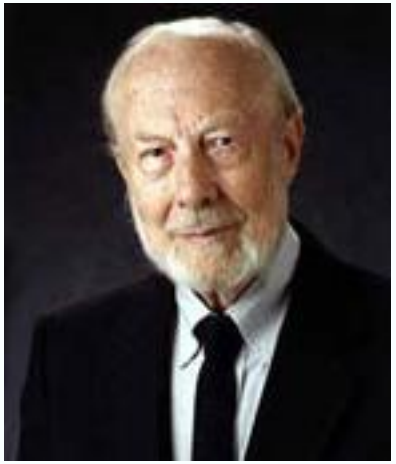
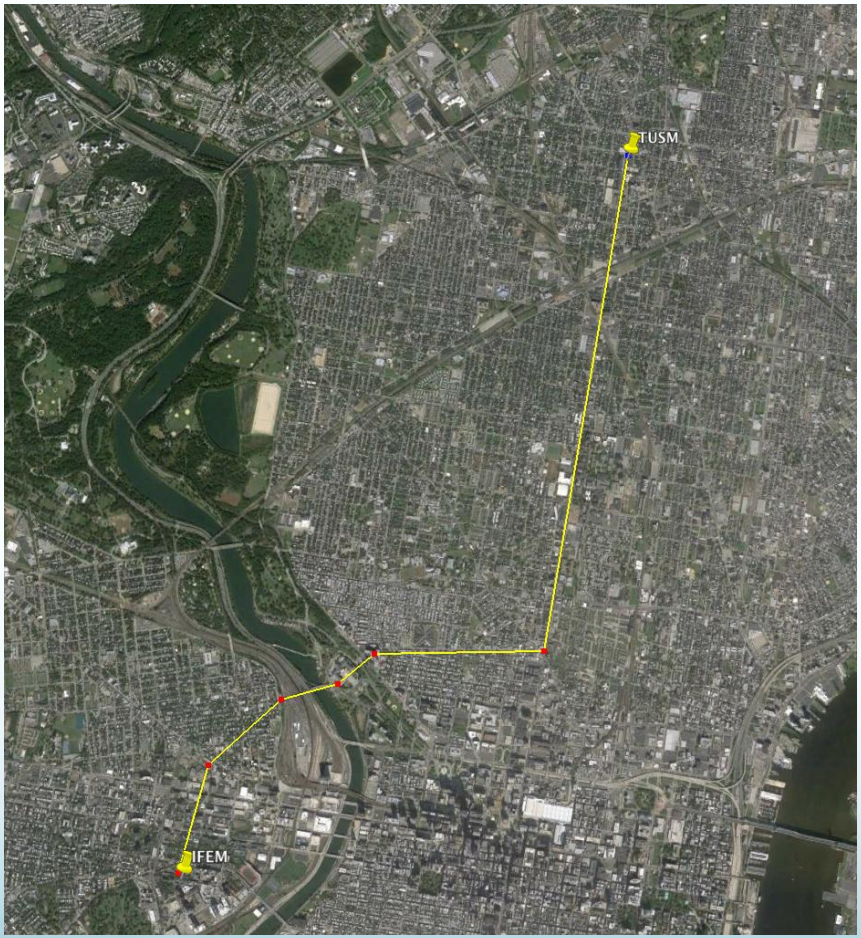
Lung Injury With Diving - Beyond Boyle's Law

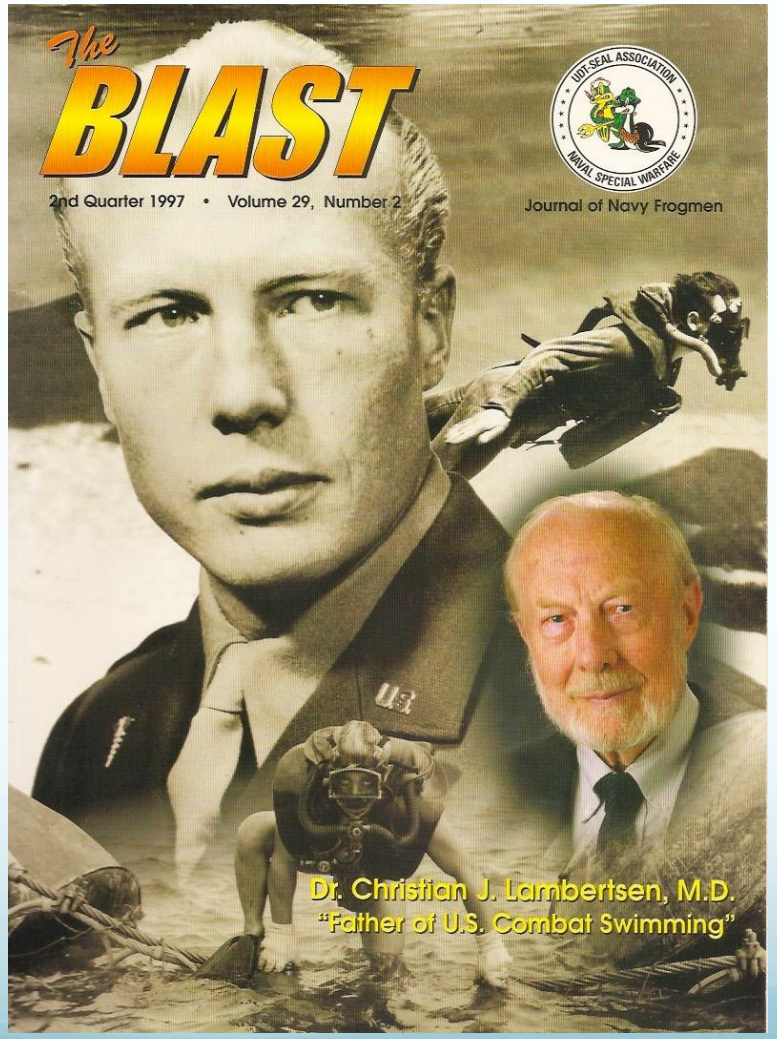
Alfred A. Bove, MD, PhD, FUHM
Temple University School of Medicine
Philadelphia, Pa

Chris Lambertsen
1917 - 2011





The 1997 Tribute



Disclosures

Honorarium - Underwater Medicine Associates

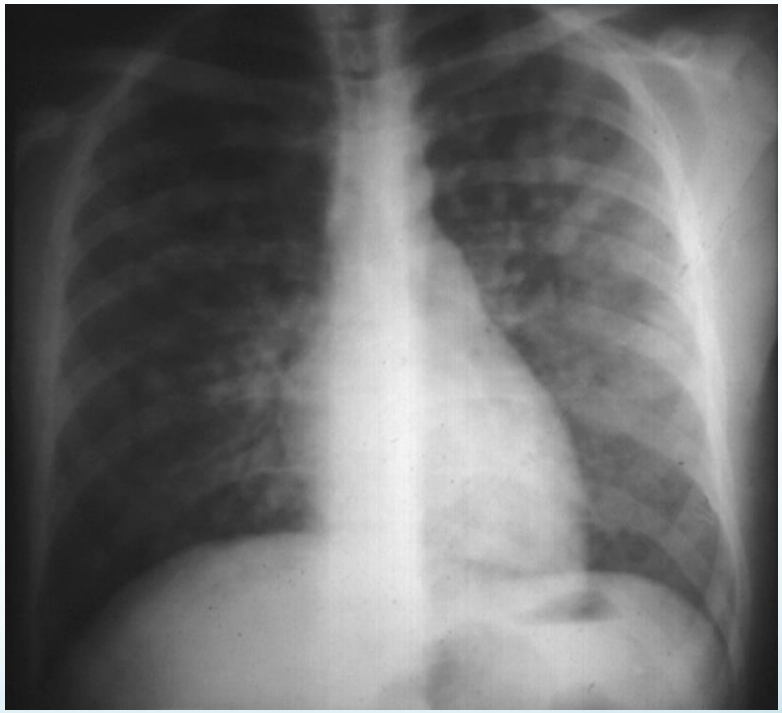
Royalty - Elsevier Sciences

Royalty - Merck

IPE

Clinical: 36 y.o. male. Coast of Maine, 60 ft/12 min. Dyspnea at depth, controlled ascent, cyanosis, cough with pink sputum, rales

