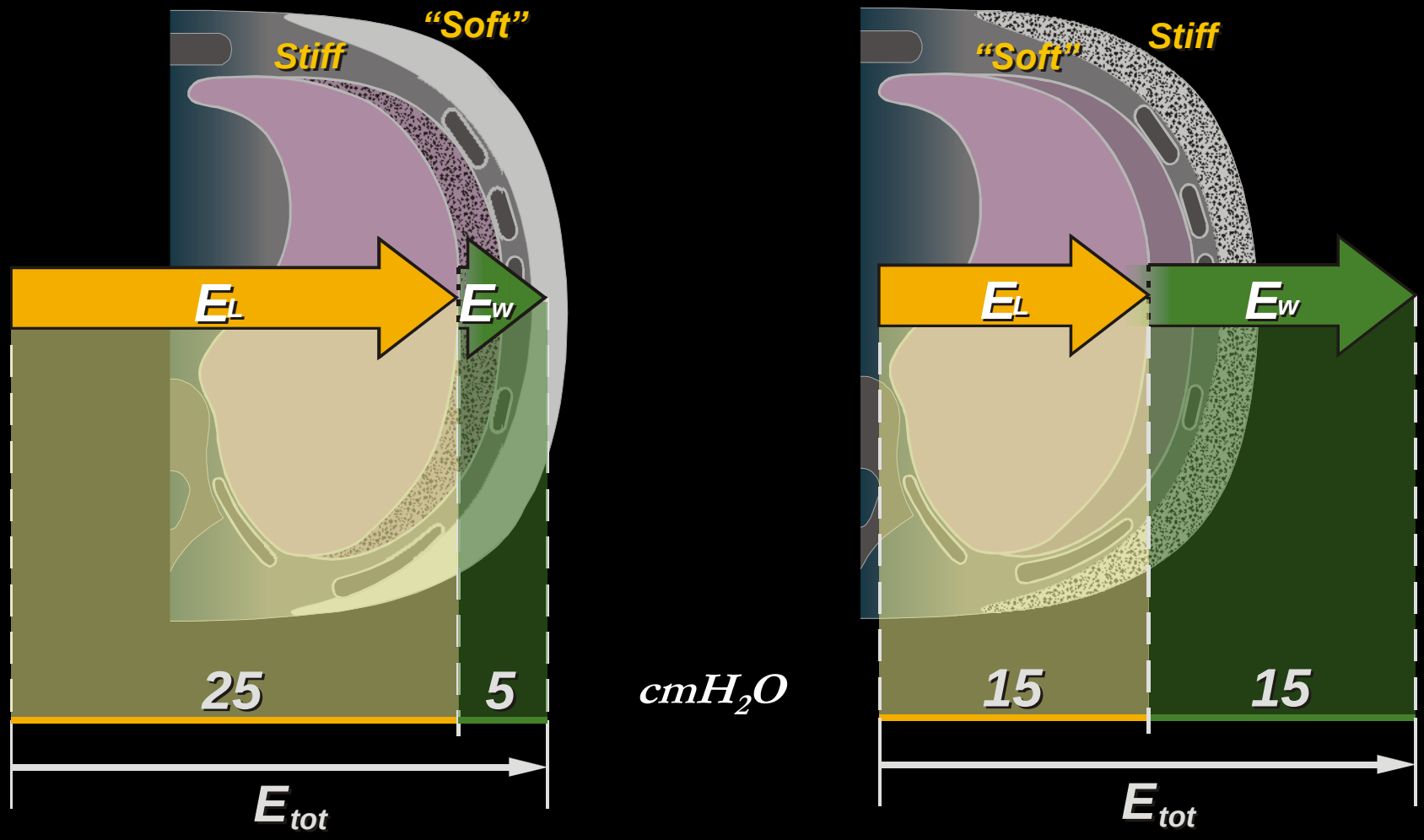
Pressure change, Flow rate → Energy

Tidal Volume, Energy → Power

What is due to the lung:

- Lung inhomogeneity
- Stress risers

Chest wall elastance



Driving pressure

On the ventilator → Paw

Paw = P_L

Drive the lungs → Transpulmonary pressure

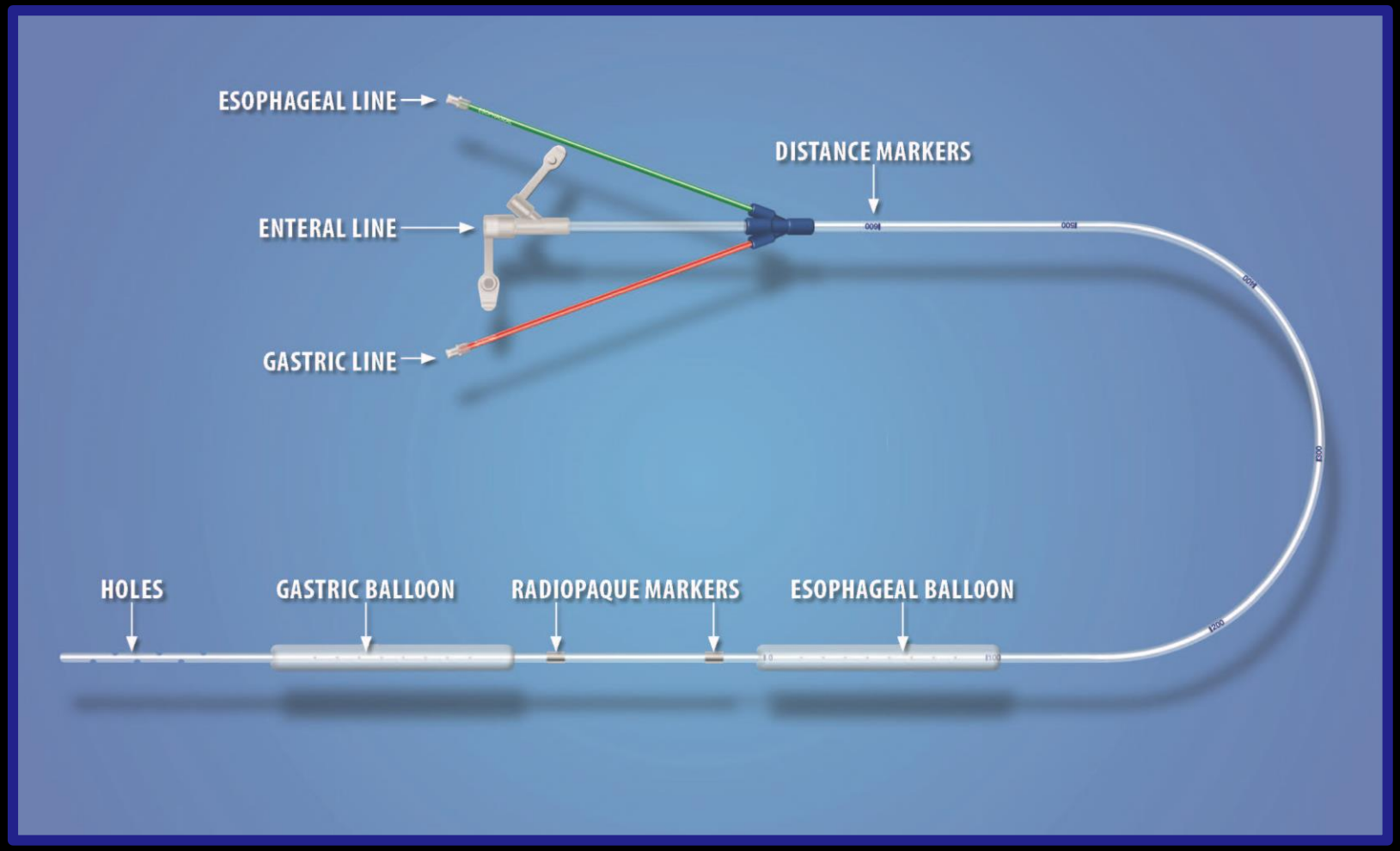
P_L + Ppl

Drive the chest wall → Pleural pressure

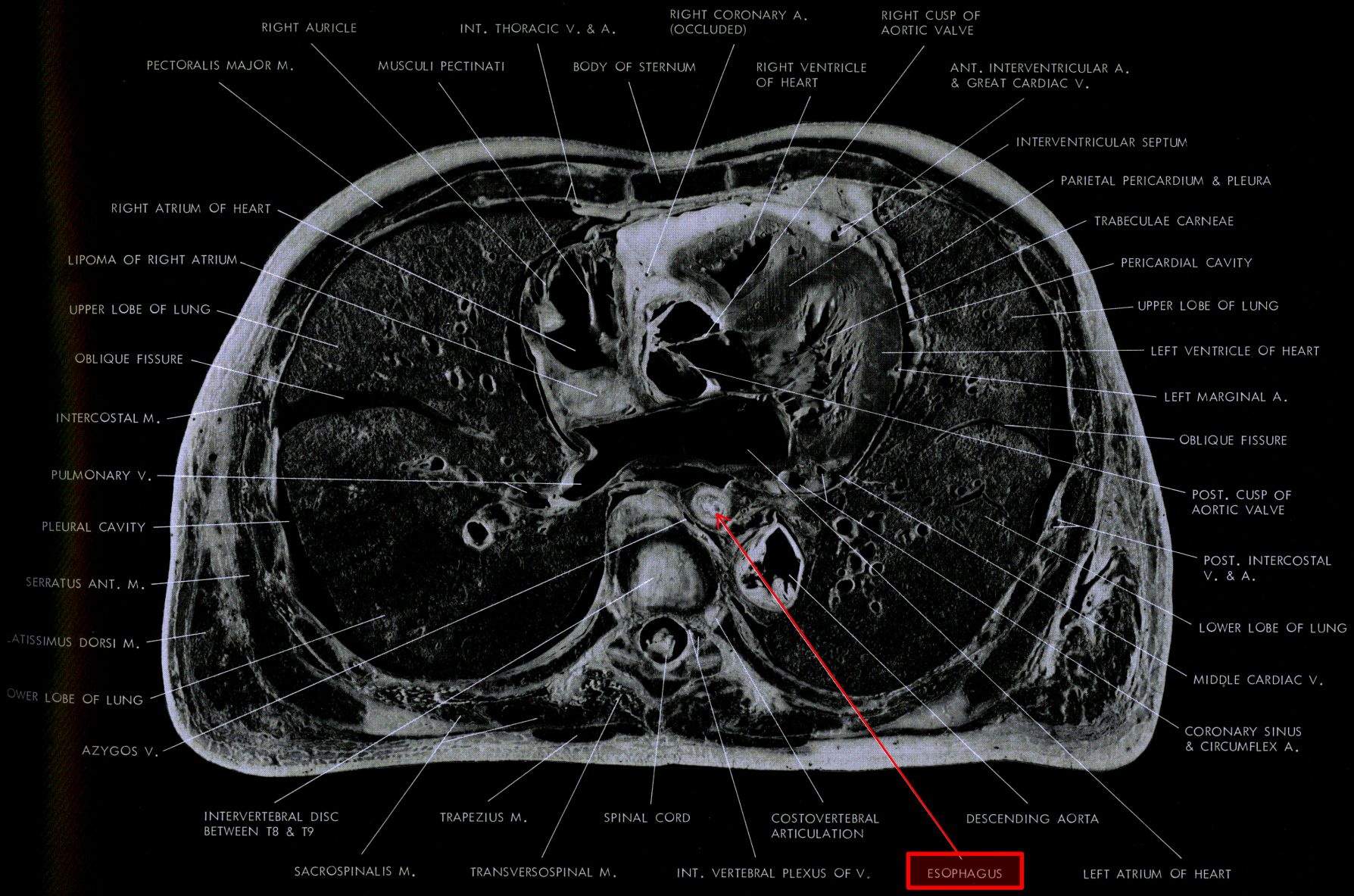
Ppl

How to measure the pleural pressure

Esophageal and gastric baloon

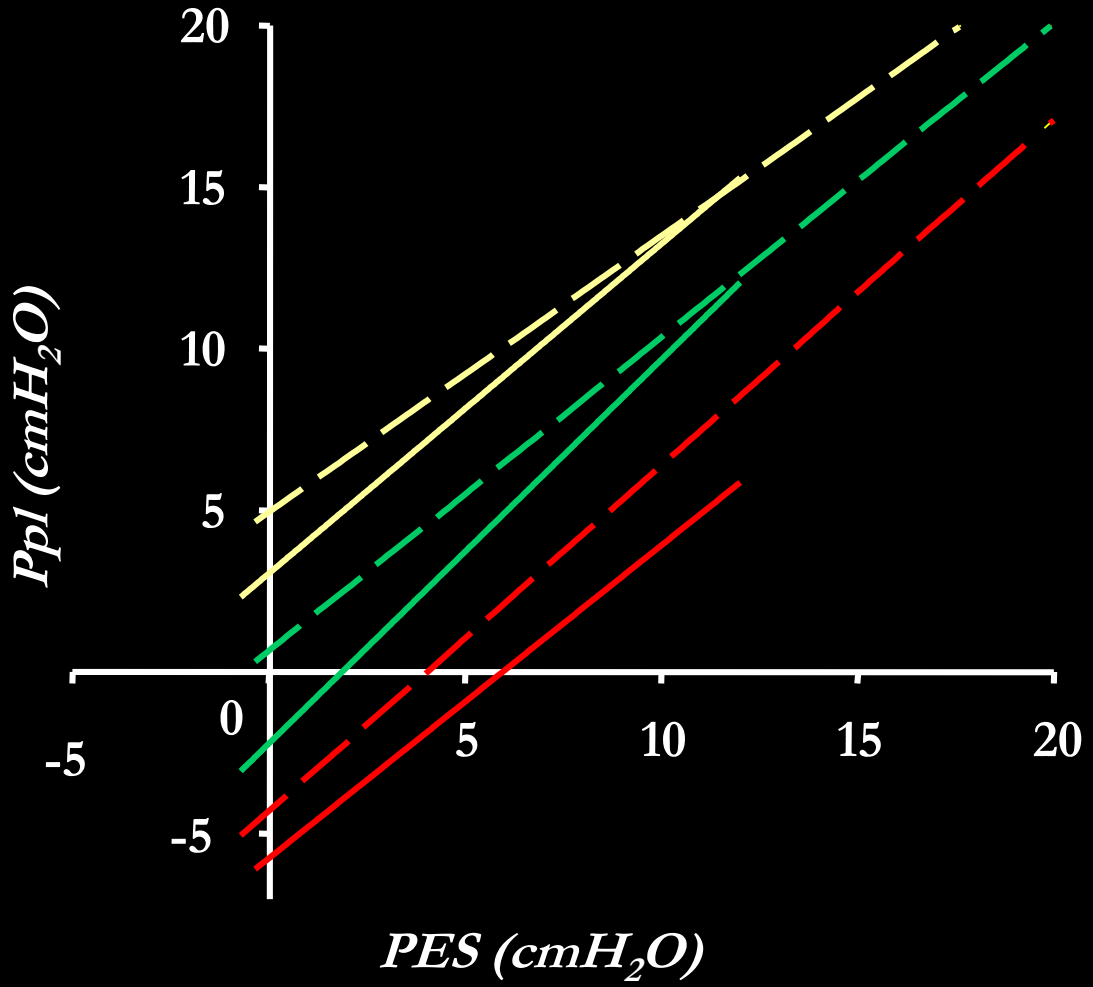


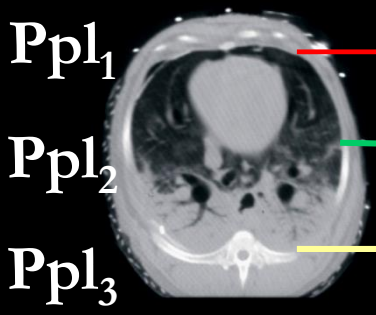
Anatomical section of a frozen cadaver between the thoracic vertebra 8 and 9



Bo WJ, Wolfman NT, Krueger WA, Meschan I. 1990.
Basic Atlas of Sectional Anatomy with Correlated Imaging. 2nd edition; WB Saunders Co. page 99