- **ABG**
  - **PO2 75**
  - **PCO2 36**
  - **Ph 7.30**
  - **% Sat 84**



SIPE

- **A 61 yo female, 5’5” & 115 lbs. otherwise healthy, no hx of heart disease. Life-long athlete. Trains 5 - 6 days per wk (running, biking, swimming, rowing) @ moderate intensity. Competed in running races, ocean swims & 1 triathlon during the summer.**

- **Started the event with heavy exertion. Once underway, severe chest tightness while swimming. This situation worsened during the course of the ¼ mi swim. She had to stop and tread water, wheezing/ gasping for air.**

- **During the bike ride (10 miles) she was coughing up salty tasting, pink foamy fluid that was worsened by increasing speed. This continued throughout the run (3.1 mi).**

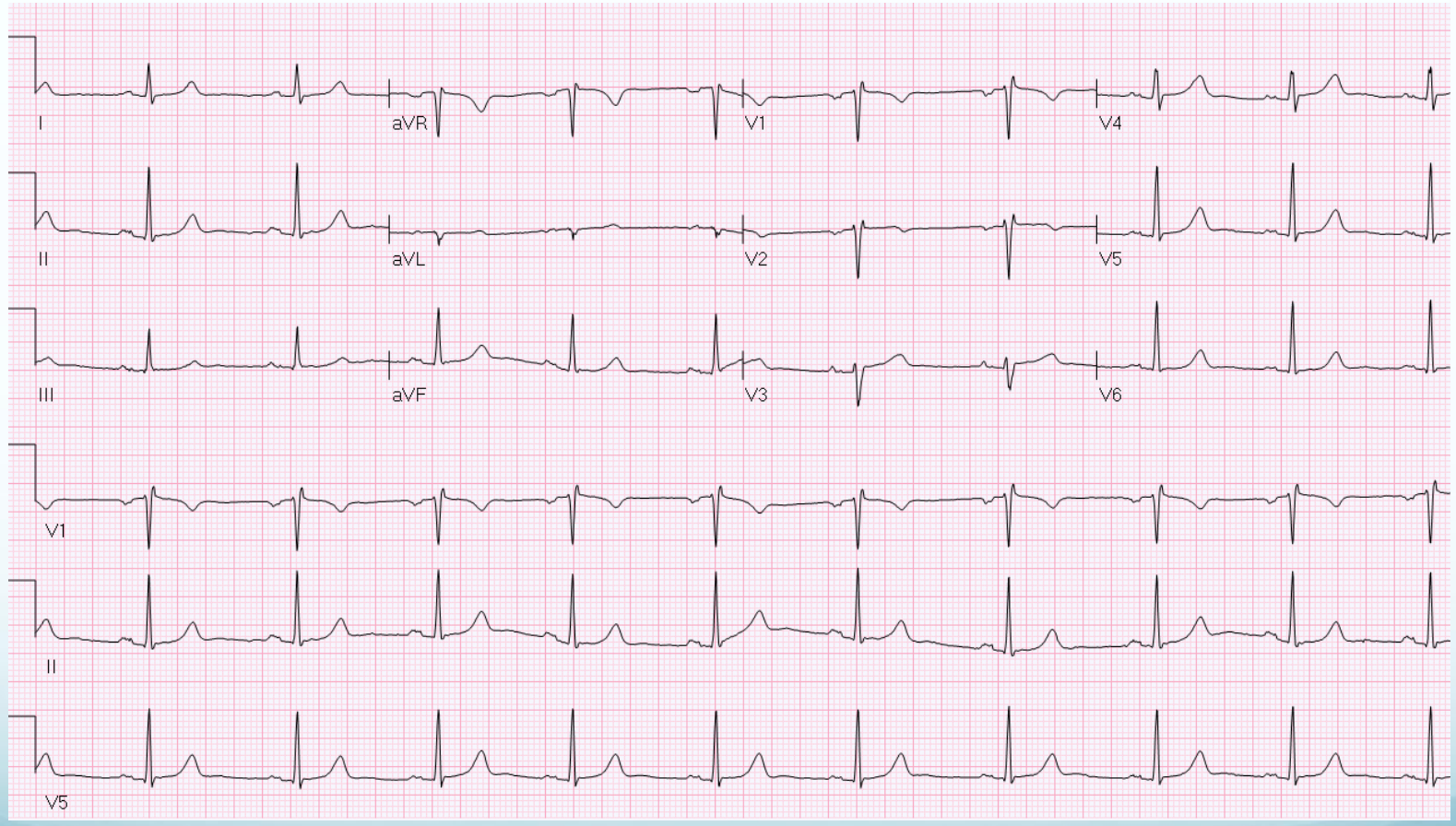
SIPE

- Exam normal BP 144/86, P 66
- Echo
  - LVDd 4.6 cm
  - LVDs 2.3 cm
  - VS,PW 9 mm
  - EF65%
  - Trace MR
  - Grade I Diastolic Dysfunction
- ECG normal
  - SR
  - HR 64
- Chest CT
  - 3rd day: Ground glass infiltrates throughout
  - 7th day: all findings resolved

Stress Test

Bruce stage 5 (16 mets)
Normal ECG response
No perfusion defects
Hypertensive response

SIPE



Mechanisms

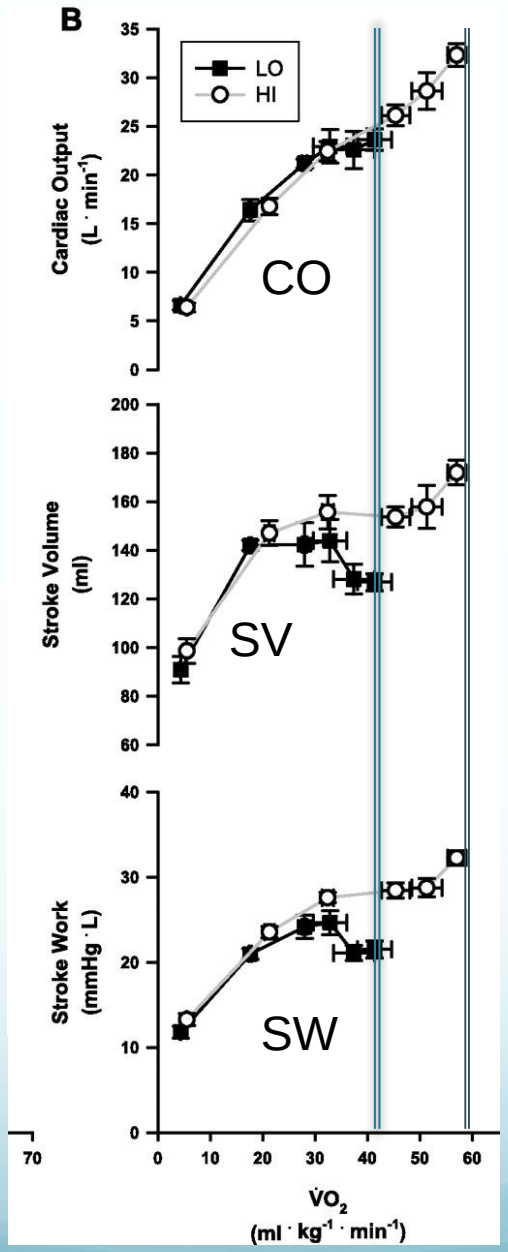
- Immersion Induced central blood shift
  - 500-600 Ml
  - Increased volume load
- Impaired Diastolic LV relaxation
  - Increased LVEDP with volume loading
  - Increased pulmonary venous pressure
- Exercise induced increase in cardiac output
- Increased afterload from cold exposure

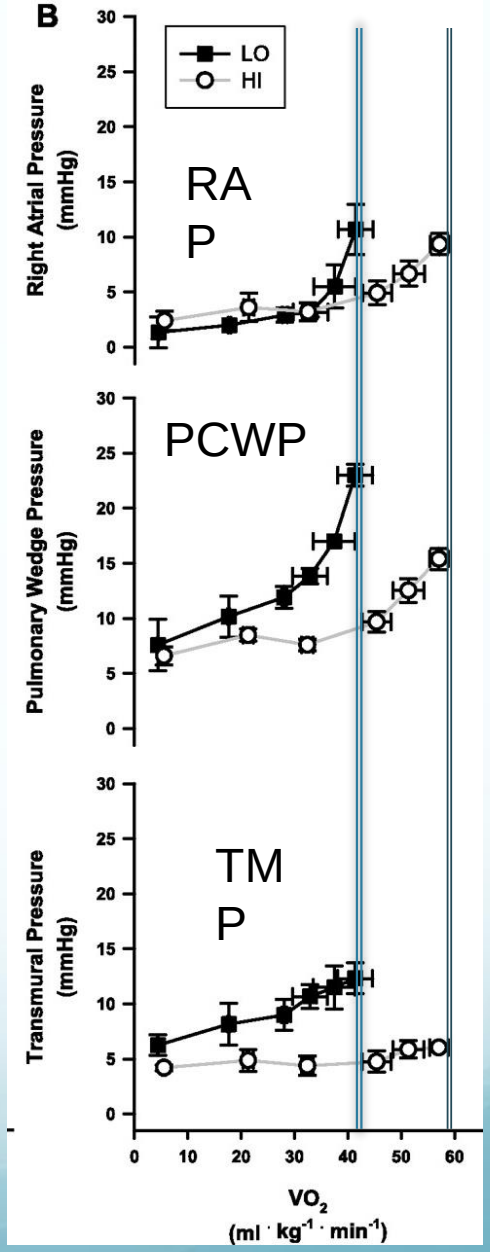
Diastole

- Training Effects

	LO (n = 3)	HI (n = 5)
Age, yr	29.7±2.0	29.6±2.1
Height, cm	179±1	182±2
Mass, kg	83.9±3.8	75.9±1.8
BSA m2	2.0±0.0	2.0±0.0
MVO2 ml/kg/min	43.3±3.4	60.2±1.4*

Stickland, M. K. et al.
J Appl Physiol 2006;100:1895





THE LANCET, JANUARY 14, 1989

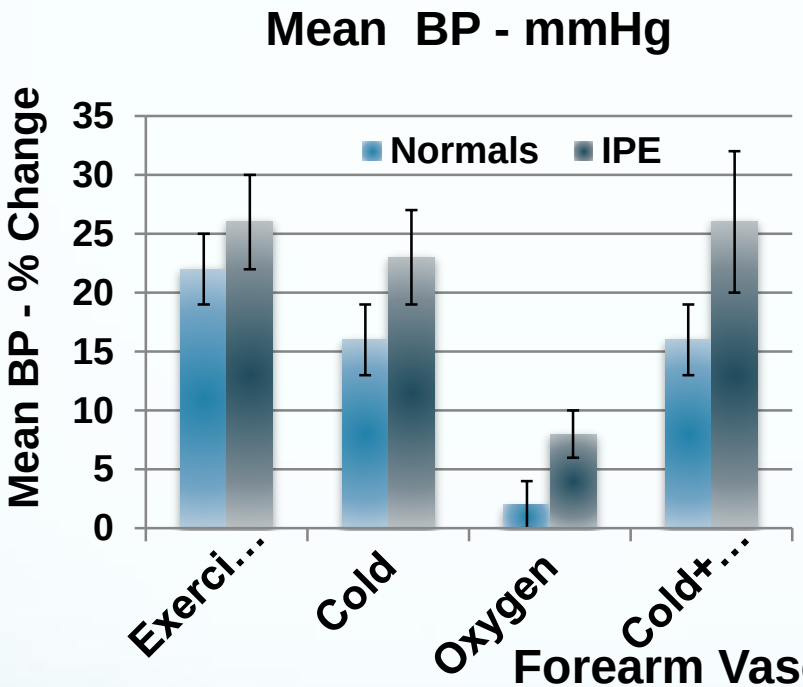
COLD-INDUCED PULMONARY OEDEMA IN SCUBA DIVERS AND SWIMMERS AND SUBSEQUENT DEVELOPMENT OF HYPERTENSION

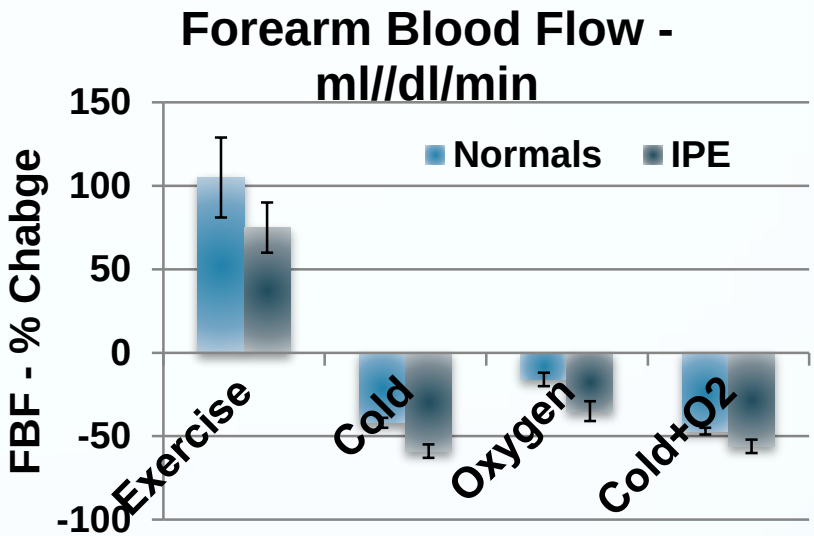
P. T. WILMSHURST
A. CROWTHER
M. NURI*
M. M. WEBB-PEPLOE

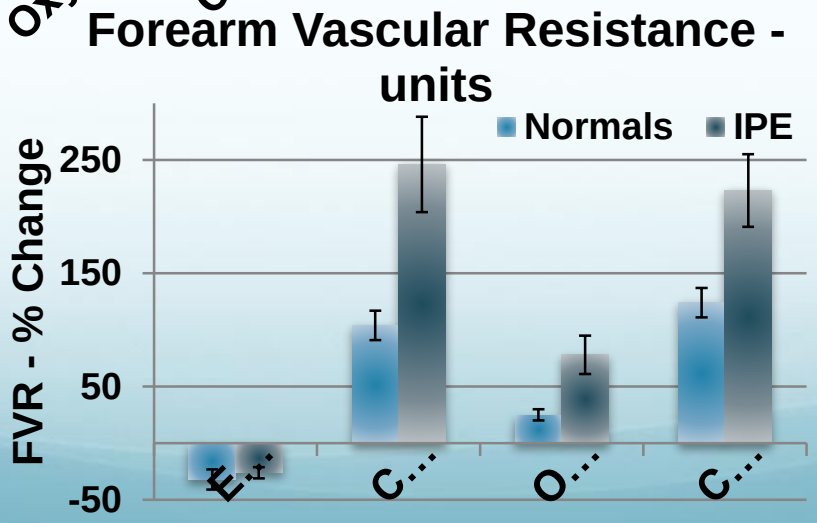
Department of Cardiology, St. Thomas' Hospital, London SE1 7EH

Eleven divers (three female) each of whom had had up to seven episodes of pulmonary oedema when in water were compared with ten divers (two female) with a similar length of diving experience but no cardiorespiratory symptoms. There was no significant difference in age between the abnormal divers (mean 45-6, SE 2-6, range 38-60 years) and the normal divers (40-8,4-4,23-66 years), or in height or weight.