PES and Ppl





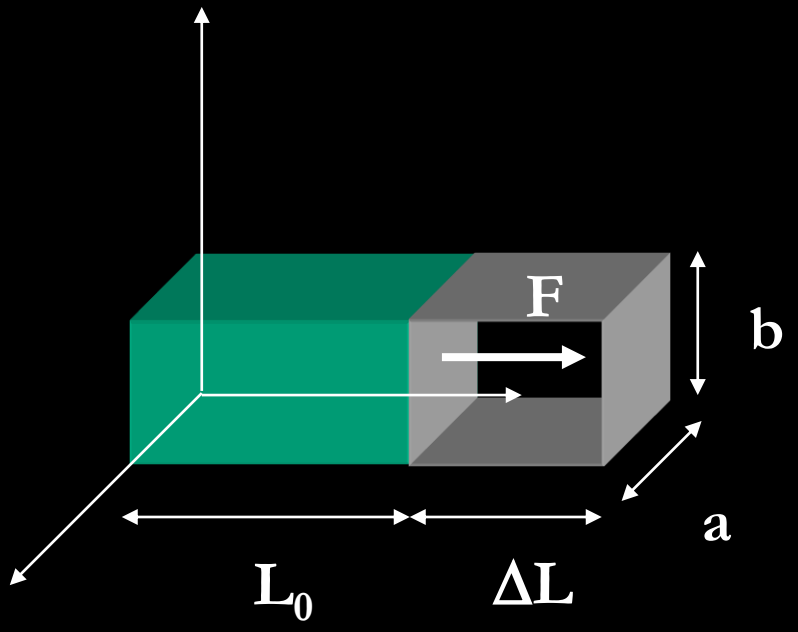
Inspiratory

Expiratory

6 dogs, oleic acid

Pelosi et al. Am J Respir Crit Care Med pp 122-130, 2001

Stress and Strain



$S=a*b$

Stress → $\sigma=F/S$ Transpulmonary pressure

Strain → $\varepsilon=\Delta L/L_0$ V_T/EELV

Clinical equivalents

Stress ≈ PL transpulmonary pressure

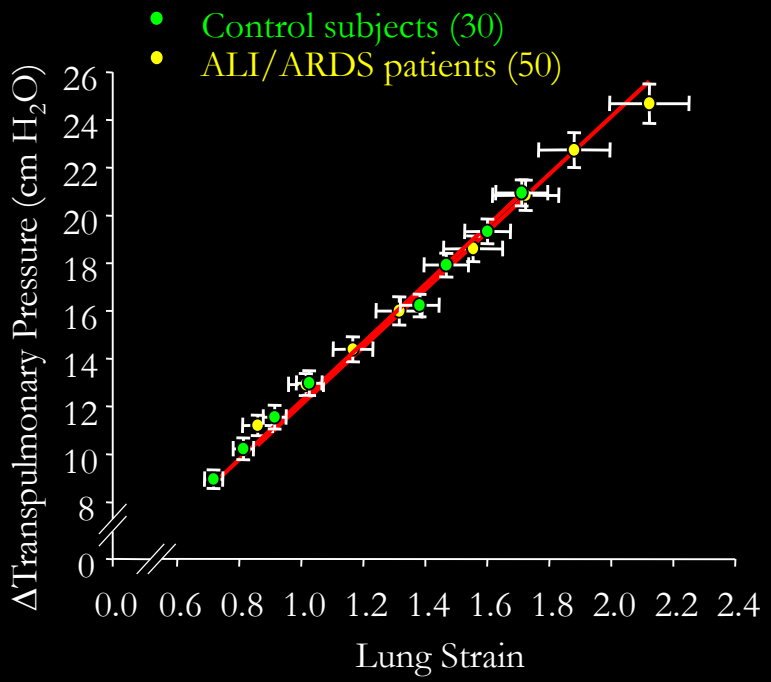
Strain ≈ V_T / FRC

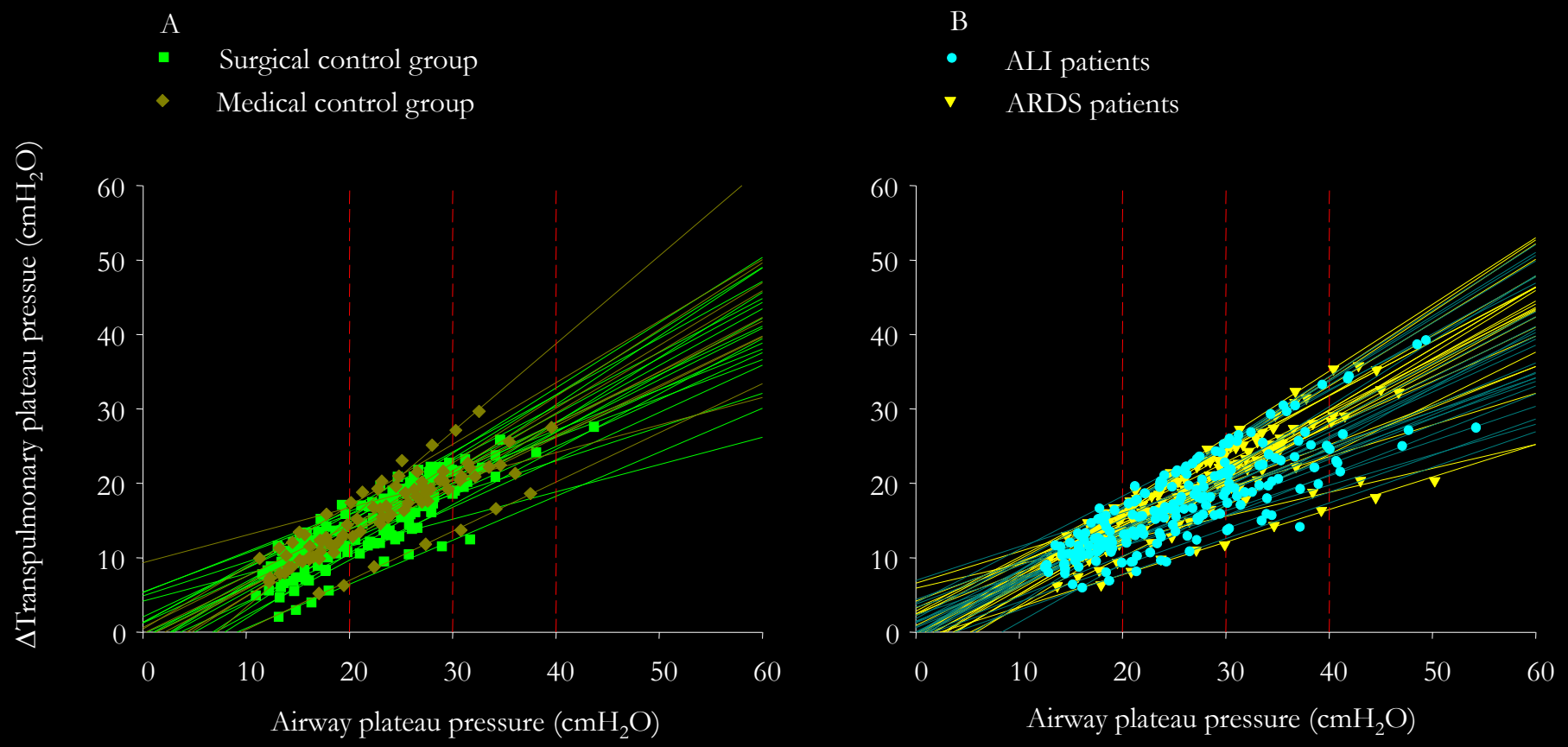
The linkage is the specific elastance

$$PL = E_{lspec} * \frac{V_T}{FRC}$$

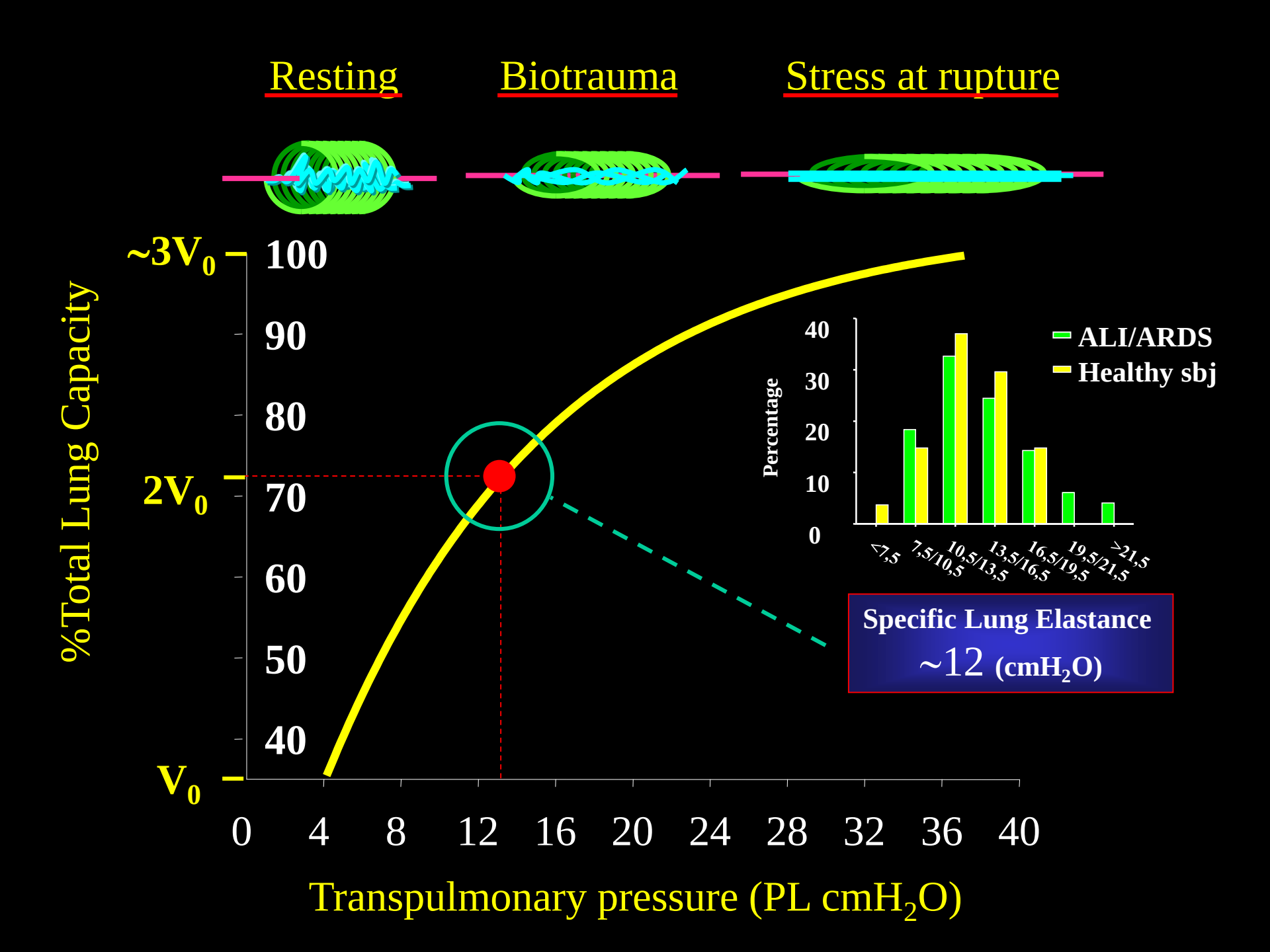
Barotrauma **Volotrauma**

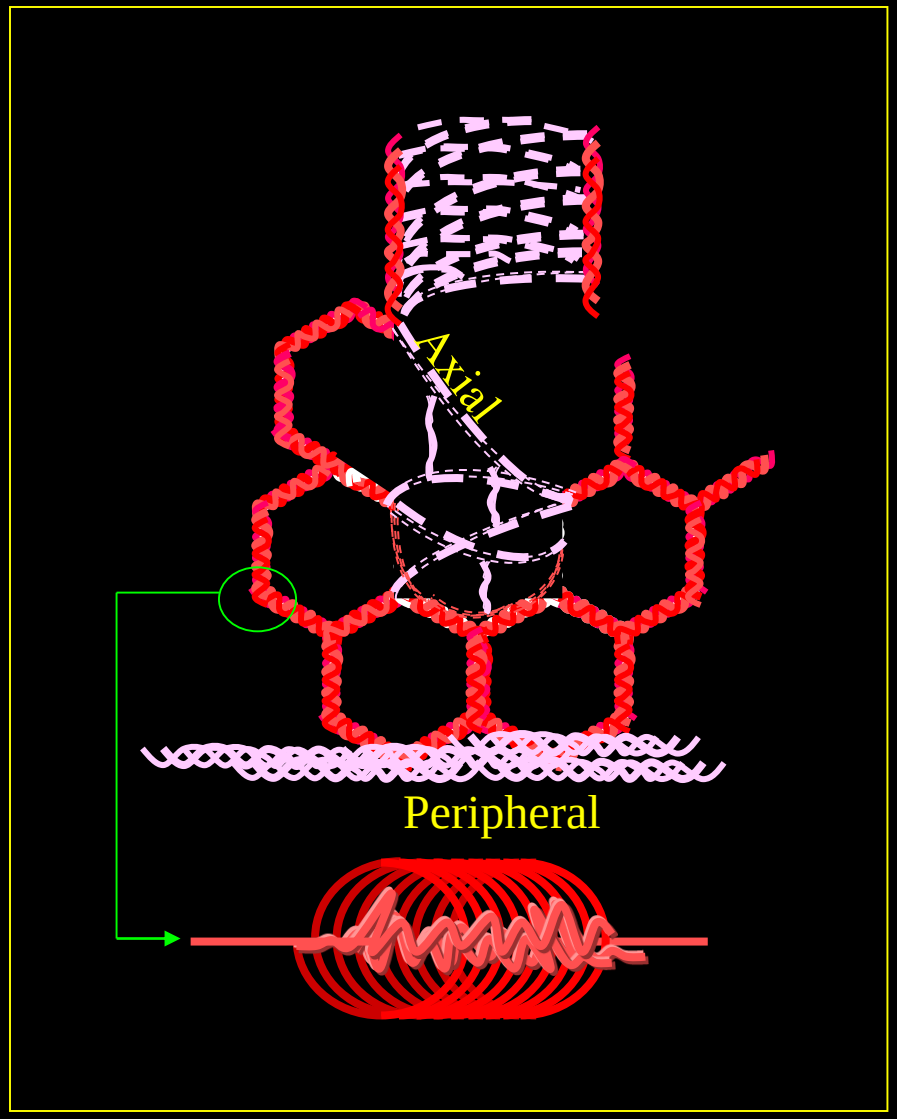
Specific lung elastance in ARDS is ≅ normal



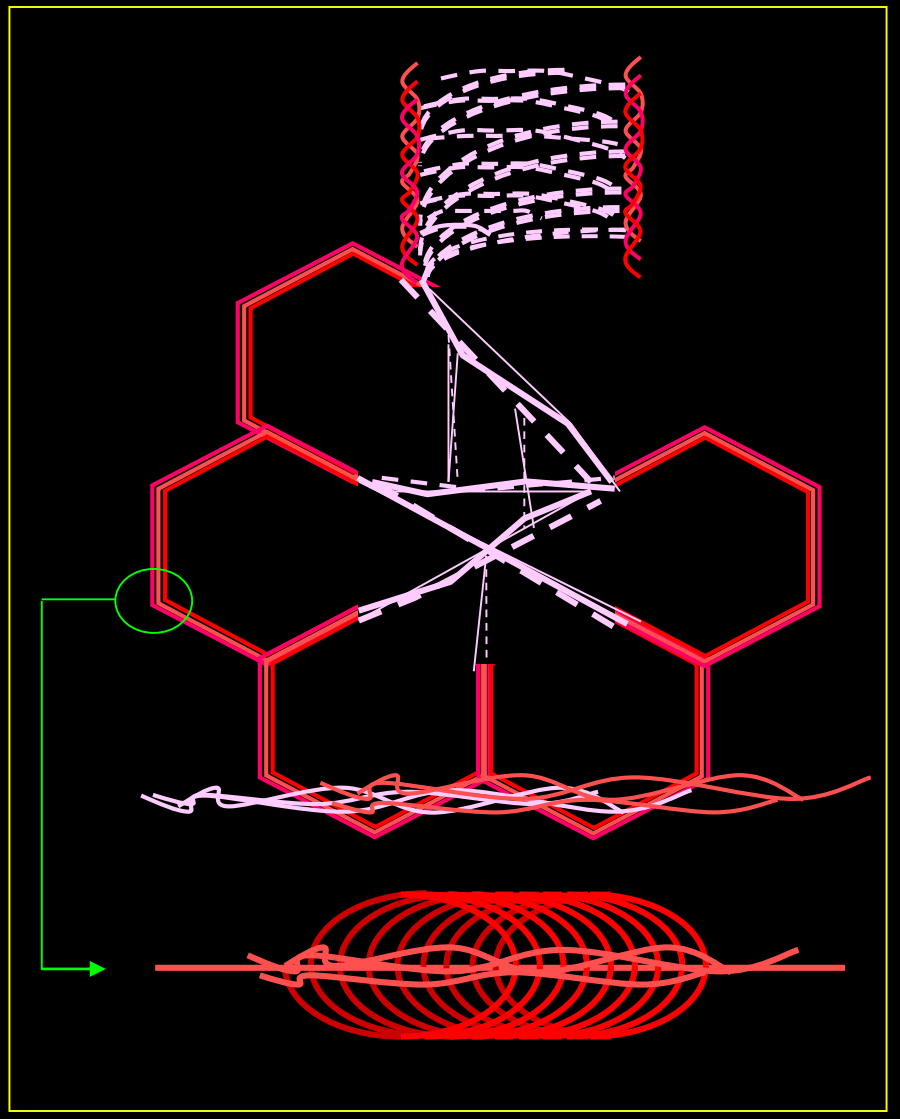


Chiumello et al, Am J Respir Crit Care Med. 2008


Resting
Biotrauma
Stress at rupture
~3V0
2V0
V0
100
90
80
70
60
50
40
%Total Lung Capacity
0
4
8
12
16
20
24
28
32
36
40
Transpulmonary pressure (PL cmH2O)
Percentage
40
30
20
10
0
≤7,5
7,5/10,5
10,5/13,5
13,5/16,5
16,5/19,5
19,5/21,5
>21,5
ALI/ARDS
Healthy sbj
Specific Lung Elastance
~12 (cmH2O)

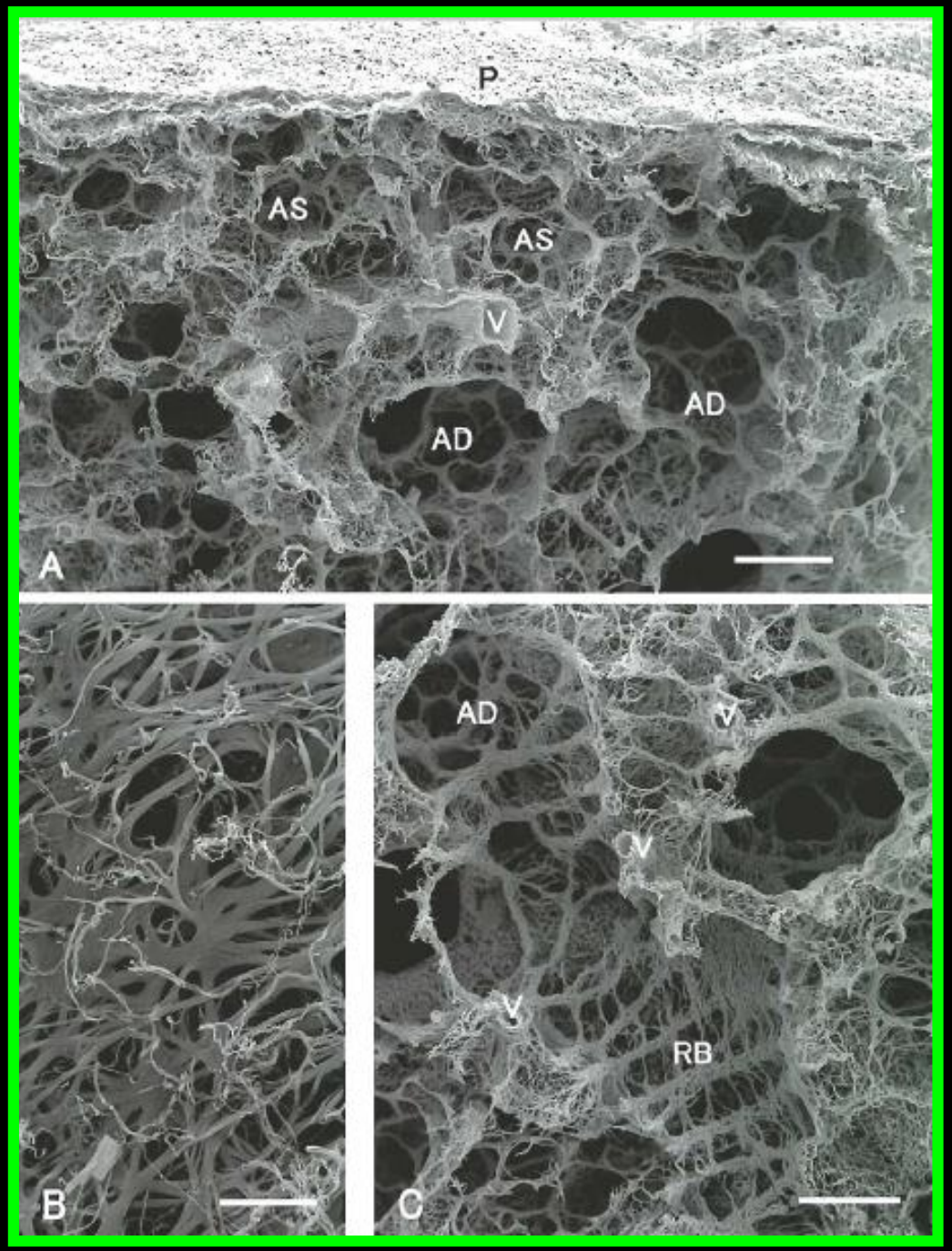


FRC



80% TLC

AS =alveolar sac
P=pleura
V=blood vessel



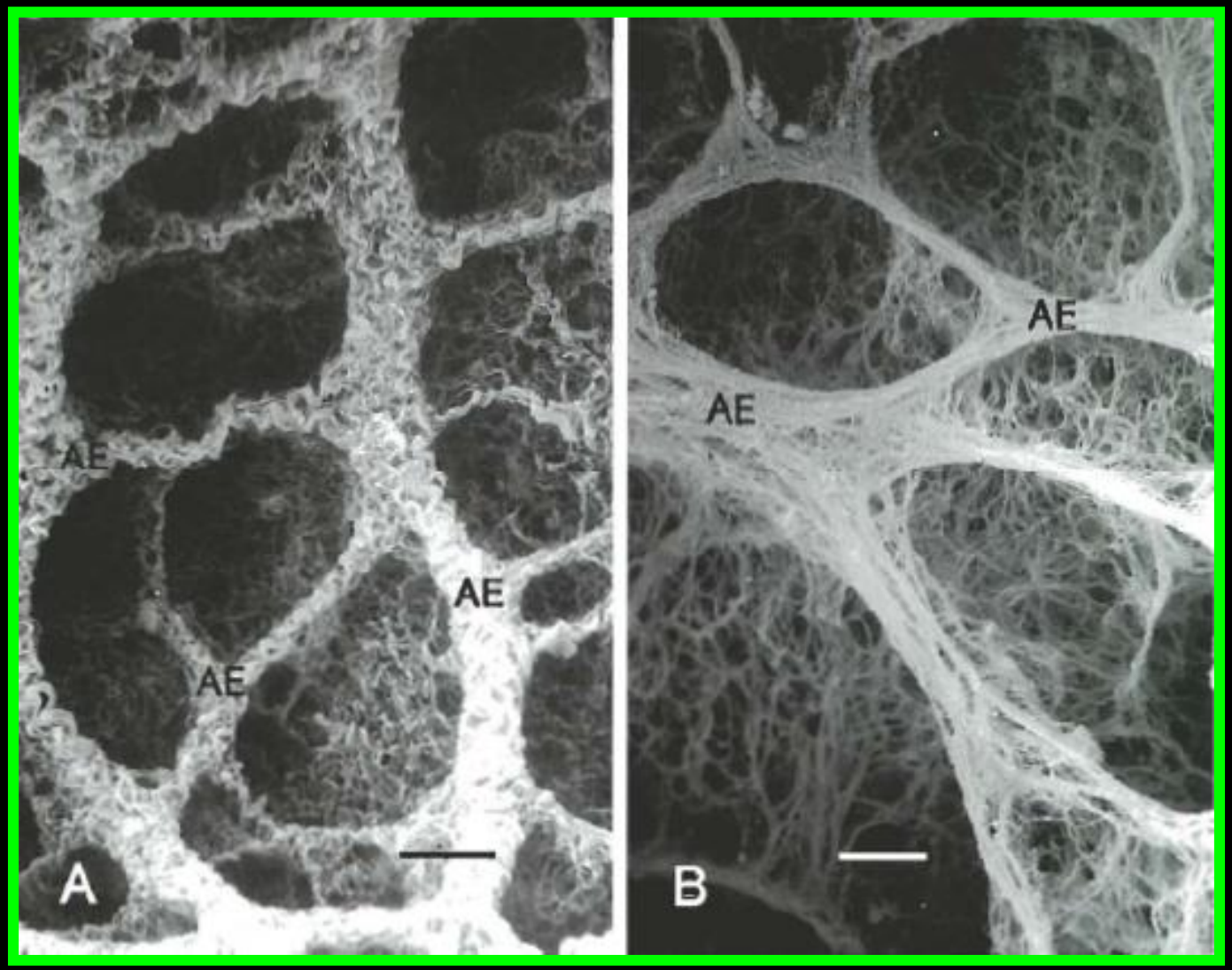
Continuum of elastin fiber network (scale bar 200 μm)

Elastin fiber network in the outer surface of the pleura (scale bar 10 μm)

Elastin fiber network in the respiratory bronchioli (RB) and in the alveolar duct (AD) (scale bar 200 μm)

Toshima et al. Arch Histol Cytol. 67(1):31-40 (2004)

Collagen fiber network in rat lung



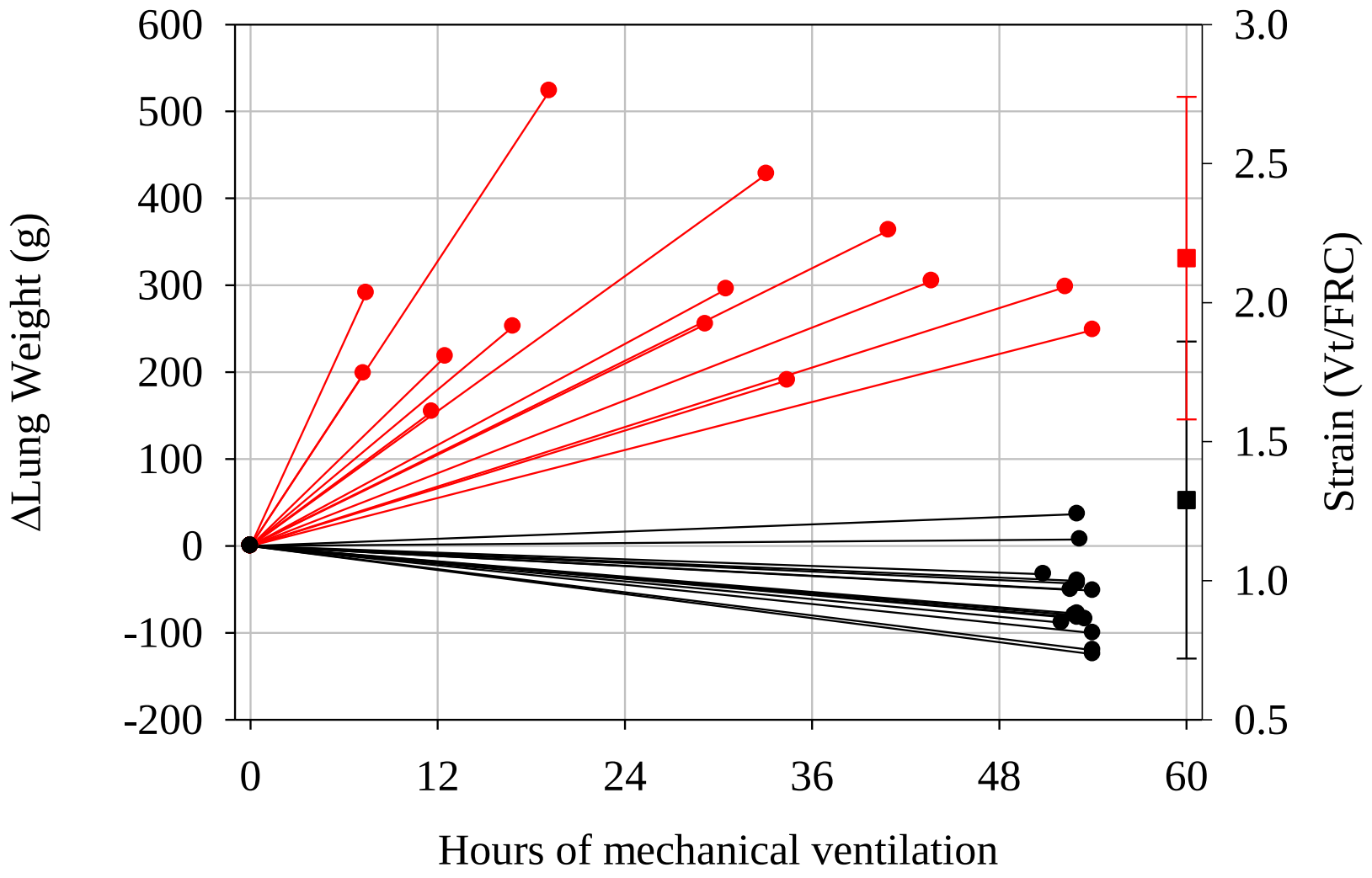
Collapsed

Inflated

AE =alveolar entrances
(scale bar 100 μm)

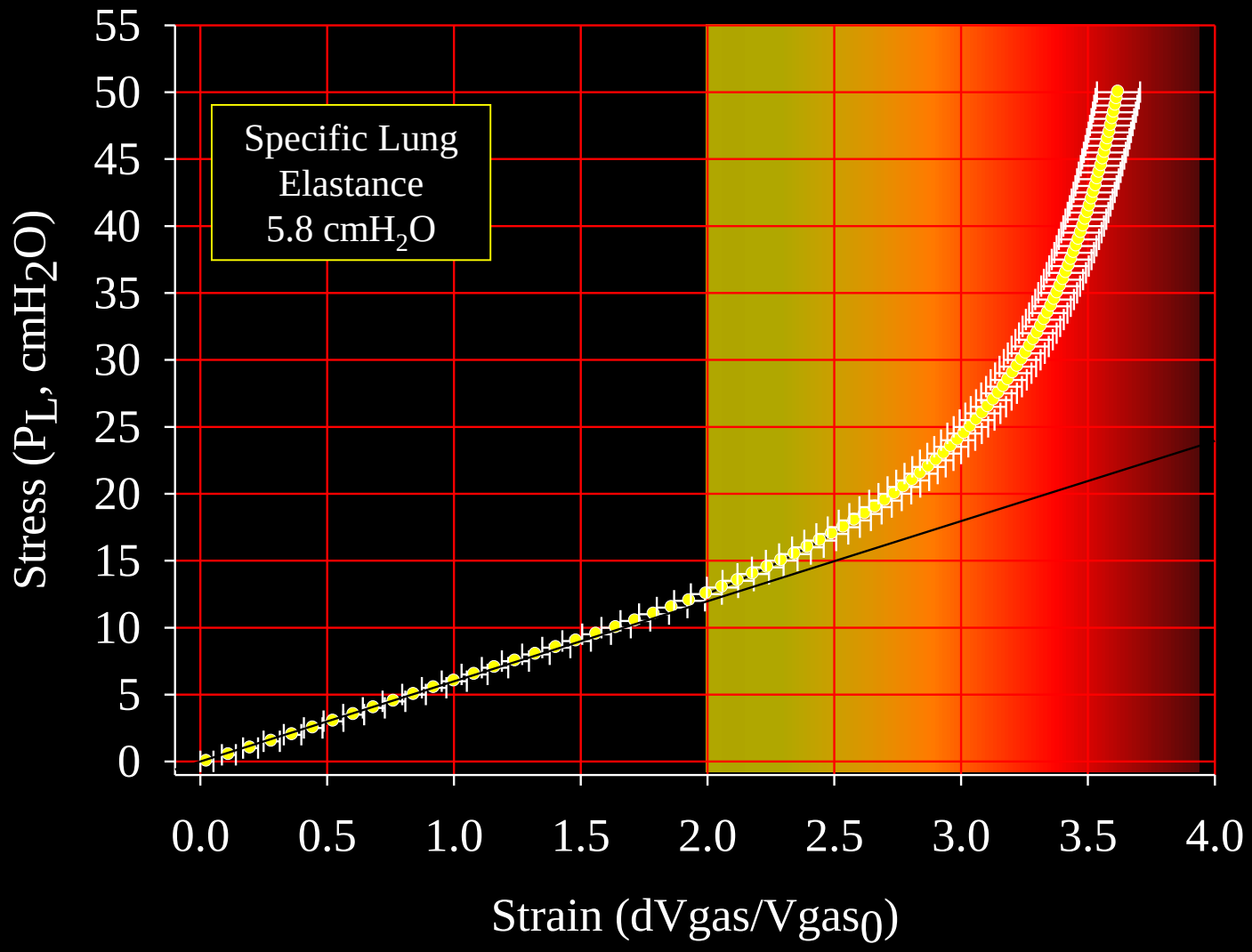
Toshima et al. Arch Histol Cytol. 67(1):31-40 (2004)

Time course of ventilator induced lung injury



Protti A. et al. Am J Respir Crit Care Med. 2011 Feb 4.

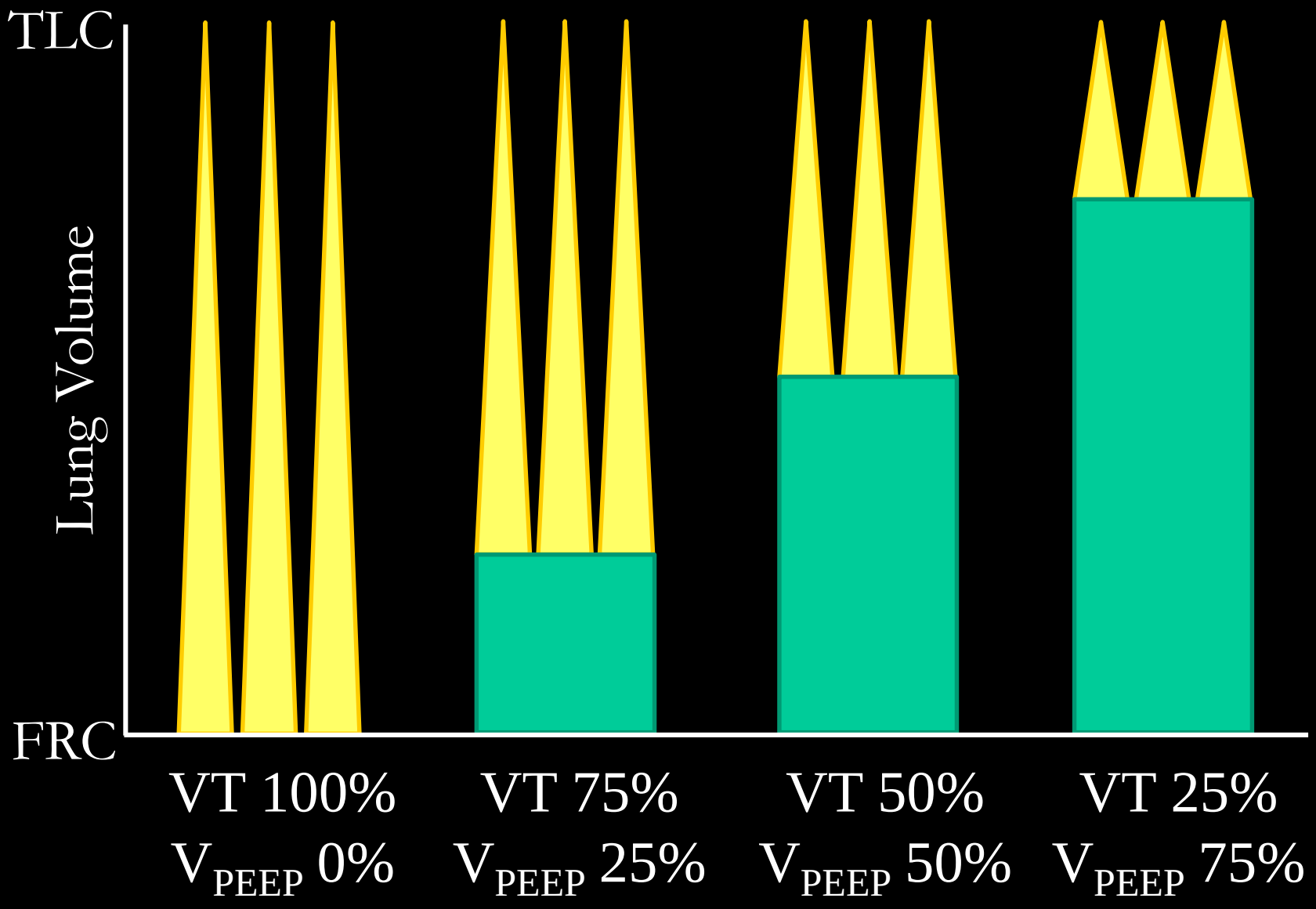
Stress-strain curve of healthy pigs



Protti A. et al. Am J Respir Crit Care Med. 2011 Feb 4.

Volumes and Pressures

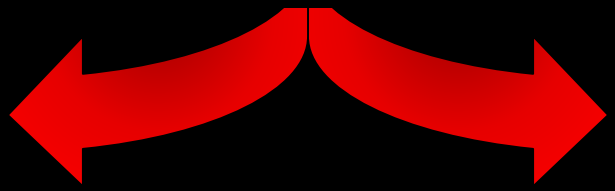
	FRC [mL]	TLC [mL]	TLC/FRC	Espec [cmH_2O]	PL to TLC [cmH_2O]
MICE	0.3-0.5	1-1.5	2-2.3	?	?
RATS	2.5-3	10	2-3	4	8-12
PIGS	300	780	2.6	6	15.6
MEN	2200	7000	2.2	12	26.4



Protti et al. Crit Care Med. 2013 Feb 4.

Tidal Strain

$P*\Delta V$ = Energy Input



Dissipated

- Surface Tension
- Sliding EM
- Opening and Closing

Undissipated

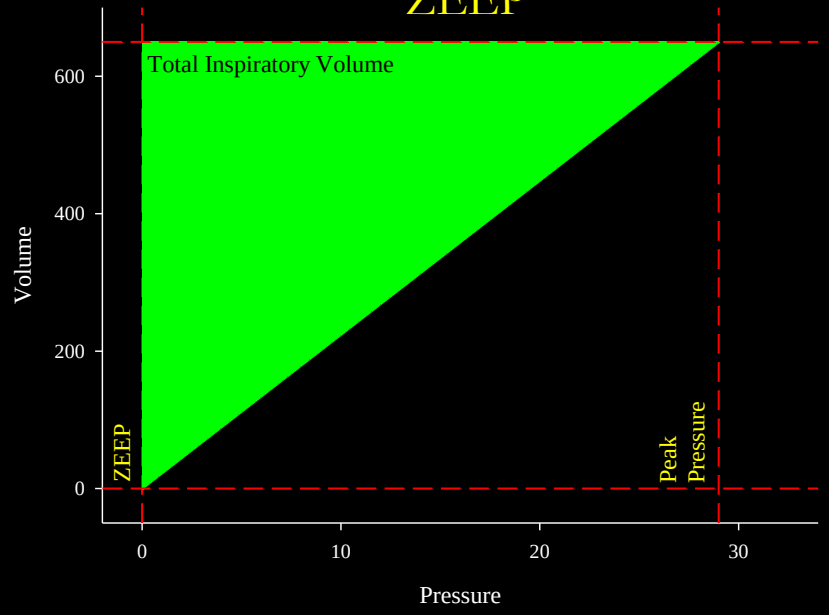
- Elastic System

Continuous Strain

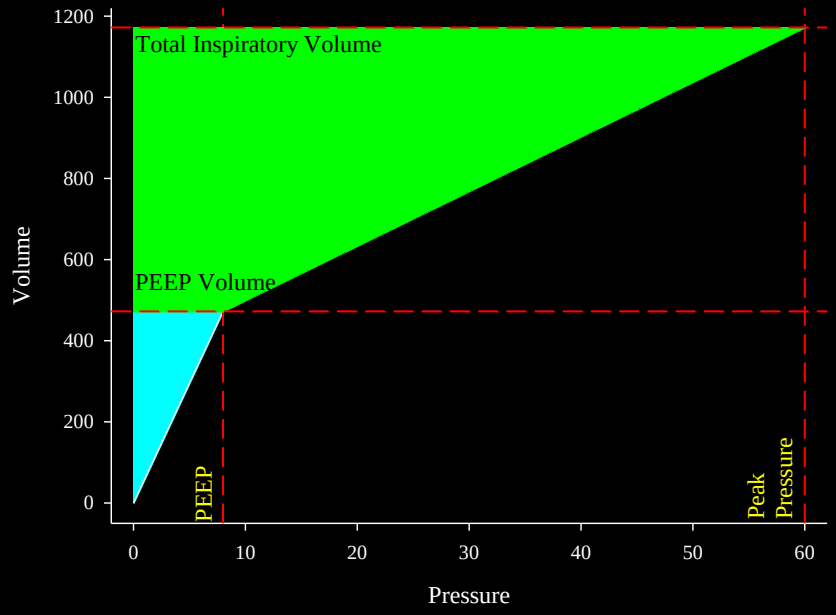
PEEP $*\Delta V$ = Energy Input = 0

EXAPLES OF ENERGY COMPUTATIONS AT DIFFERENT PRESSURES

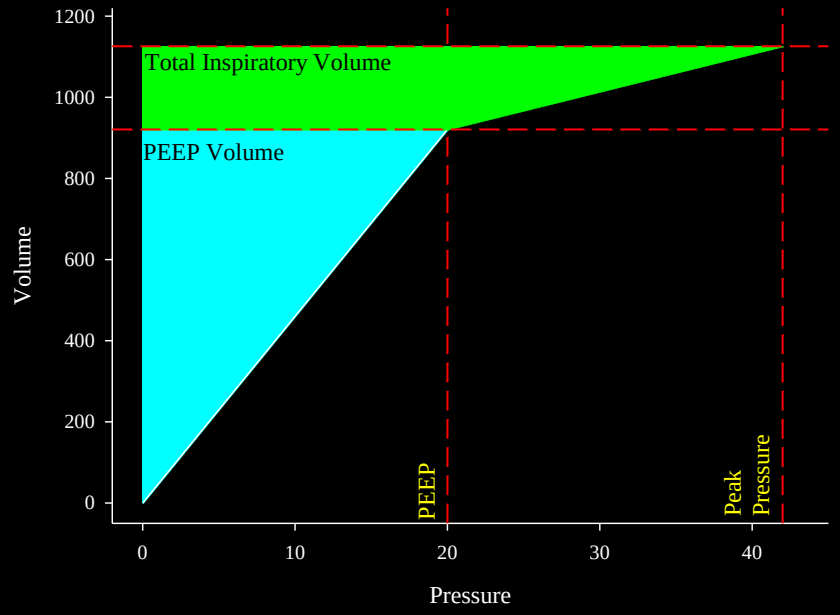
ZEEP



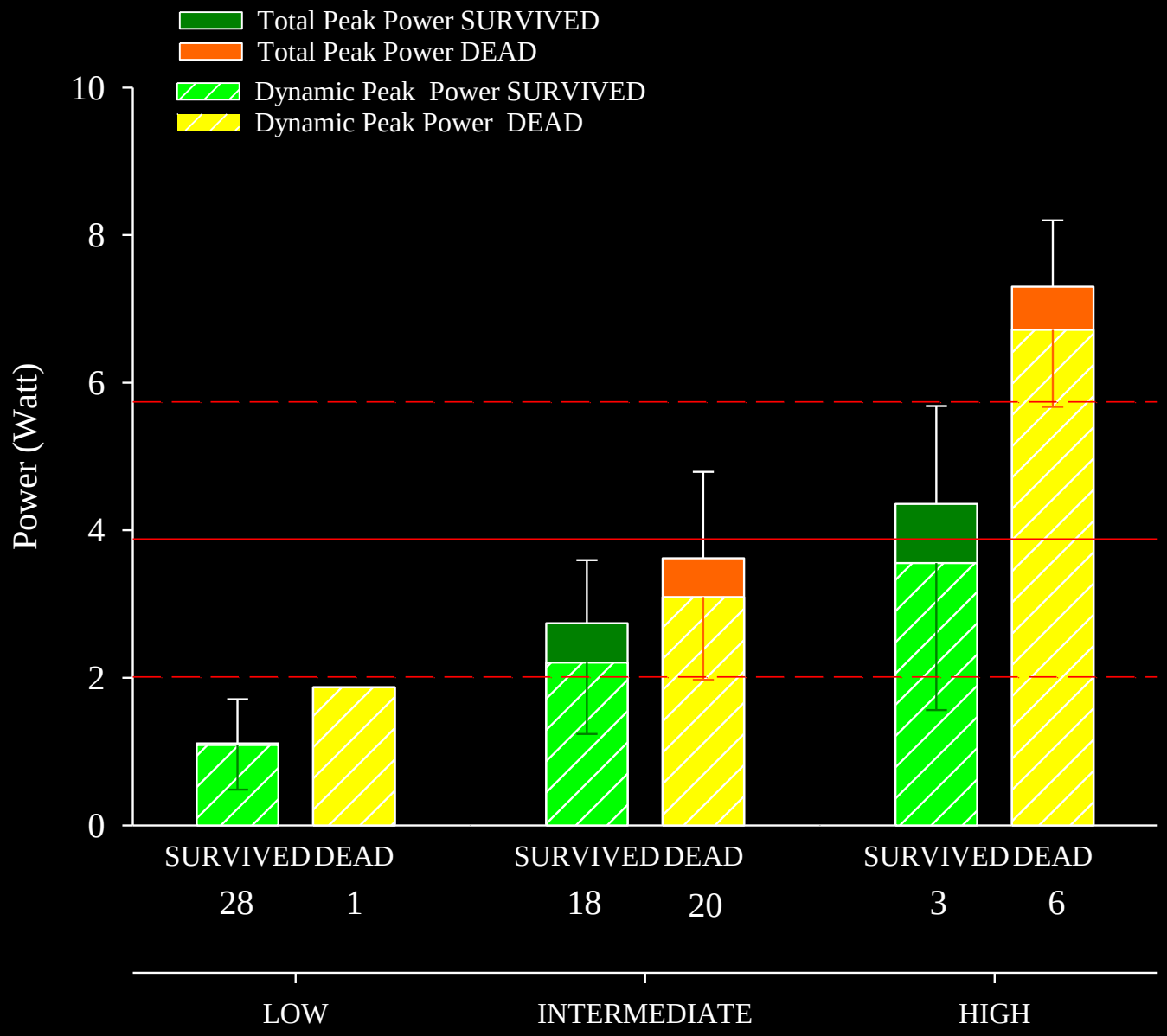
LOW PEEP



HIGH PEEP



76 PIGS


Total Peak Power SURVIVED
Total Peak Power DEAD
Dynamic Peak Power SURVIVED
Dynamic Peak Power DEAD
Power (Watt)
10
8
6
4
2
0
SURVIVED
DEAD
28
1
SURVIVED
DEAD
18
20
SURVIVED
DEAD
3
6
LOW
INTERMEDIATE
HIGH