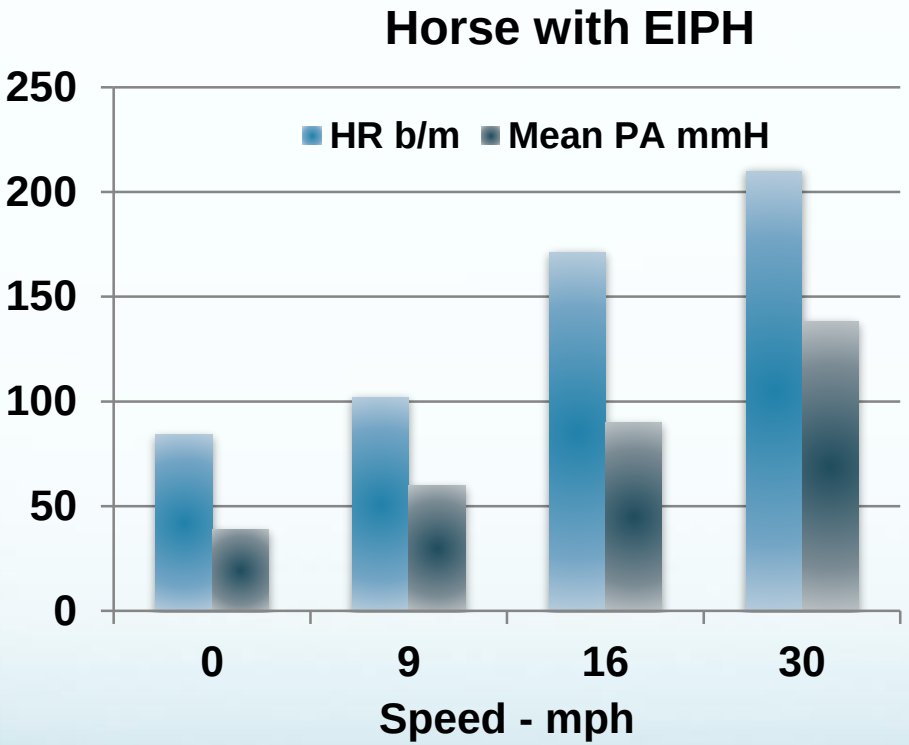
Wilmshurst et al 1989



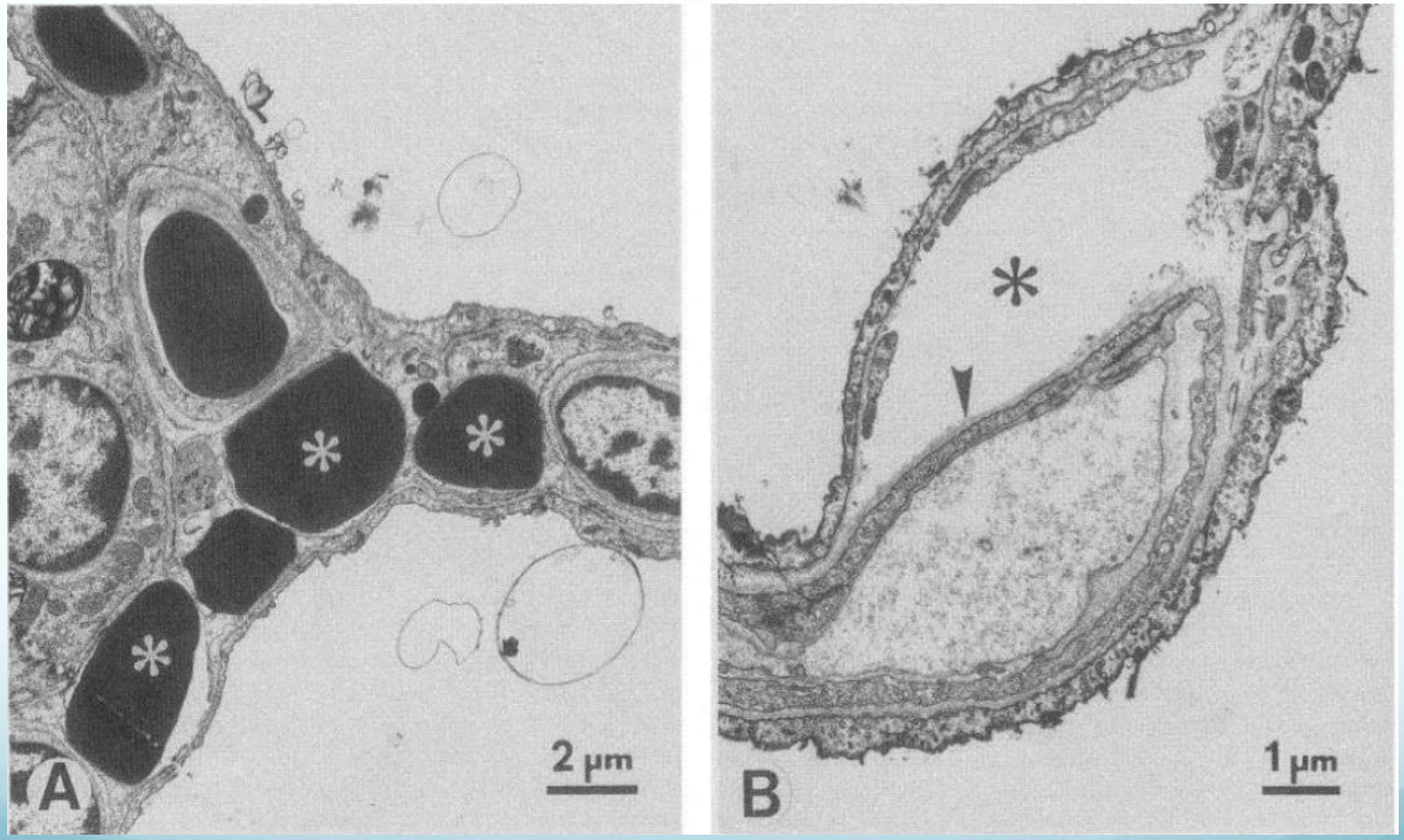




West Et al 1992



Horse with EIPH

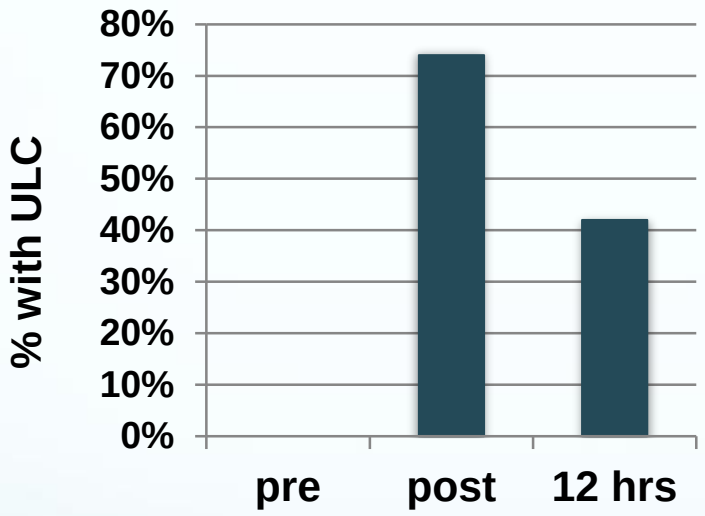


West 1992

Reduce capillary wall stress
- Reduce capillary hydrostatic pressure, possibly by increasing contractility of left ventricle
- Avoid large falls in alveolar pressure, e.g., by relieving any upper airway obstruction
- Avoid overinflation of alveoli

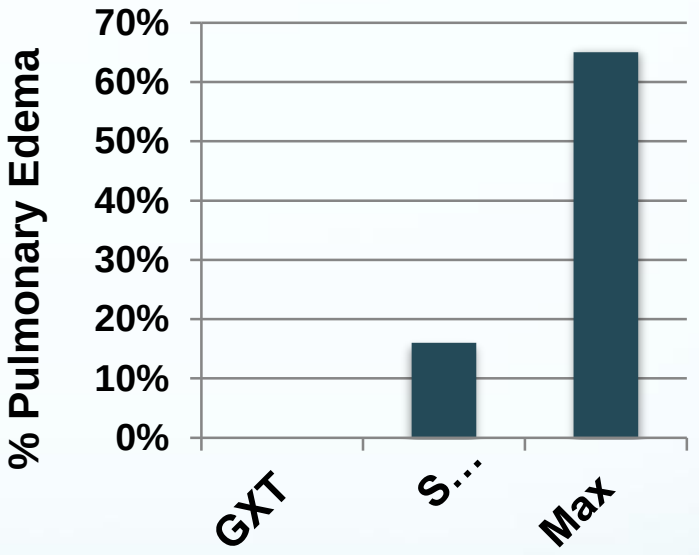
Exercise Effects

Ultrasound Lung Comets post Ironman



Pingitore A Am J Physiol Heart Circ Physiol. 2011;301:H2161

X-ray evidence of PE



Zavorsky GS Acta Physiol (Oxf). 2007;189:305

SIPE

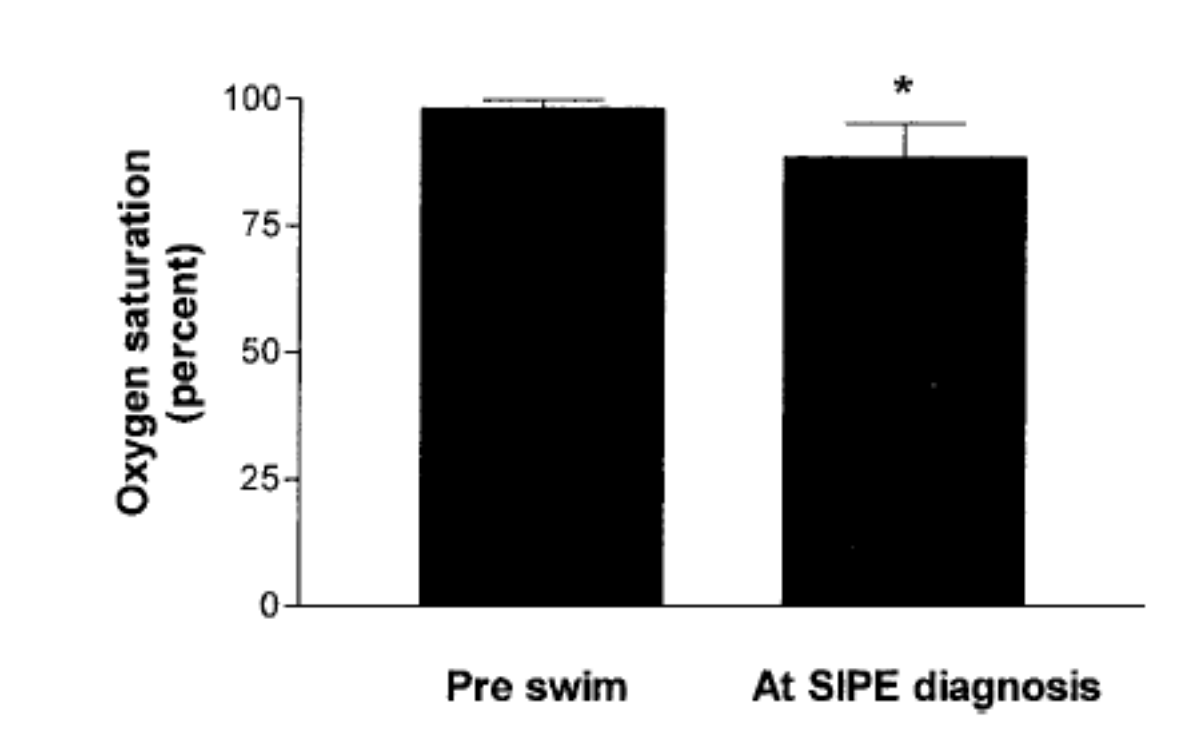
Swimming-Induced Pulmonary Edema*

Clinical Presentation and Serial Lung Function

Yochai Adir, MD; Avi Shupak, MD; Amnon Gil, MD; Nir Peled, MD; Yoav Keynan, MD; Liran Domachevsky, MD; and Daniel Weiler-Ravell, MD, FCCP CHEST 2004; 126:394–399

Symptoms and Signs	Subjects, No. (%)
Dyspnea	70 (100)
Cough	67 (95.7)
Hemoptysis	39 (55.7)
Sputum production	63 (90)
Chest pain	6 (8.6)
Basal inspiratory crackles	64 (91)
Wheezing	6 (8.6)

SIPE



Adir et al. CHEST 2004; 126:394–399

SIPE-Risk Factors

Variable	% Cases	OR	P
Age >50	4.5	3.35	.09
Female	3.0	2.08	.07
HTN*	8.2	4.87	.002
Diabetes	14.3	7.63	.14
Fish Oil*	4.6	3.10	.003
Fluid > 1 liter	3.9	2.18	.08
Wetsuit*	3.7	2.73	.007
> 1 mile*	5.5	3.32	.004