Tidal volume 38 ml/Kg
Plateau pressure 27 cmH_2O
Lethal in 54 hours 15 breaths/min

but

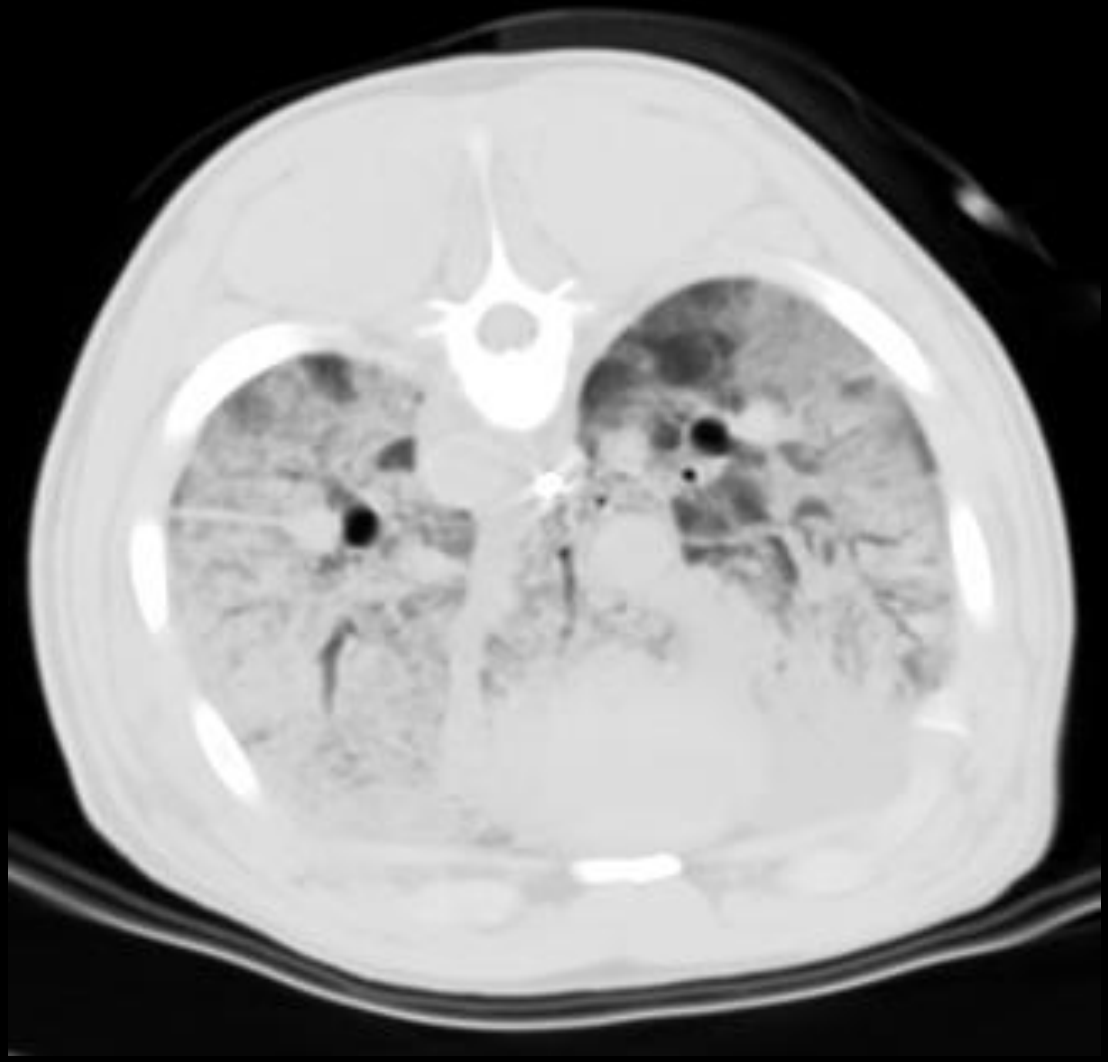
RESPIRATORY RATE

- 3 breaths/min
- 6 breaths/min
- 9 breaths/min
- 12 breaths/min
- 15 breaths/min

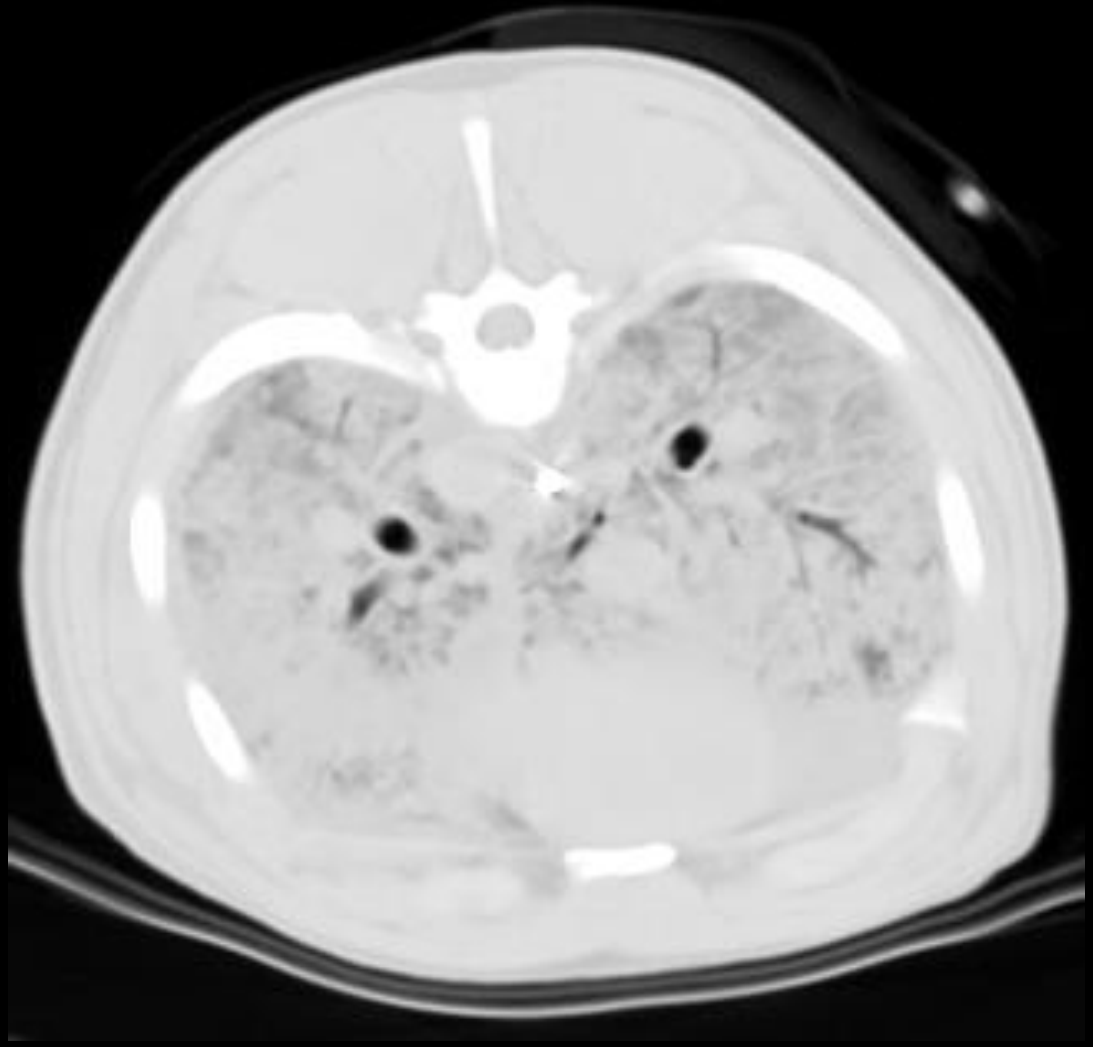
Baseline

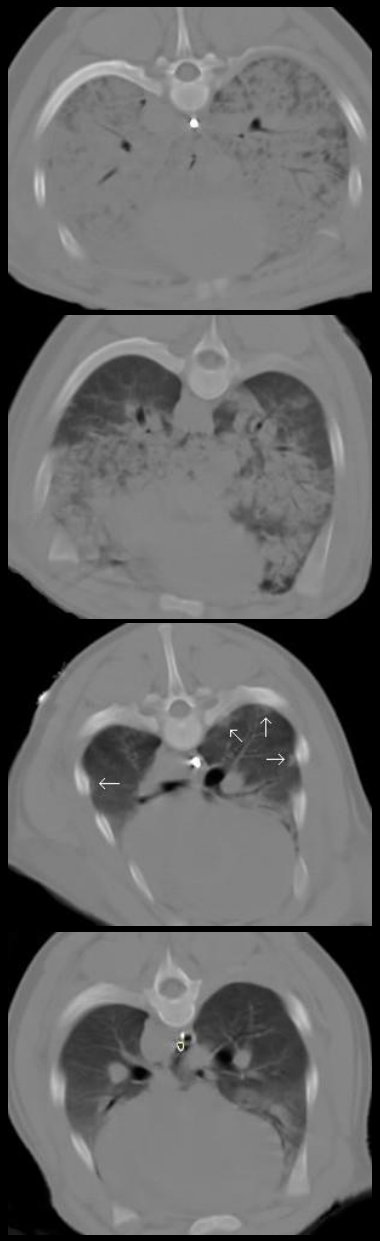
After 12 hours…

After 45 hours…



After 50 hours!





Whole lung edema

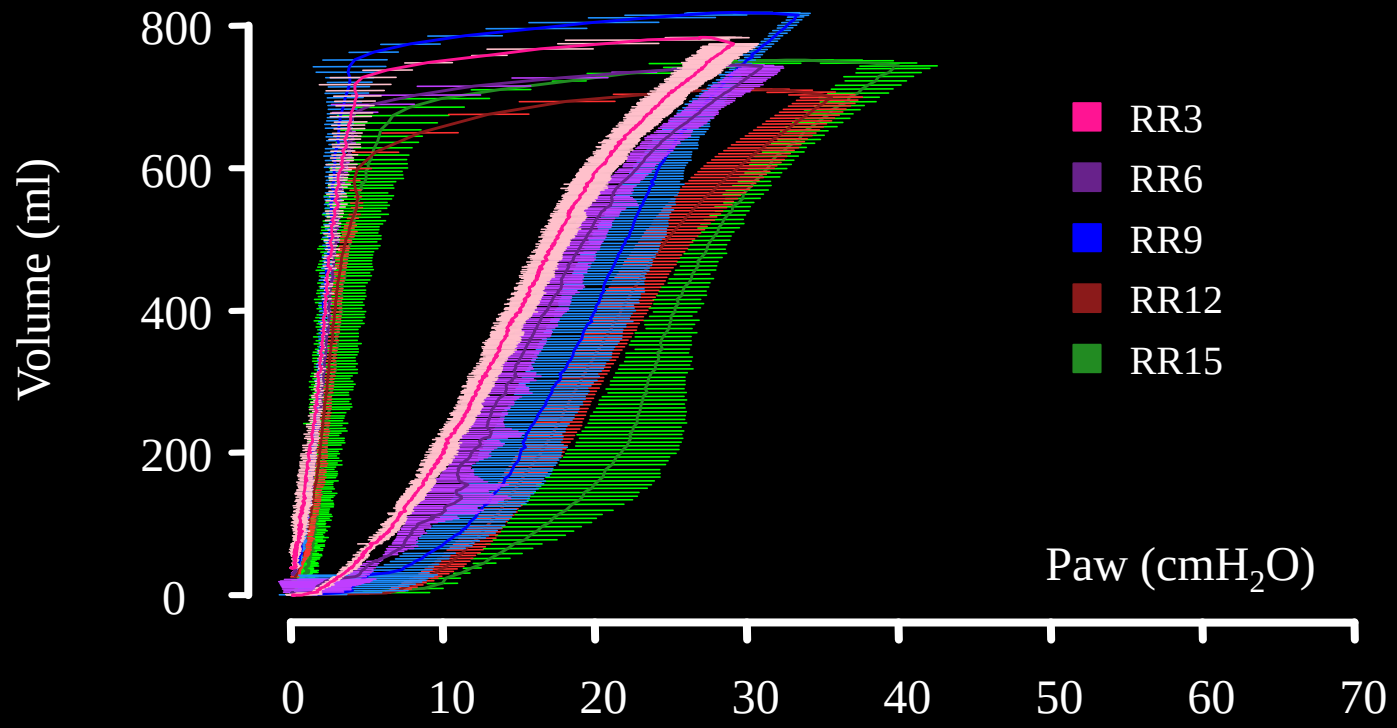
One-field edema

Isolated densities

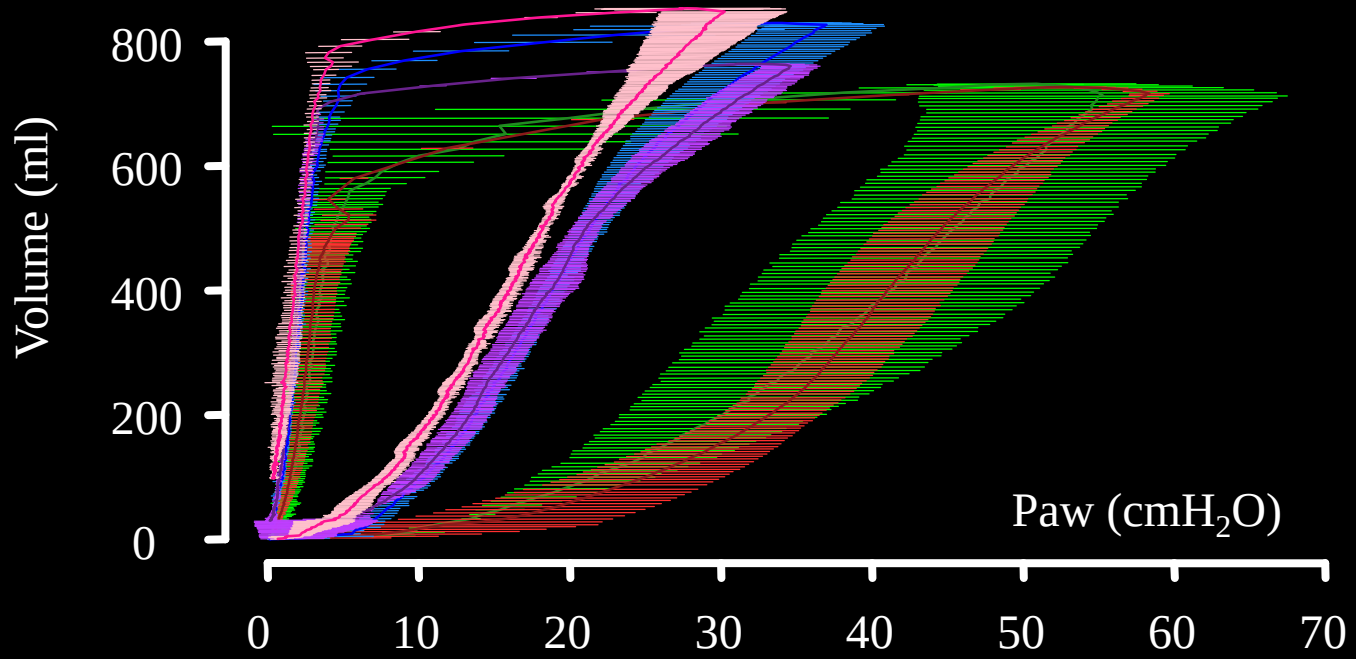
Baseline

0 5 10 15 20 25

Delivered dynamic transpulmonary energy load (J/min)


800
600
400
200
0
Volume (ml)
RR3
RR6
RR9
RR12
RR15
Paw (cmH2O)
0
10
20
30
40
50
60
70

Start


800
600
400
200
0
Volume (ml)
Paw (cmH2O)
0
10
20
30
40
50
60
70

End

Therefore VILI arises from mechanical power:

PL × TV × RR

VILI

What is due to the ventilator/ventilation:

- Tidal Volume
- Pressure change
- Flow rate
- Respiratory rate

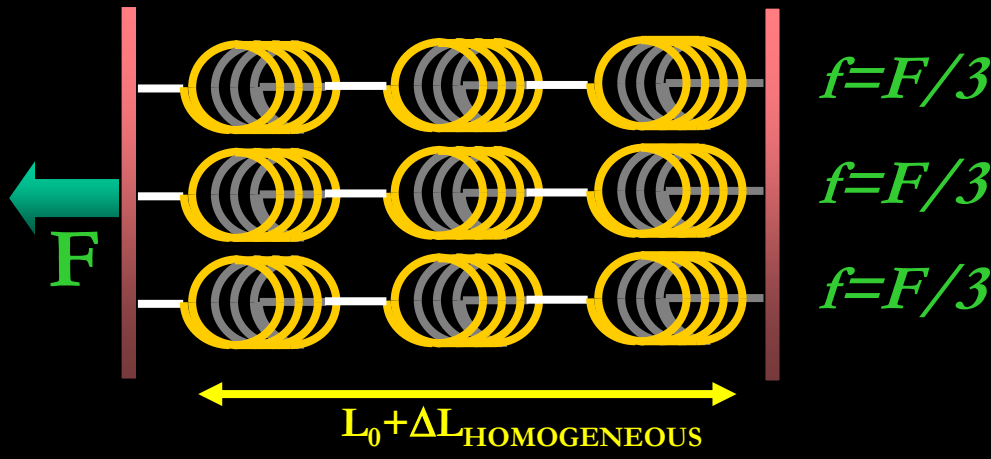
Pressure change, Flow rate → Energy

Tidal Volume, Energy → Power

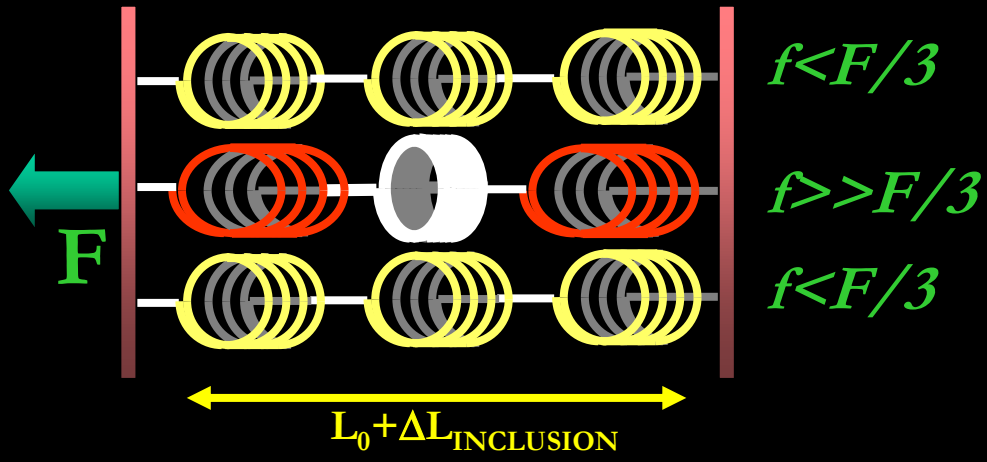
What is due to the lung:

- Lung inhomogeneity
- Stress risers

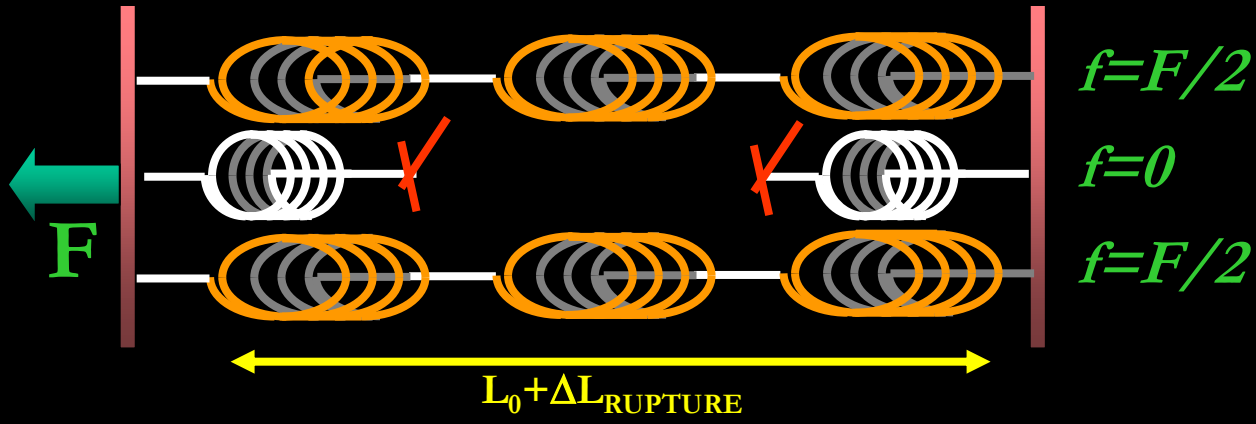
HOMOGENEOUS SYSTEM



INCLUSION



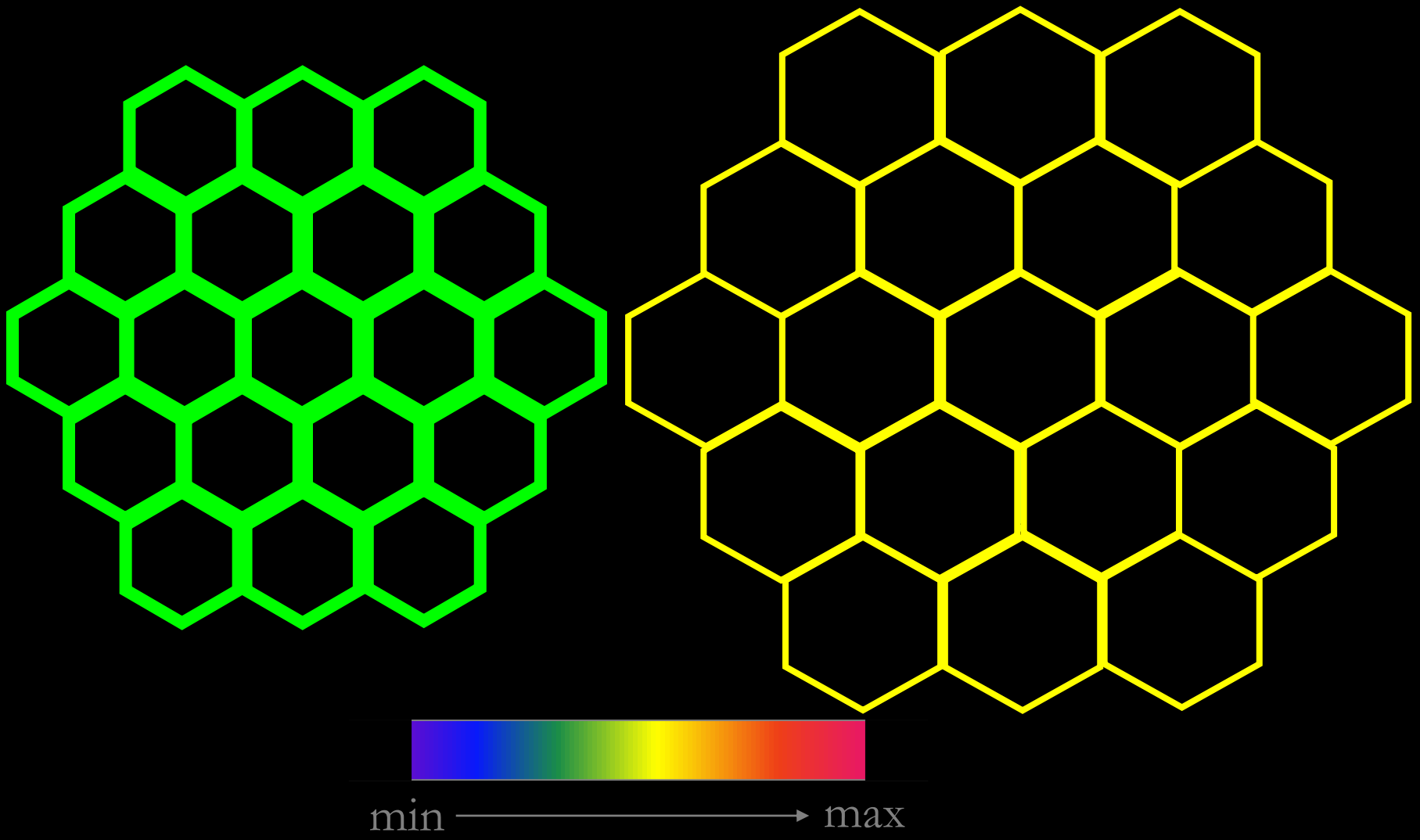
RUPTURE



L. Gattinoni, 2003

Stress distribution:

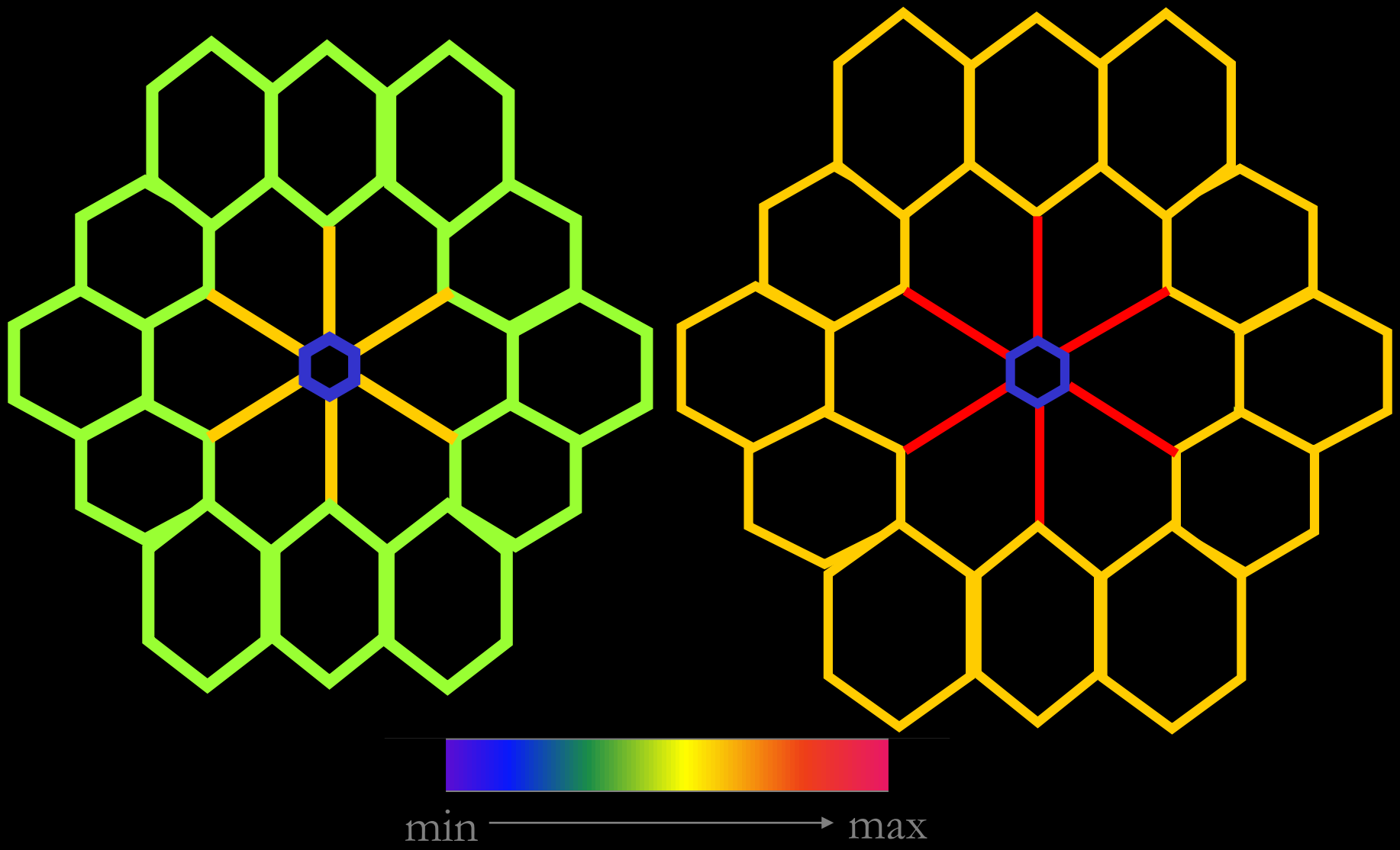
homogeneous system



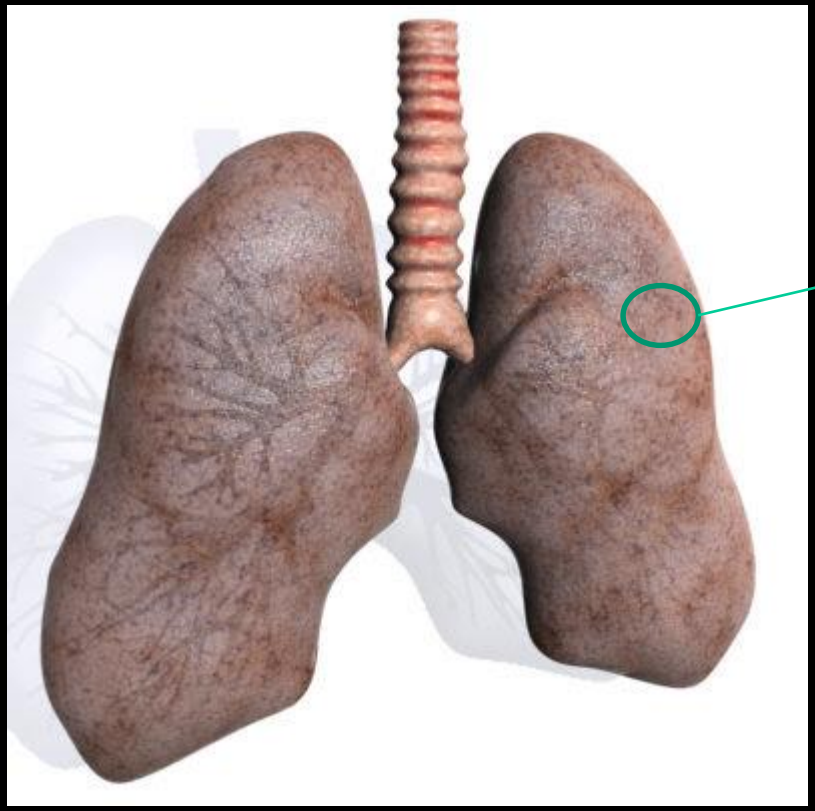
Mead J et al. J. Appl. Physiol. 28(5):596-608 1970

Stress distribution:

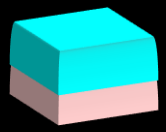
high stiffness zone



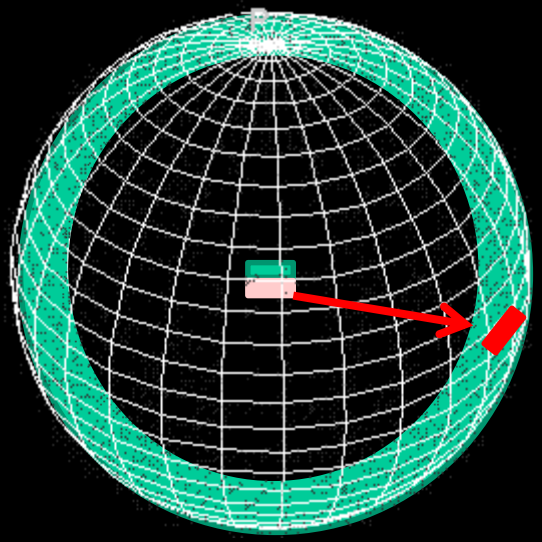
Mead J et al. J. Appl. Physiol. 28(5):596-608 1970



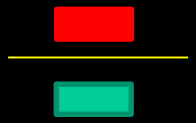
Voxel
Vgas



Gas fraction = V_{gas0}/V_{voxel}

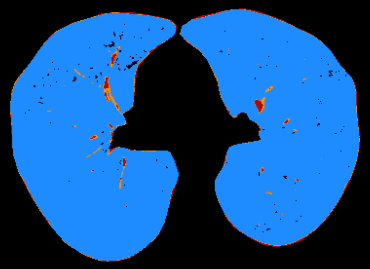


Weighted gas ratio = V_{gas1}/V_{gas0} * fraction of tissue

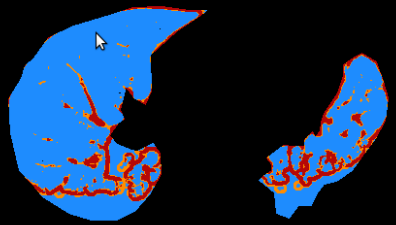


Cressoni et al. Am J Respir Crit Care Med. 2014 Jan 15;189(2):149-58

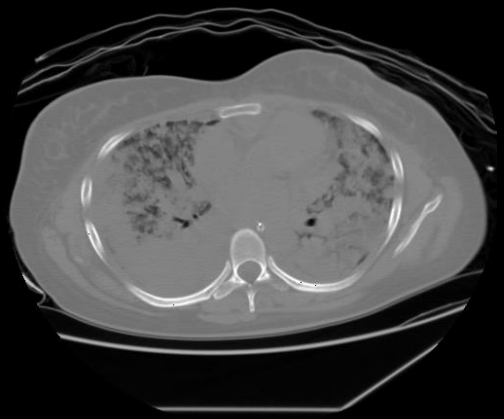
Average ratio in normal subjects : 1.37±0.15