Miller et al. American Journal of Emergency Medicine 2010;28, 941

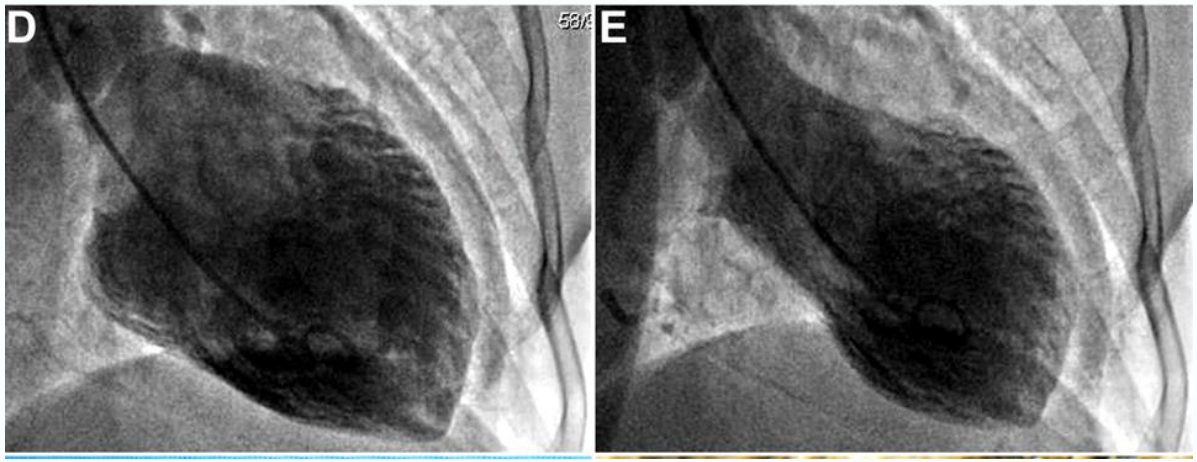
IPE Predictors

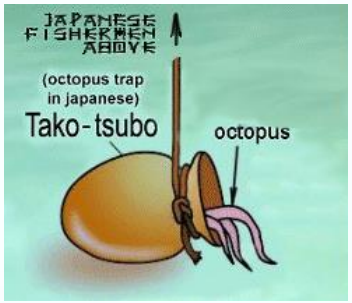
- Gempp et al - 73 cases of IPE

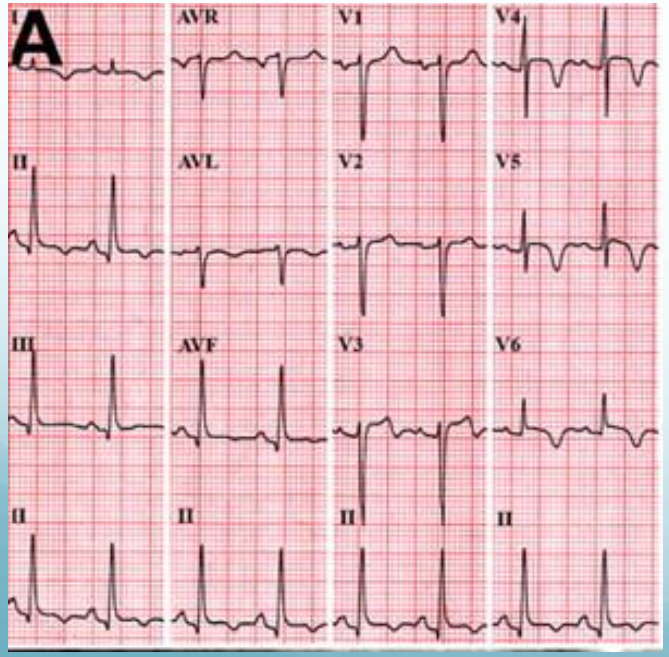
depth fsw	105±35		
dive time	28±12		
Temp F°	60±31		
age	48±10		
BMI	25		
male	47	64%	
female	26	36%	
HTN	24	33%	⇐ Recurrence Risk
DM	1	1%	
Heart Dis	2	3%	
pulm Dis	4	5%	
Stress	26	36%	?

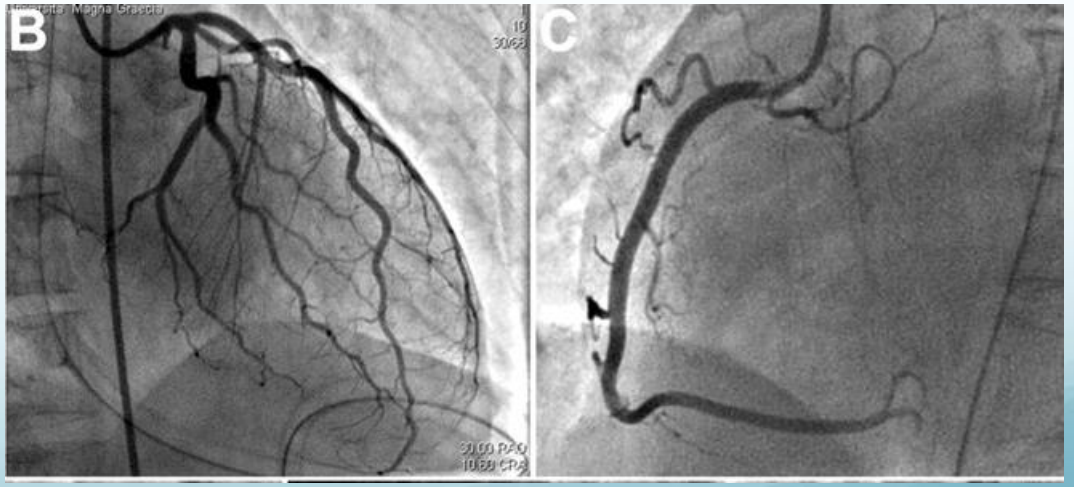
Gempp et al. Int J Cardiol. 2014;172:528-9

Tako-stubo ?

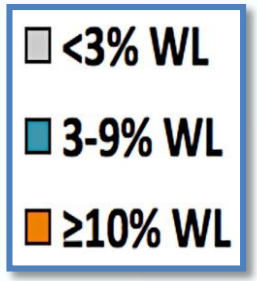

D
E


JAPANESE FISHERMEN ABOVE
(octopus trap in japanese)
Tako-tsubo
octopus

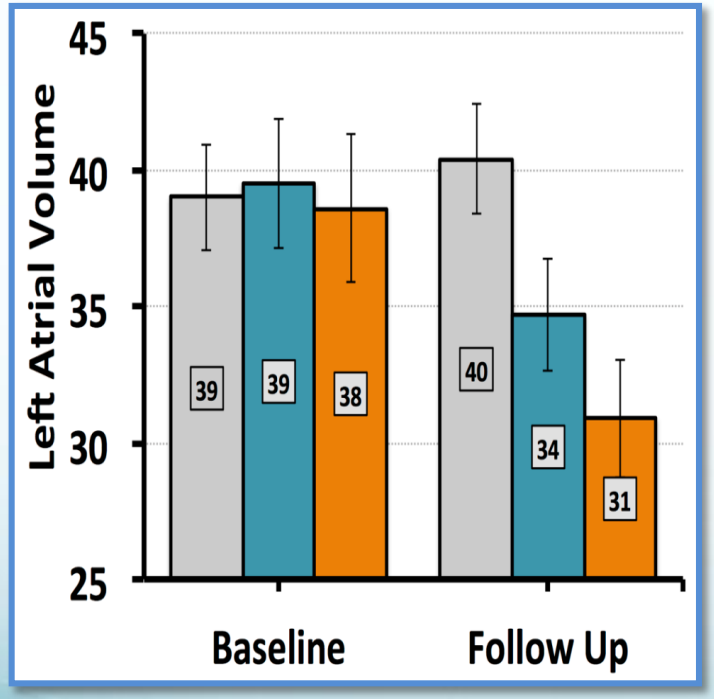

A
I
AVR
V1
V4
II
AVL
V2
V5
III
AVF
V3
V6
II
II
II
II


B
C

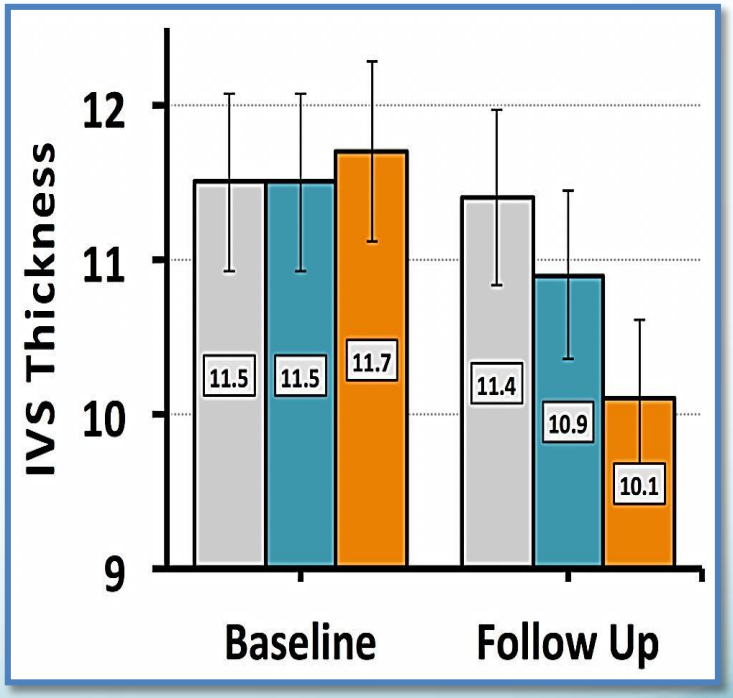
Structural Remodeling In Obesity



LA Volume (Indexed)