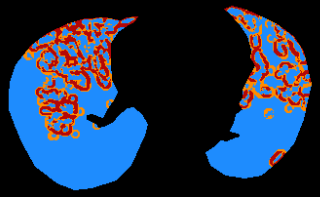


Healthy subject



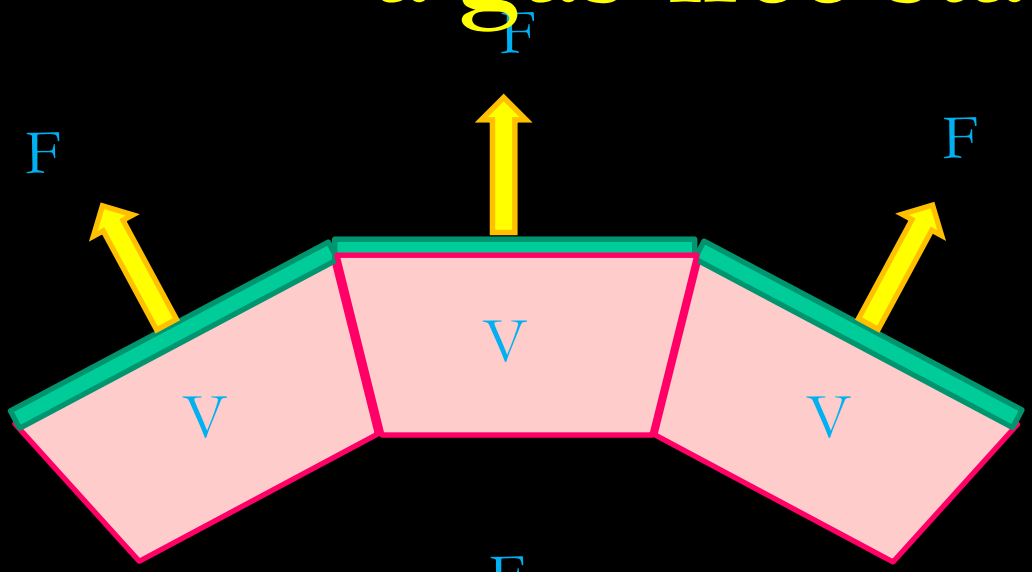
Moderate ARDS



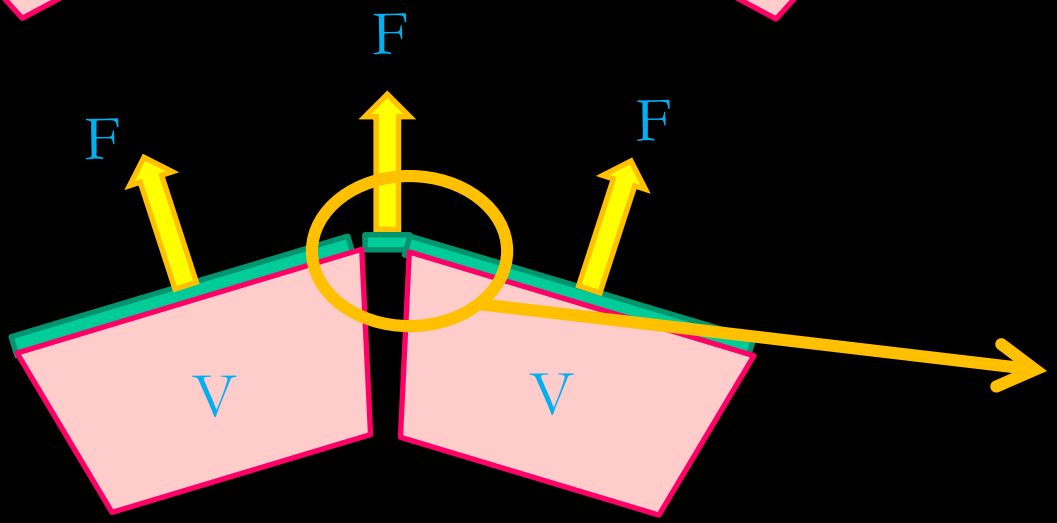


Severe ARDS

Lung expansion from a gas-free state

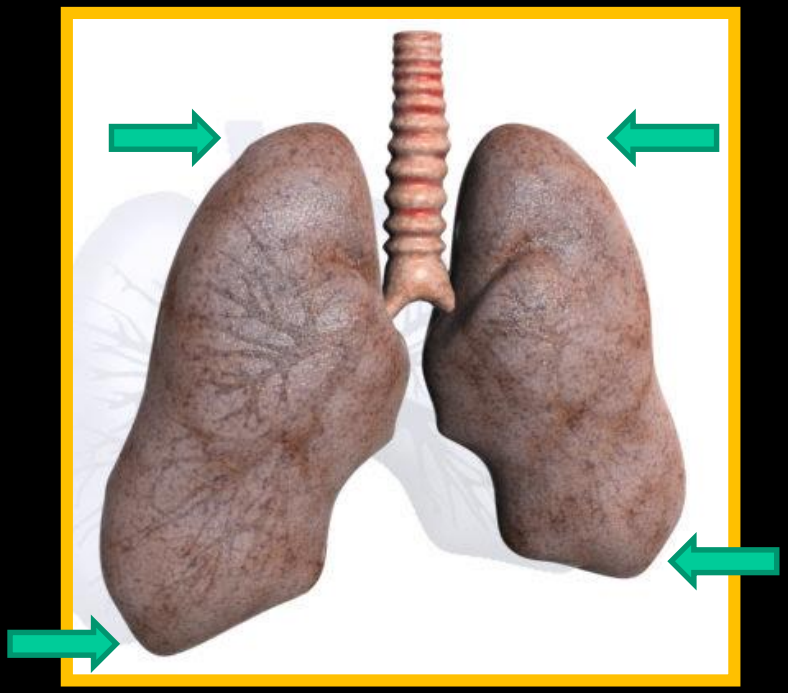


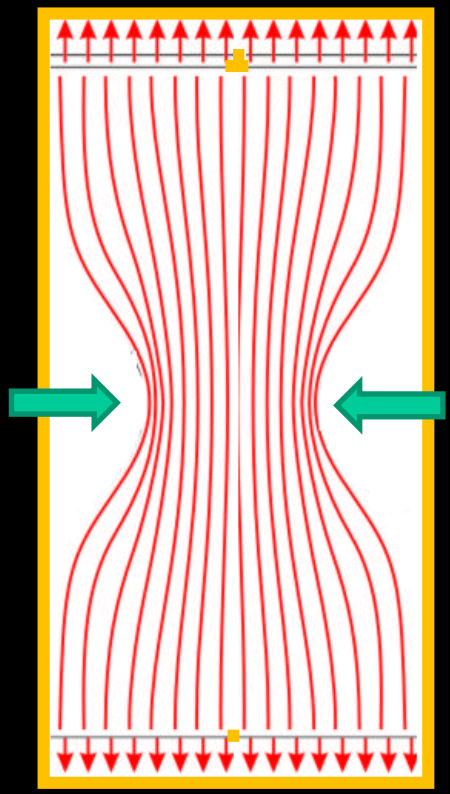
Homogeneous lung



STRESS RISER

Stress risers and shape

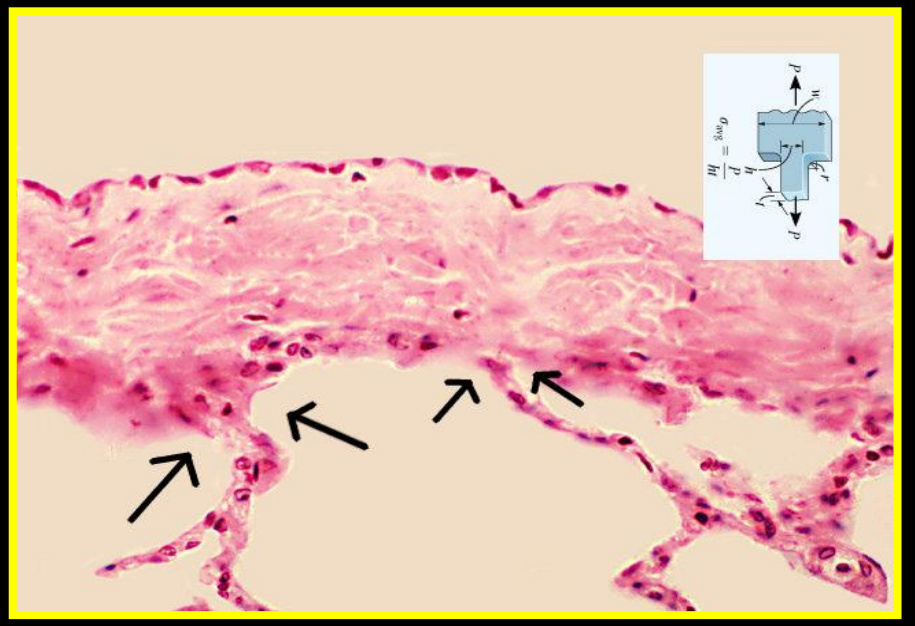


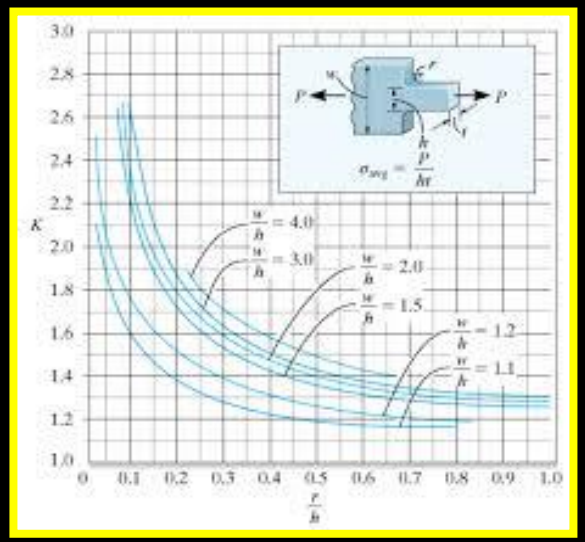


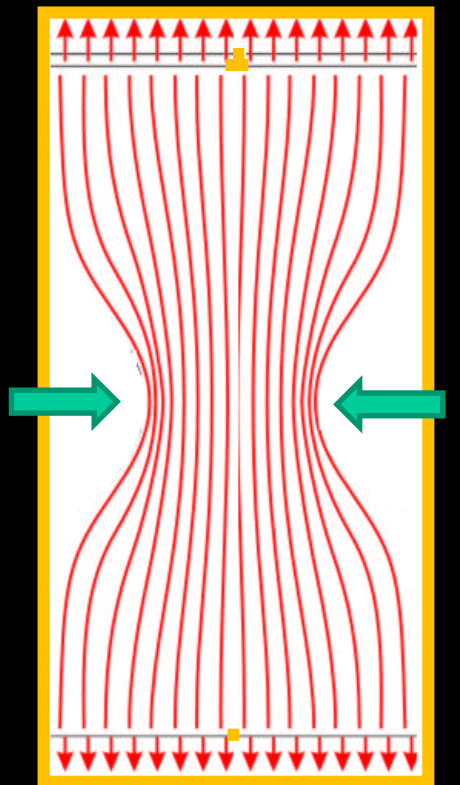
Lung dishomogeneity and ARDS

	Mild (N=82)	Moderate (N=71)	Severe (N=12)	P
Dishomogeneity	1.49 ± 0.17	1.58 ± 0.29	1.75 ± 0.41	0.03
Dishomogeneity$^{2/3}$	1.30 ± 0.31	1.36 ± 0.44	1.45 ± 0.55	
Extent	0.3 ± 0.1	0.36 ± 0.16	0.46 ± 0.18	0.01
Intensity	2.69 ± 0.27	2.76 ± 0.27	2.84 ± 0.41	0.31
Intensity$^{2/3}$	1.93 ± 0.42	1.97 ± 0.42	2.01 ± 0.55	

Courtesy of Dr. Cressoni



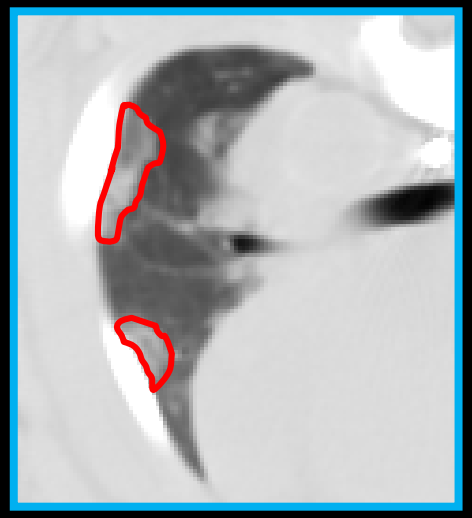

3.0
2.8
2.6
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
K
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
r/h
w/h = 4.0
w/h = 3.0
w/h = 2.0
w/h = 1.5
w/h = 1.2
w/h = 1.1
P
P
σ_avg = P/Ht



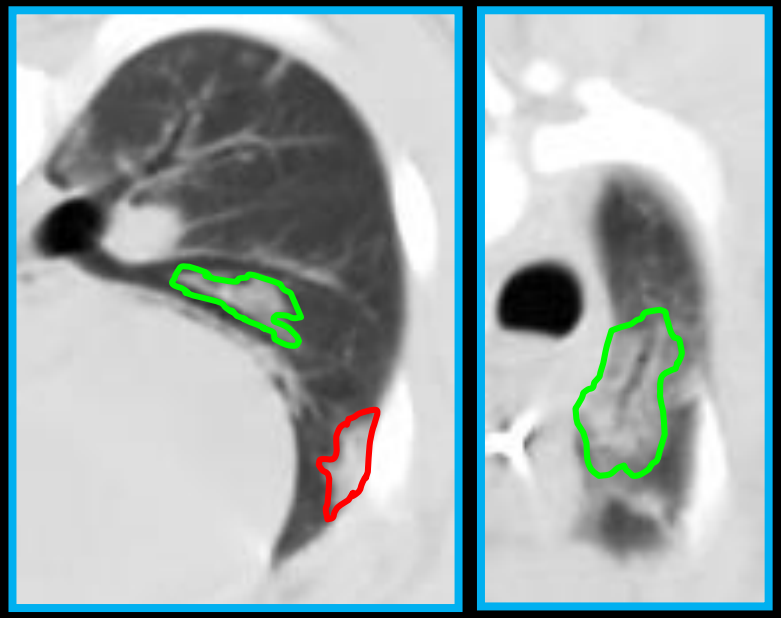
Hypothesis

Lesions should first occur where physiological stress risers are located

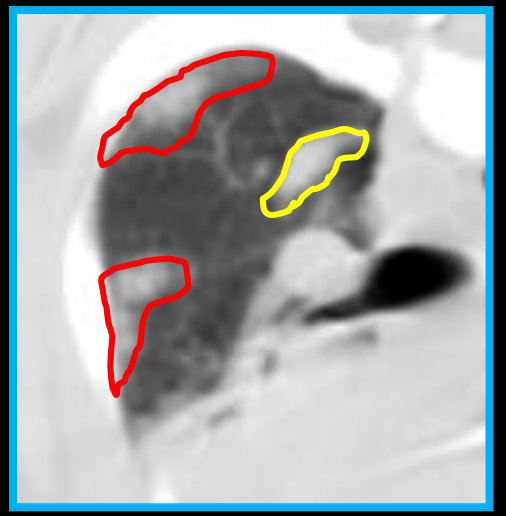
KIND OF DENSITIES



Subpleural
61 [57-76]%



Peribronchial
19 [11-23]%

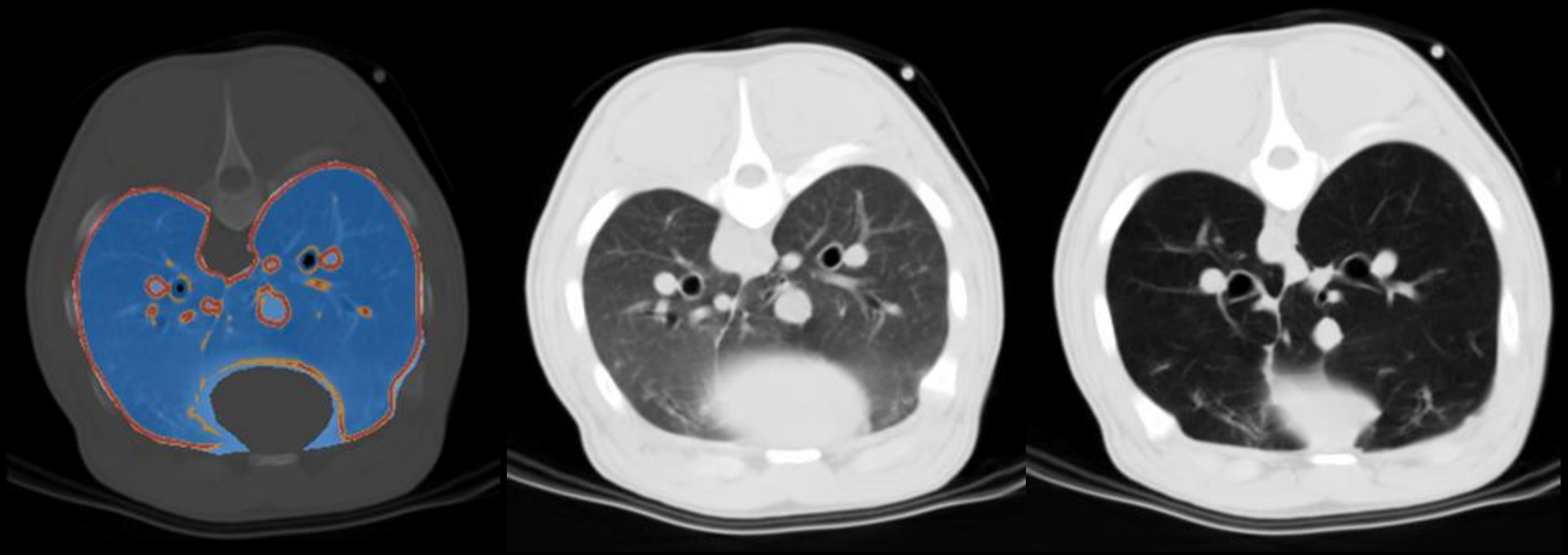


Parenchymal
19 [6-25]%

Courtesy of dr. Cressoni M.

Before appearance first new densities

END EXPIRATION **END INSPIRATION**

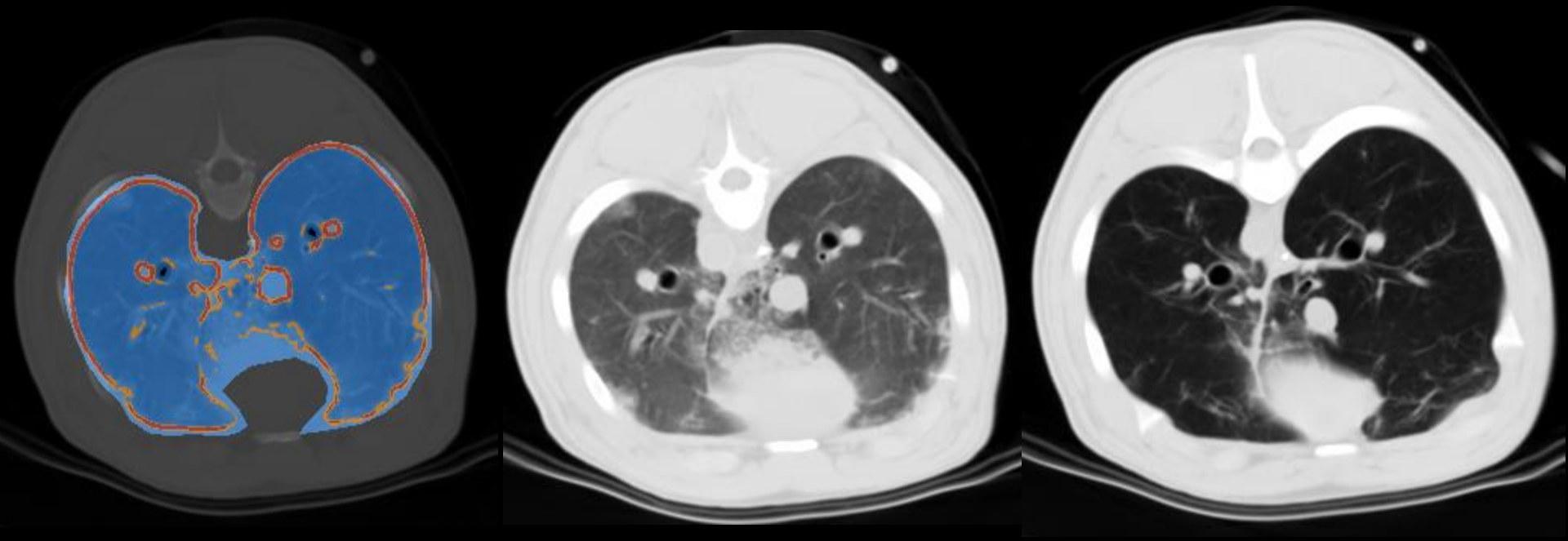


TIME 1: 5.7±6.5 hours

Courtesy of dr. Cressoni M.

First CT scan with new densities

END EXPIRATION **END INSPIRATION**



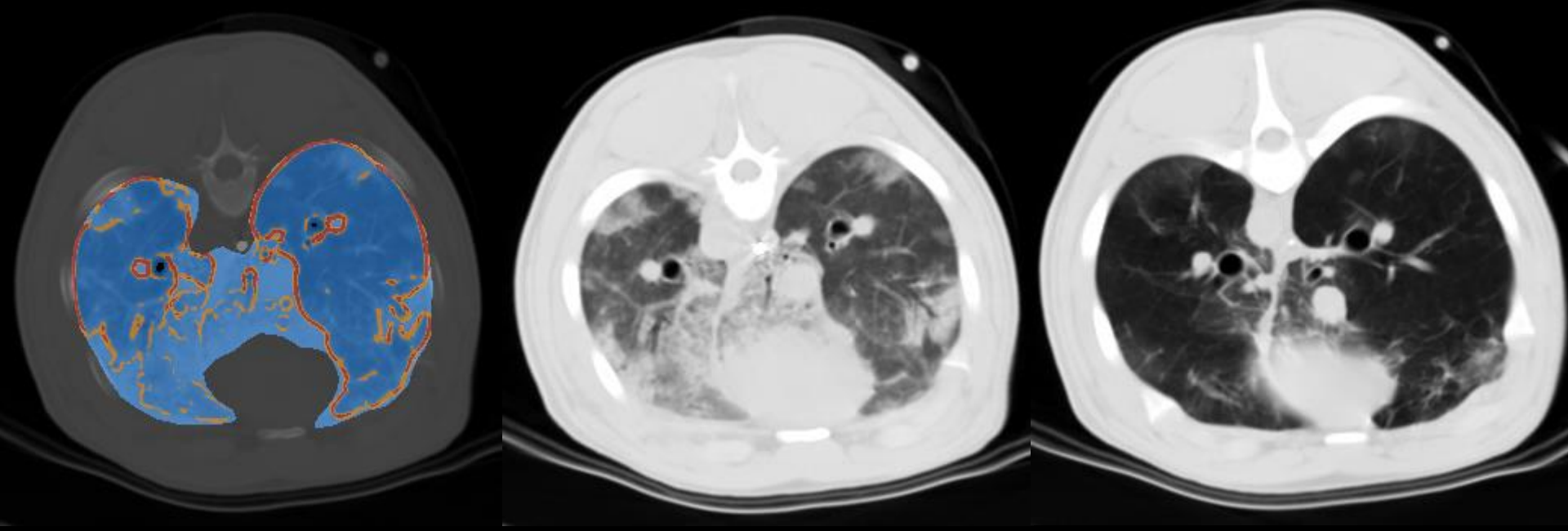
TIME 2: 8.4±6.3 hours

Courtesy of dr. Cressoni M.

Last CT scan with distinguishable densities

END EXPIRATION

END INSPIRATION



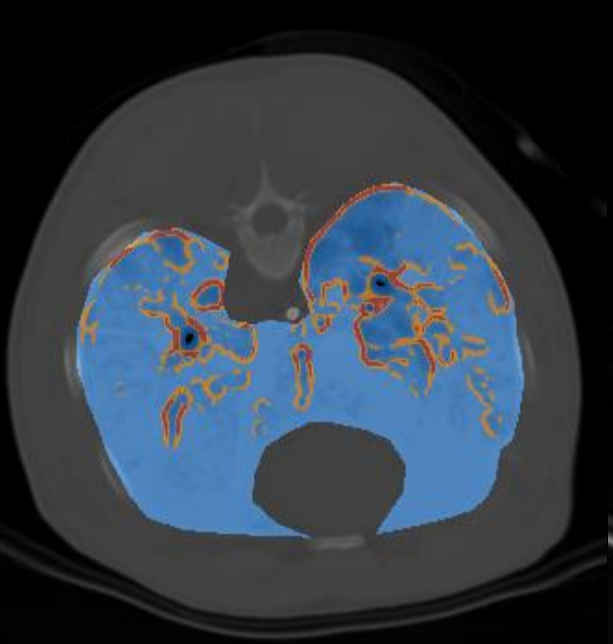
TIME 3: 15±12 hours

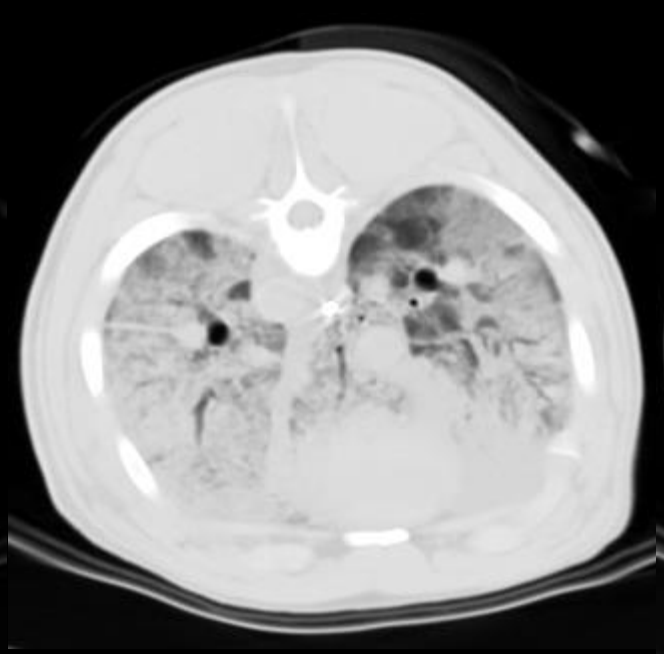
Courtesy of dr. Cressoni M.