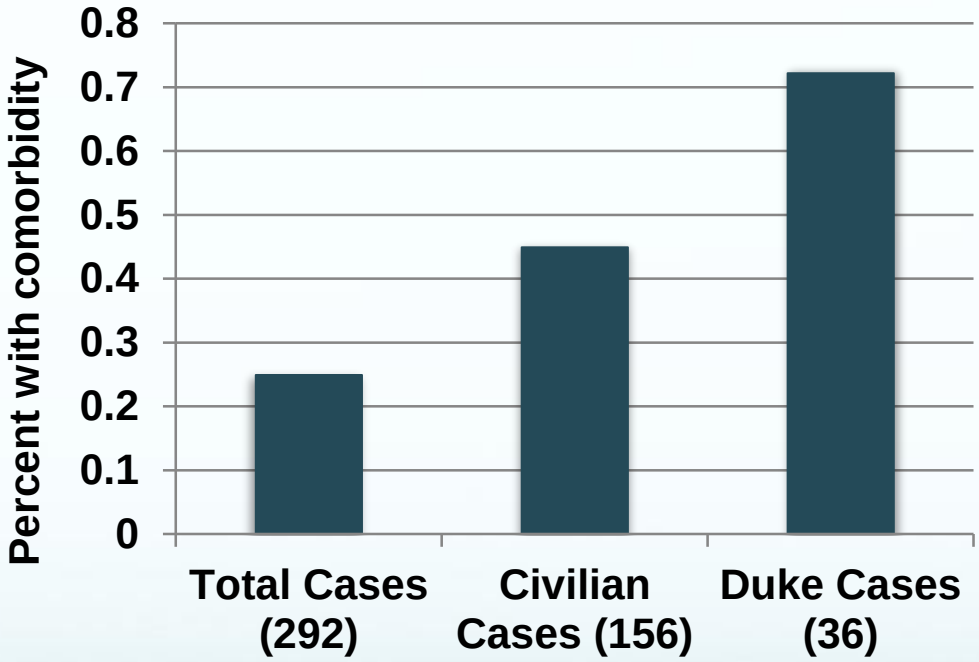


Septal Dimension



Pathak et al ACC 15, *Abed et al. JAMA 2013*

IPE Comorbidities

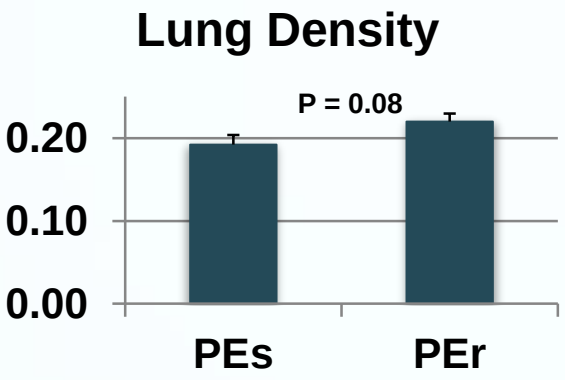


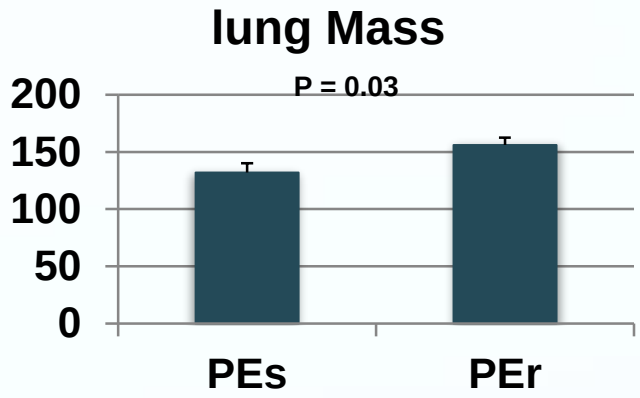
Peacher et al. Med Sci Sports Exerc. 2014 Sep 12

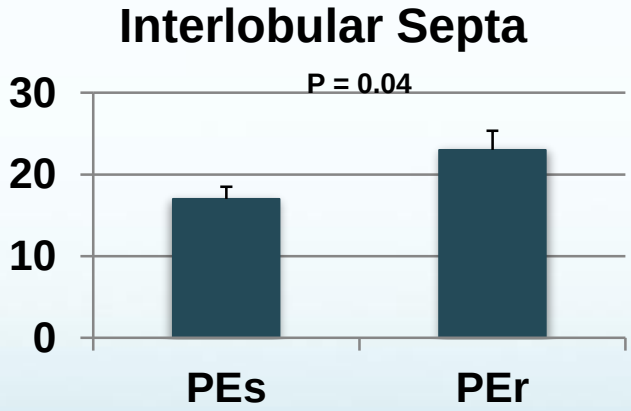
IPE Reported Conditions

- Age
- Asthma
- Atrial Fibrillation
- Coronary Disease
- Cardiomegaly
- Cardiomyopathy
- Diabetes
- Hyperlipidemia
- Hypertension
- LVH
- Obesity
- Obstructive Sleep Apnea
- Peripheral Arterial Disease
- Valvular Heart Disease