First CT scan with one-field edema

END EXPIRATION

END INSPIRATION



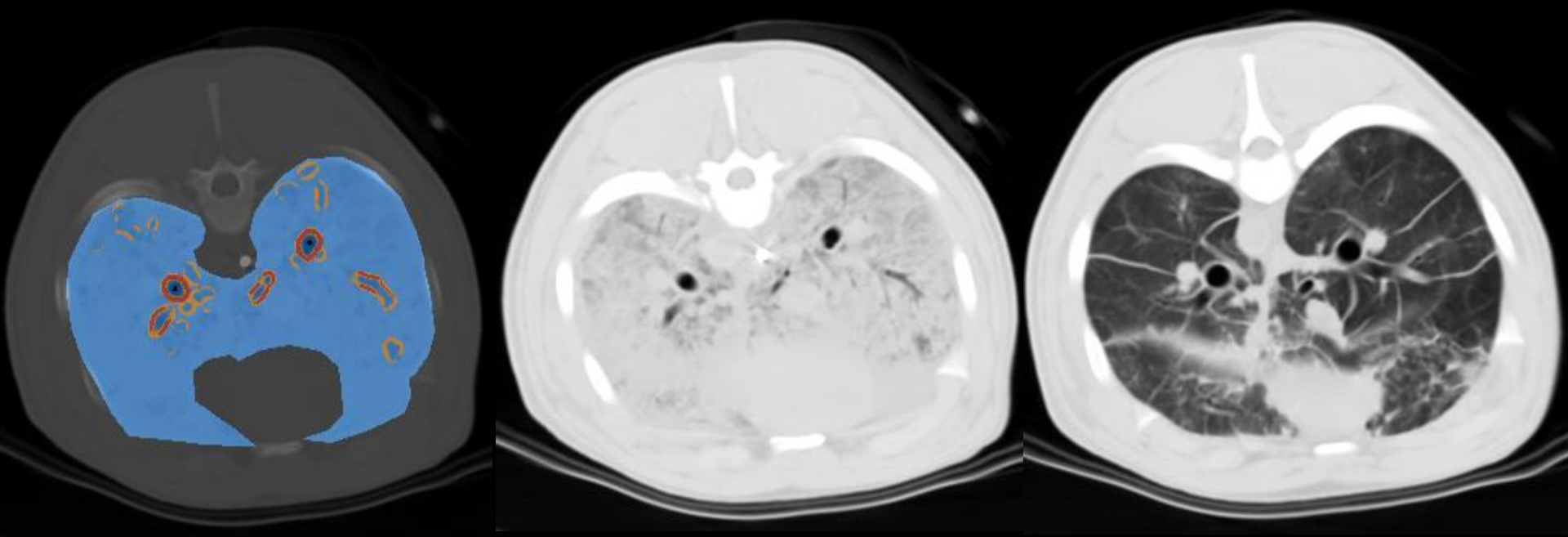


TIME 4: 18±11 hours

Courtesy of dr. Cressoni M.

First CT scan with all-field edema

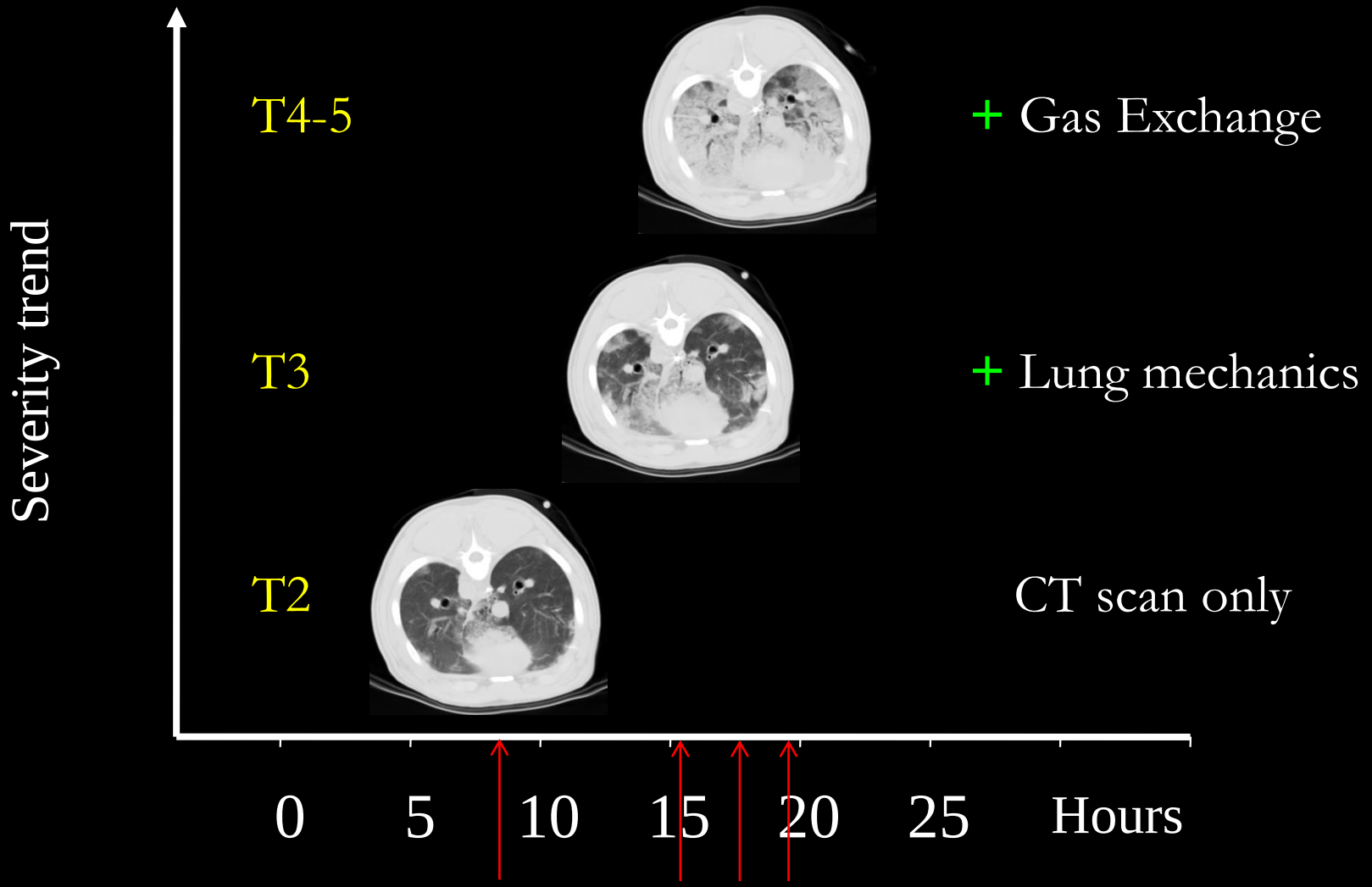
END EXPIRATION **END INSPIRATION**



TIME 5: 20±11 hours

Courtesy of dr. Cressoni M.

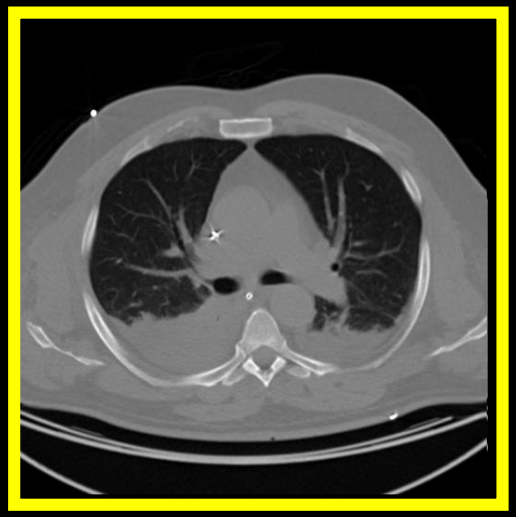
VILI cumulative time course



Courtesy of dr. Cressoni M.

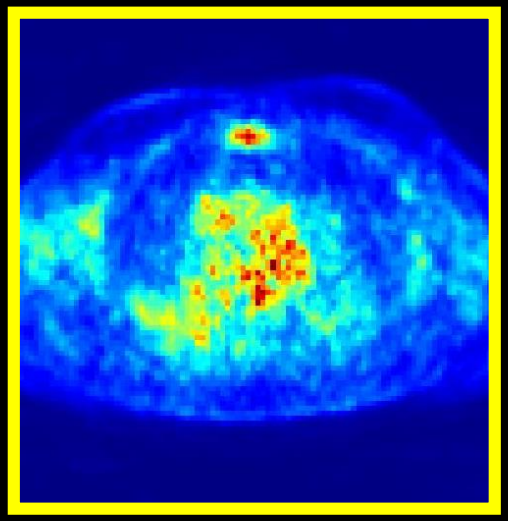
LUNG IMAGING

CT SCAN
INFLATION

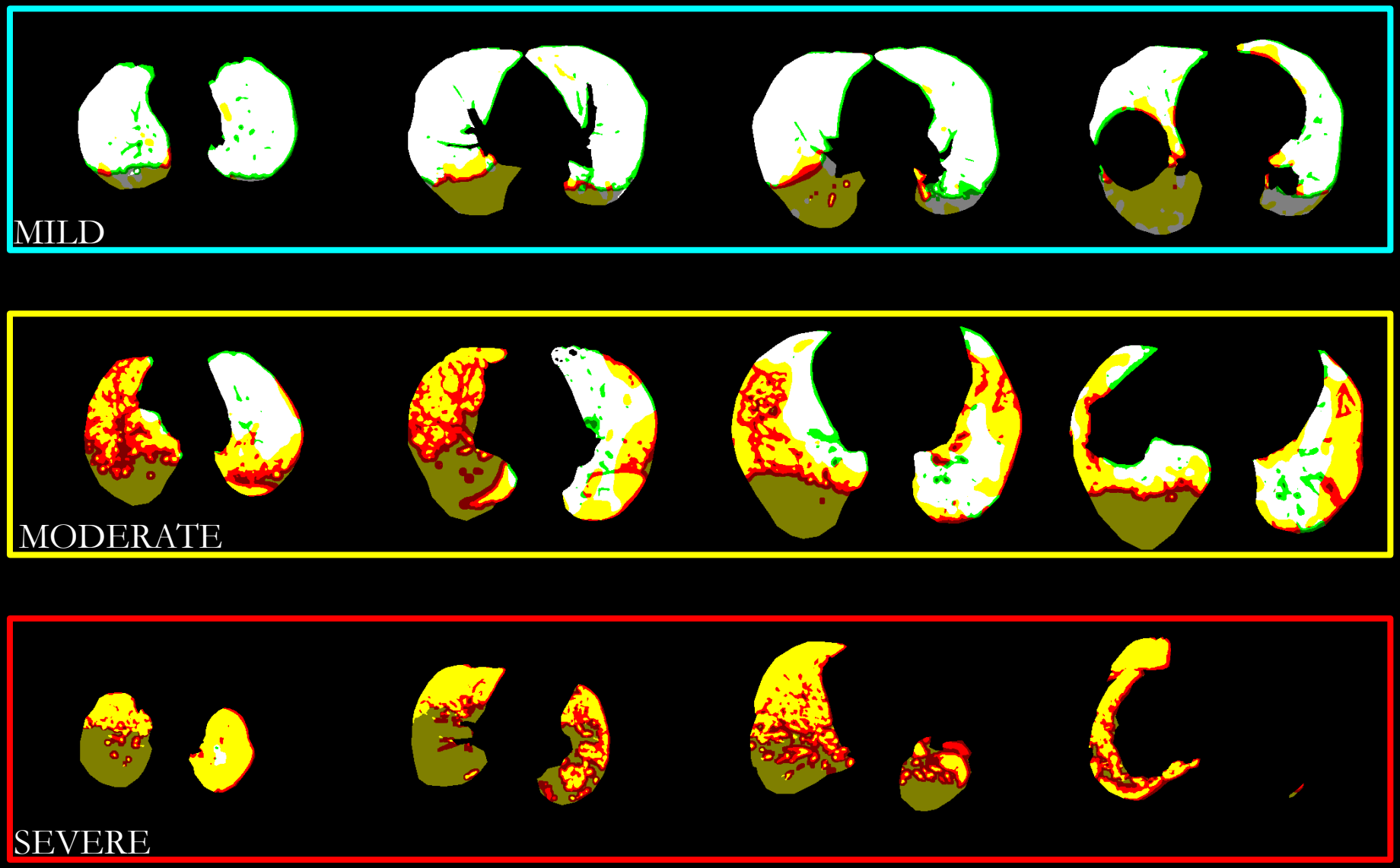


INHOMOGENEITY

PET
FDG UPTAKE



Ki/lung inhomogeneity interaction and gas/tissue composition



Prevention of VILI

- Decrease mechanical power
  - Tidal Volume
  - Pressure variation
  - Respiratory rate
  - Flow
- Increasing Homogeneity
  - PEEP
  - Prone Position

Lung protective strategy

Less energy

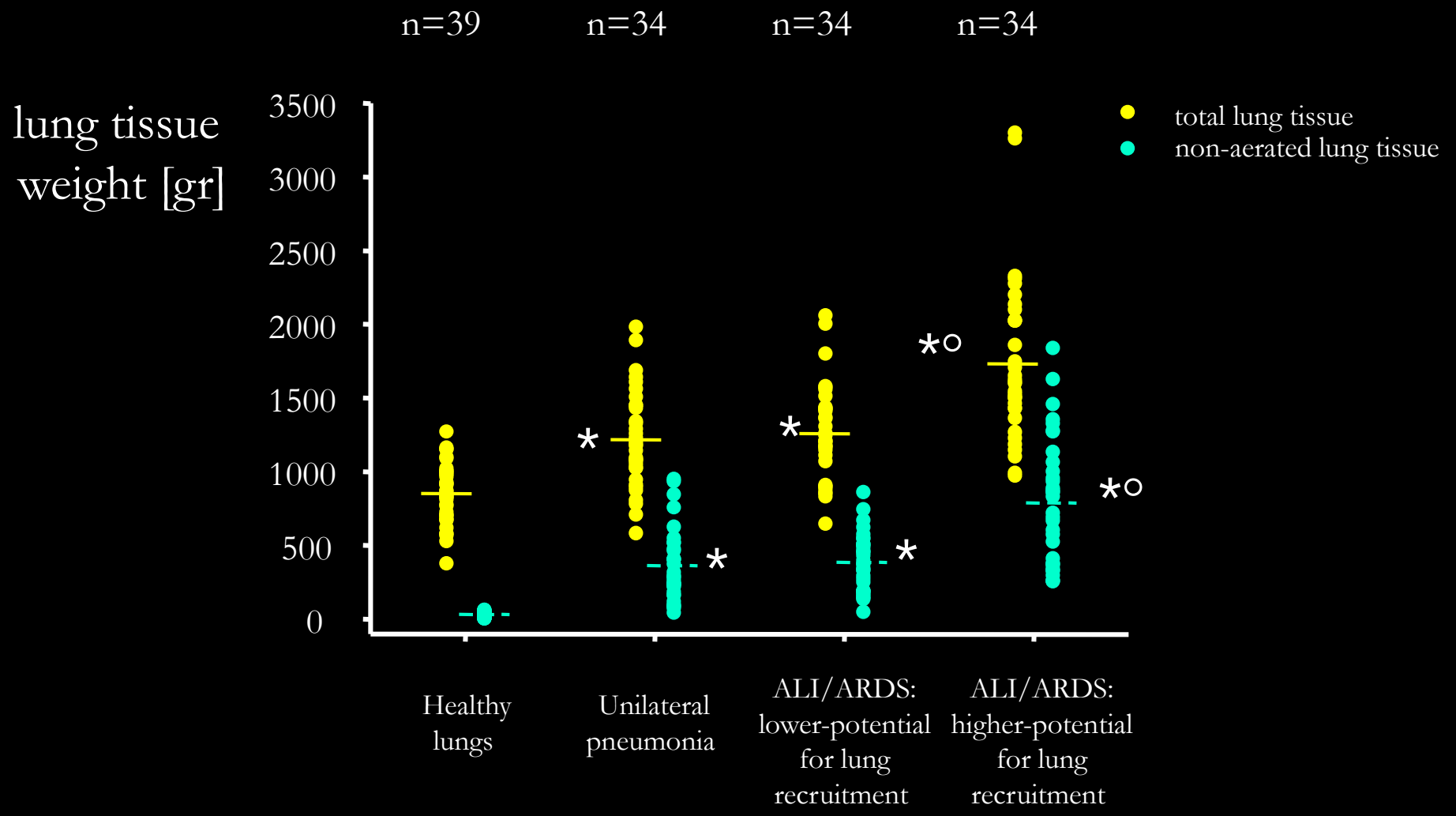
+

More homogeneous lung

Lung protective strategy recipe: the ingredients

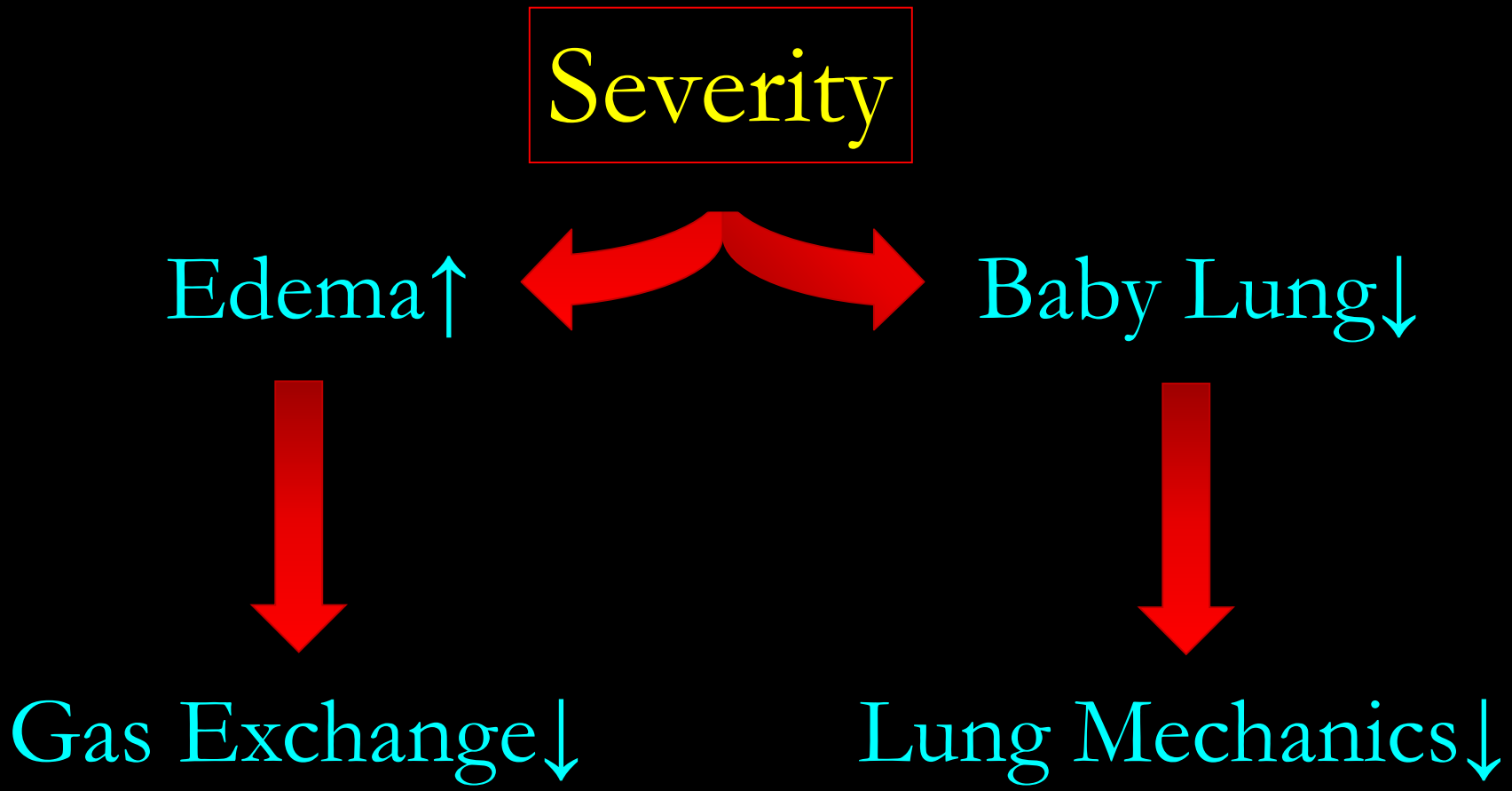
- Assess severity
- Select Tidal Volume
- Select PEEP
- Select RR-IE
- Watch hemodynamics

Lung and gasless tissue weight in acute respiratory failure

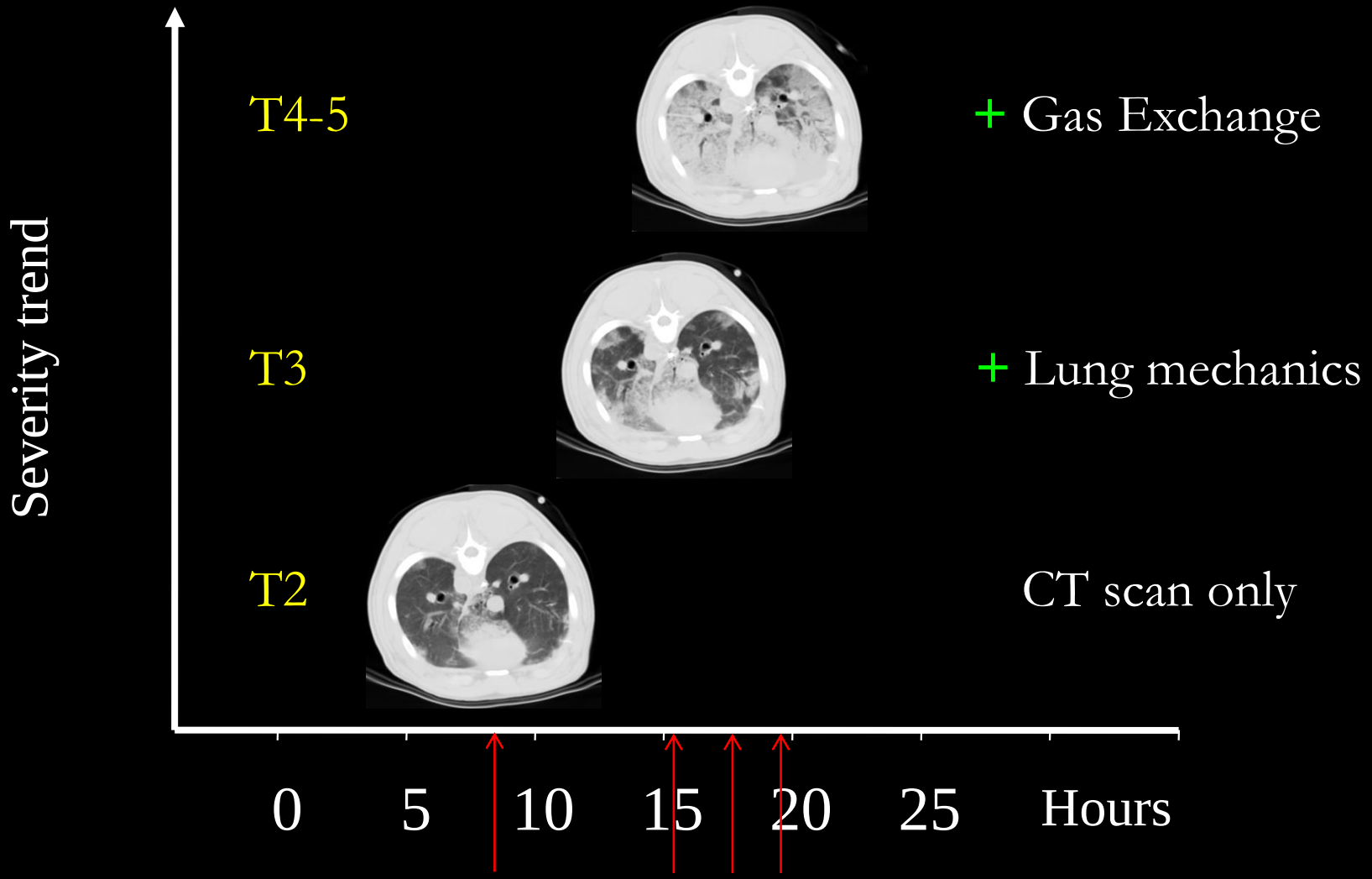


Submitted for publication

* P<0.01 vs. patients with healthy lungs, ° P<0.01 vs. other groups.

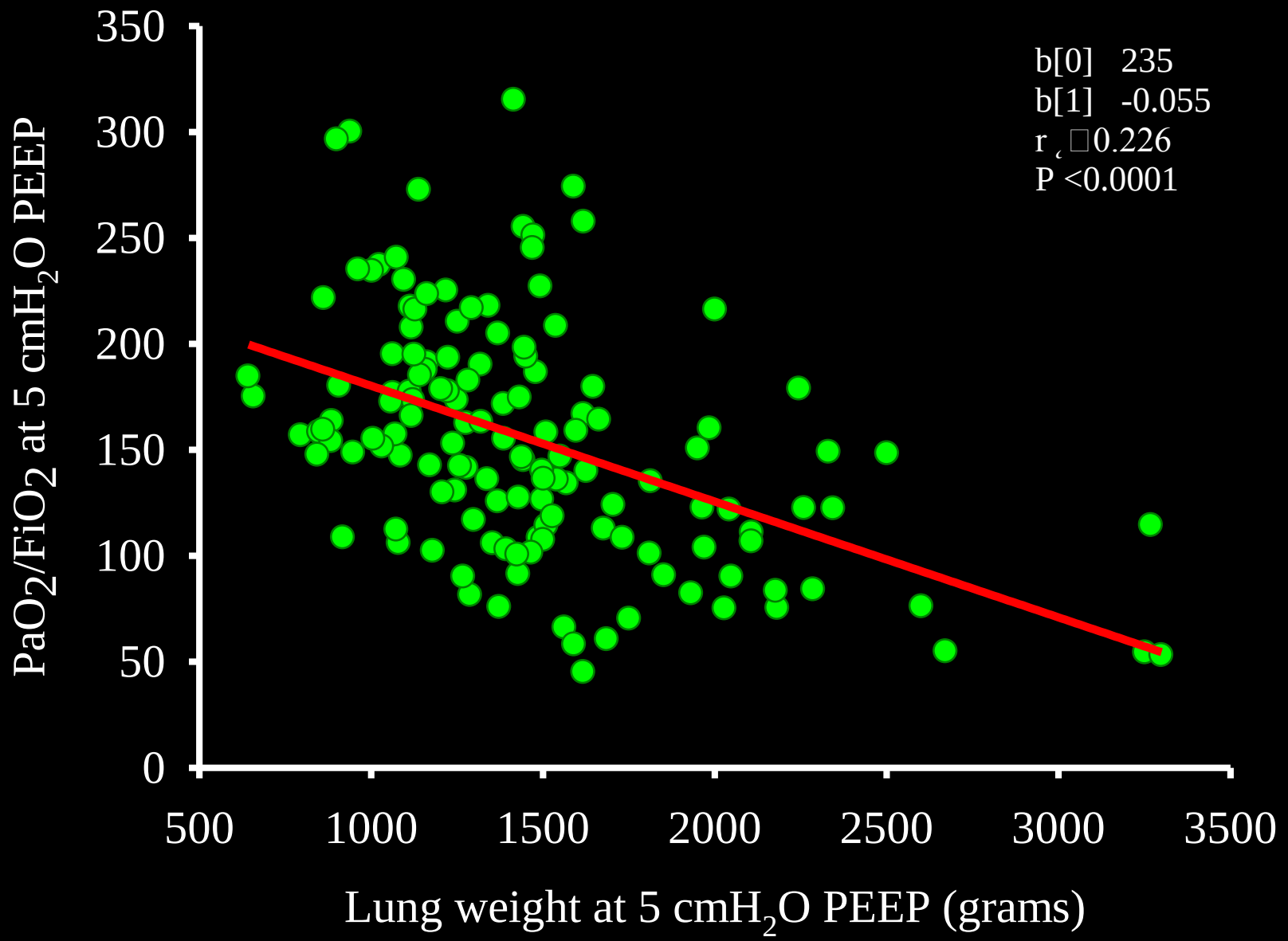

Severity
Edema↑
Baby Lung↓
Gas Exchange↓
Lung Mechanics↓

VILI cumulative time course



Courtesy of dr. Cressoni M.

139 ARDS patients



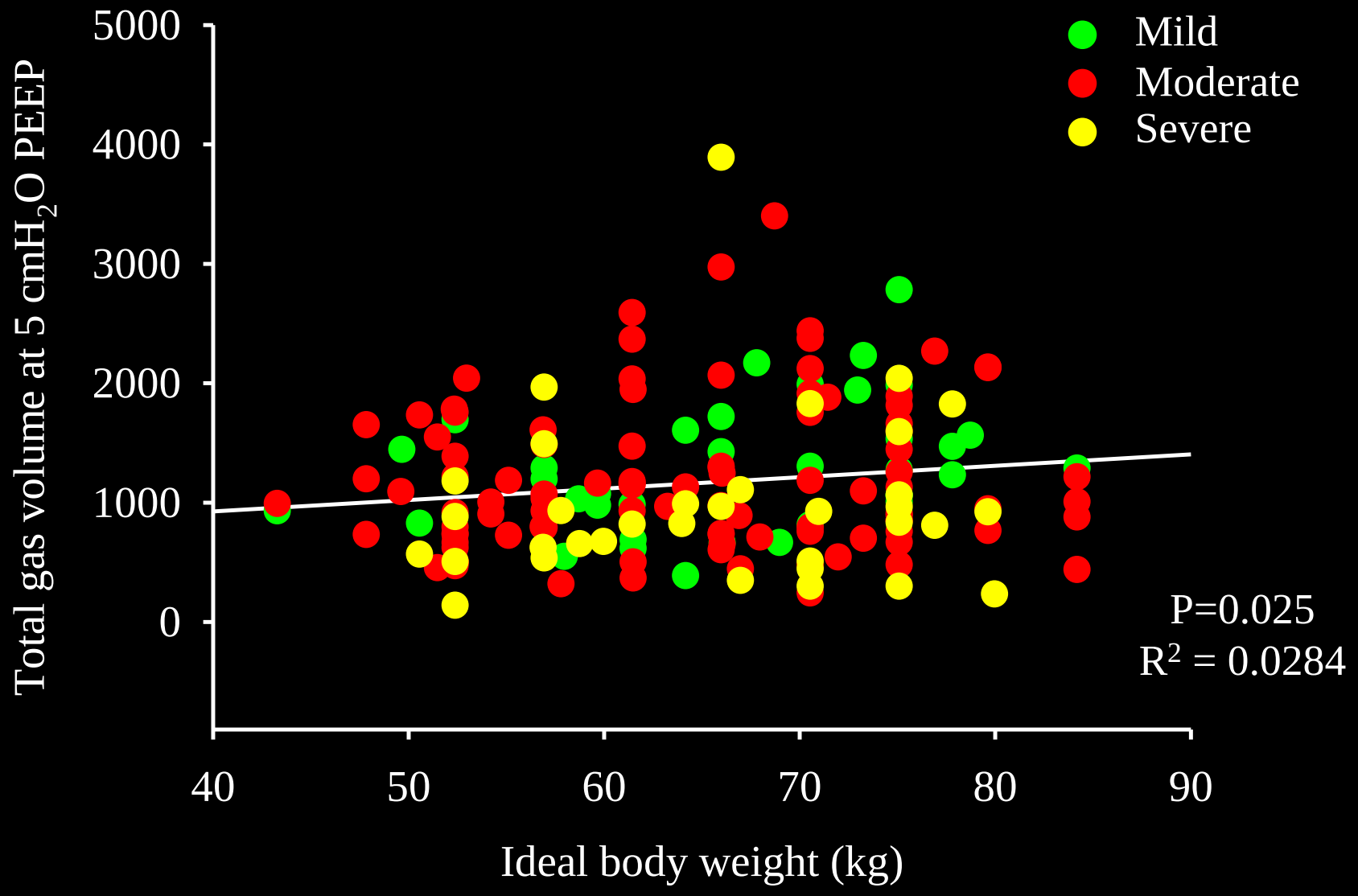
Assess severity
The simplest

P/F at 5 cmH_2O PEEP
(300, 200, 100)
Berlin definition

Lung protective strategy recipe: the ingredients

- Assess severity
- Select Tidal Volume
- Select PEEP
- Select RR-IE
- Watch hemodynamics

Lung gas volume and body weight



The ARDS lung is small and not stiff

Normal $\Rightarrow \dfrac{V_T}{FRC} = \dfrac{500\ ml}{2500\ ml} = 0.2$

ARDS $\Rightarrow \dfrac{V_T}{FRC} = \dfrac{500\ ml}{500\ ml} = 1$

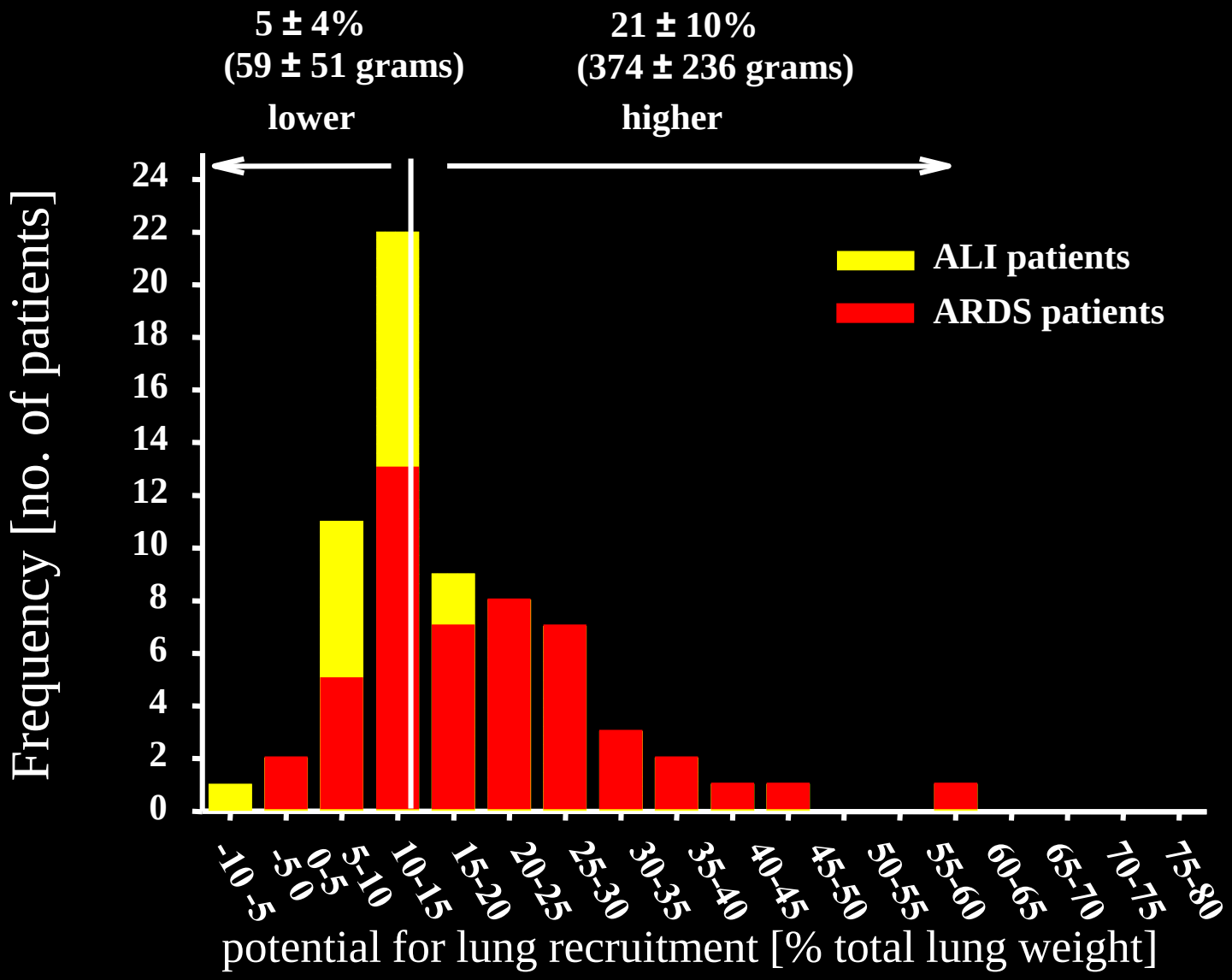
Select tidal volume
The simplest

Tidal volume
6 mL/kg IBW
(check plateau pressure)

Lung protective strategy recipe: the ingredients

- Assess severity
- Select Tidal Volume
- Select PEEP
- Select RR-IE
- Watch hemodynamics

Potential for lung recruitment



Gattinoni L, Caironi P, Cressoni M, Chiumello D, Ranieri VM, Quintel M, Russo S, Cornejo R, Bugedo G, NEJM 2006, 354(17):1775-86

PEEP selection methods comparison

- CT scan derived PEEP
- Esophageal Pressure
- The Stress Index method
- The ExPress study
- The LOVs study

ARDS

PEEP (cmH_2O)	Mild (n=7)	Moderate (n=33)	Severe (n=11)
LOV	8±2 $	11±3 $	15±3
ExPress	14±2 *	14±3 *	16±3
Stress Index	11±2	14±3 *	14±3
Esophageal pressure	13±3 *	12±4	13±4

$ p<0.05 vs severe ARDS

* p<0.05 vs LOV selection method

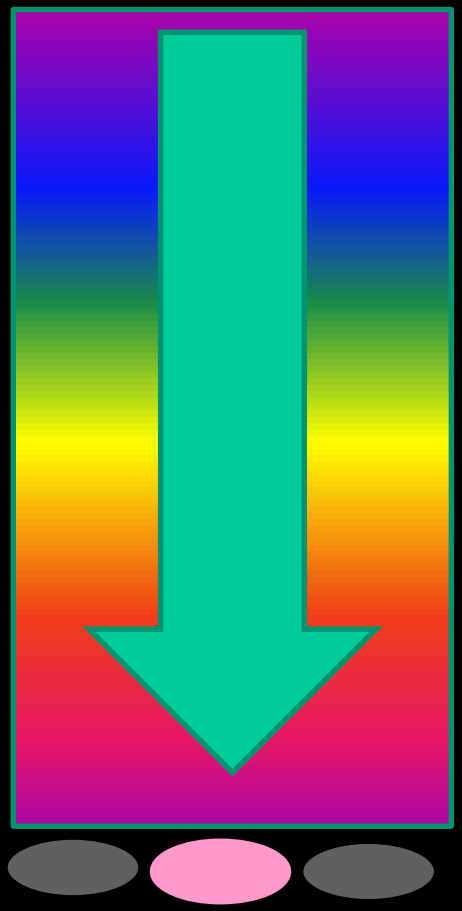
p (method) <0.001

p (classification according to Berlin definition) 0.02

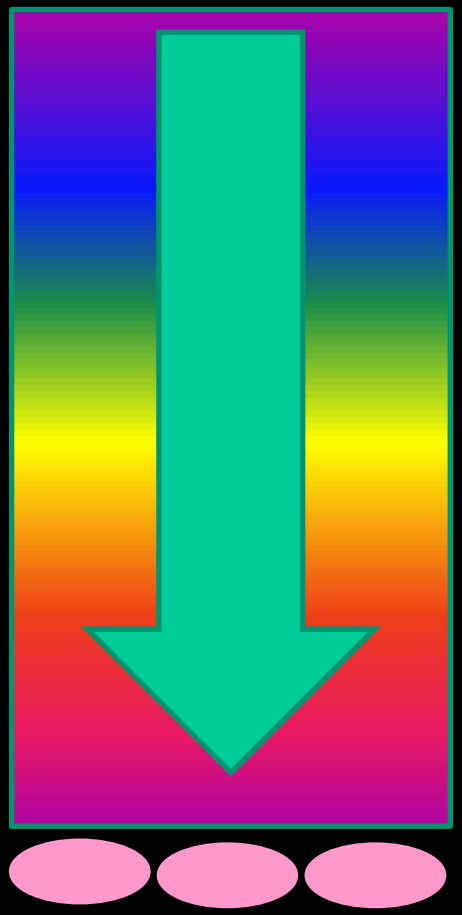
p (interaction) 0.01

Crit Care Med. 2014 Feb;42(2):252-64

Superimposed pressure



Superimposed pressure



The same transpulmonary pressure is required to keep the lung open!!!

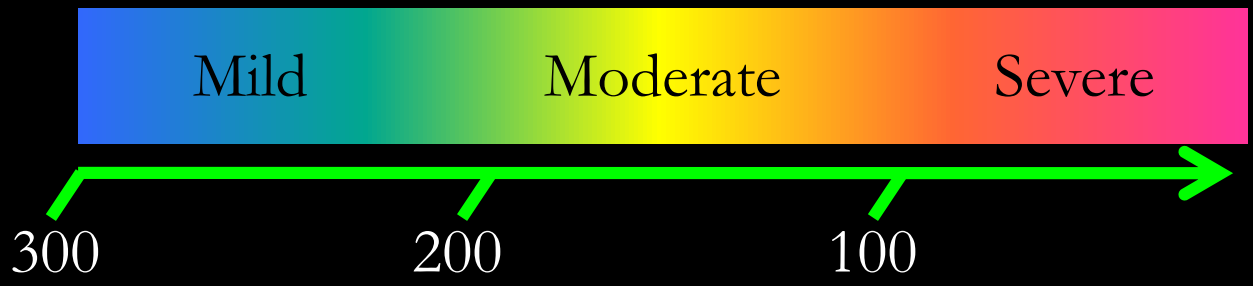
Select PEEP
The simplest

Mild ARDS: below 10 cmH_2O

Moderate: 10-15 cmH_2O

Severe: >15 cmH_2O

ARDS



Paw plat/PL plat	≤ 30 cmH_2O/≤ 20 cmH_2O
Tidal Volume/strain	6 ml/kg IBW/≤ 1.5-2
PEEP	≈ 10 cmH_2O → > 15 cmH_2O

ALTERNATIVE TREATMENTS

- ECMO
- $ECCO_2$-R
- Neuromusc.Blockade
- Prone Position
- HFO

Thank you for your attention

Grazie