Lung Susceptibility – IPE/HAPE



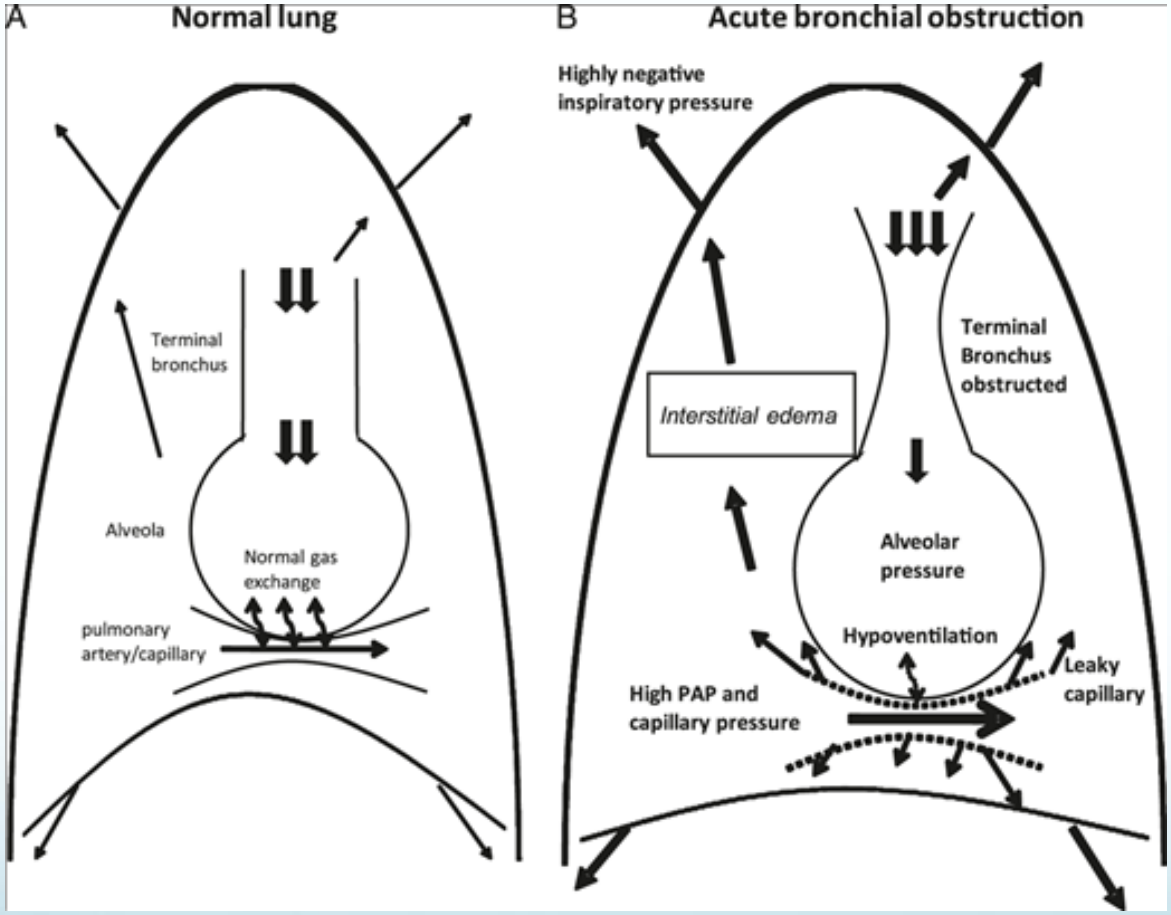




S- Susceptible
R - Resistant

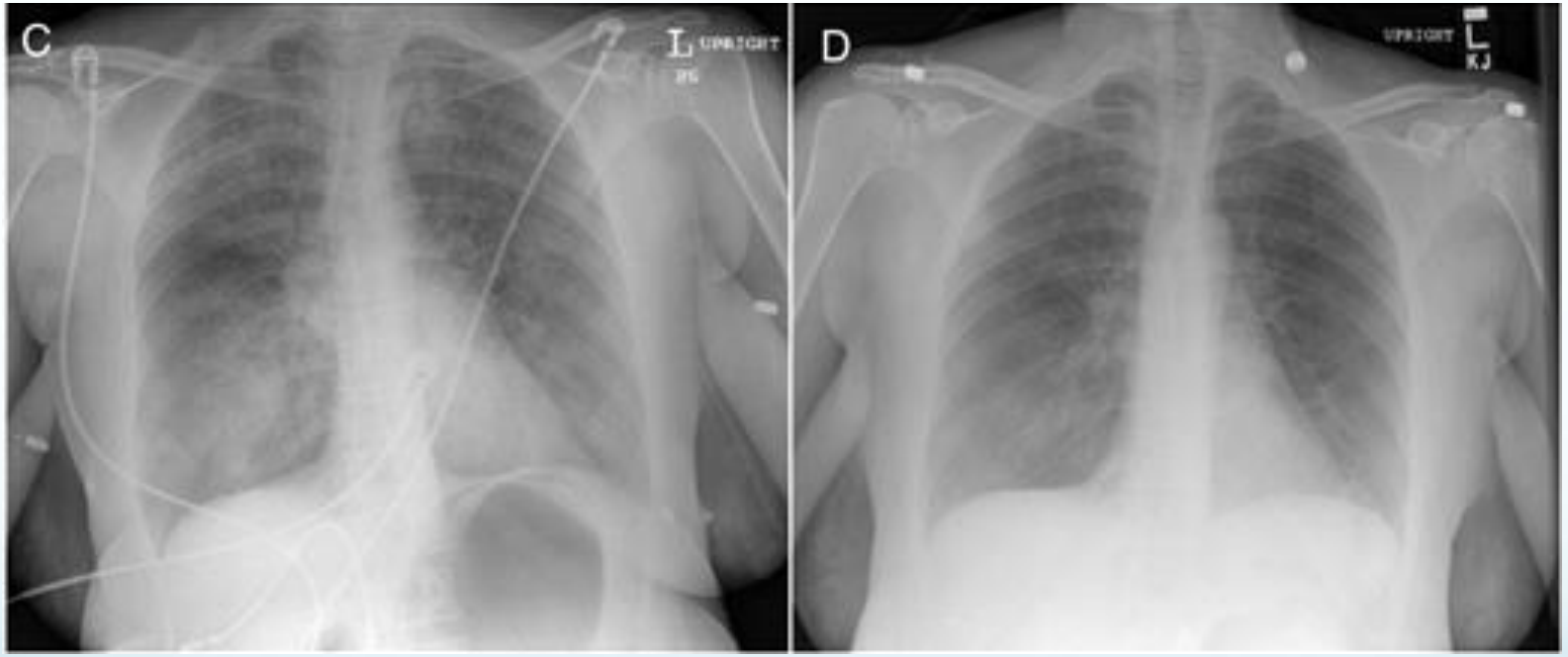
Carter et al. Aviat Space Environ Med 2014;85:9-14

Negative Pressure Pulmonary Edema



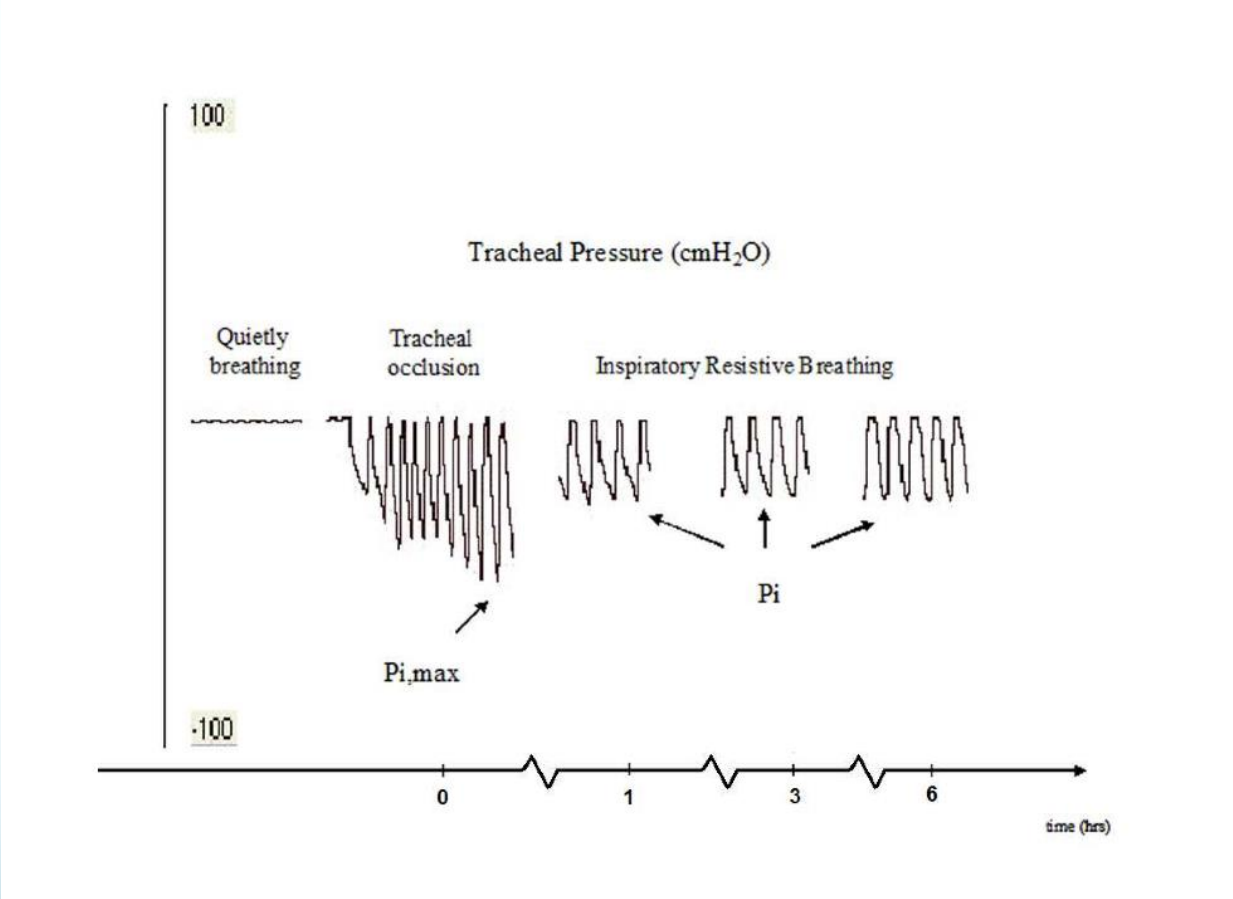
Negative Pressure Pulmonary Edema Following Bronchospasm Krodel DJ et al. *Chest.* 2011;140:1351-1354

Negative Pressure Pulmonary Edema



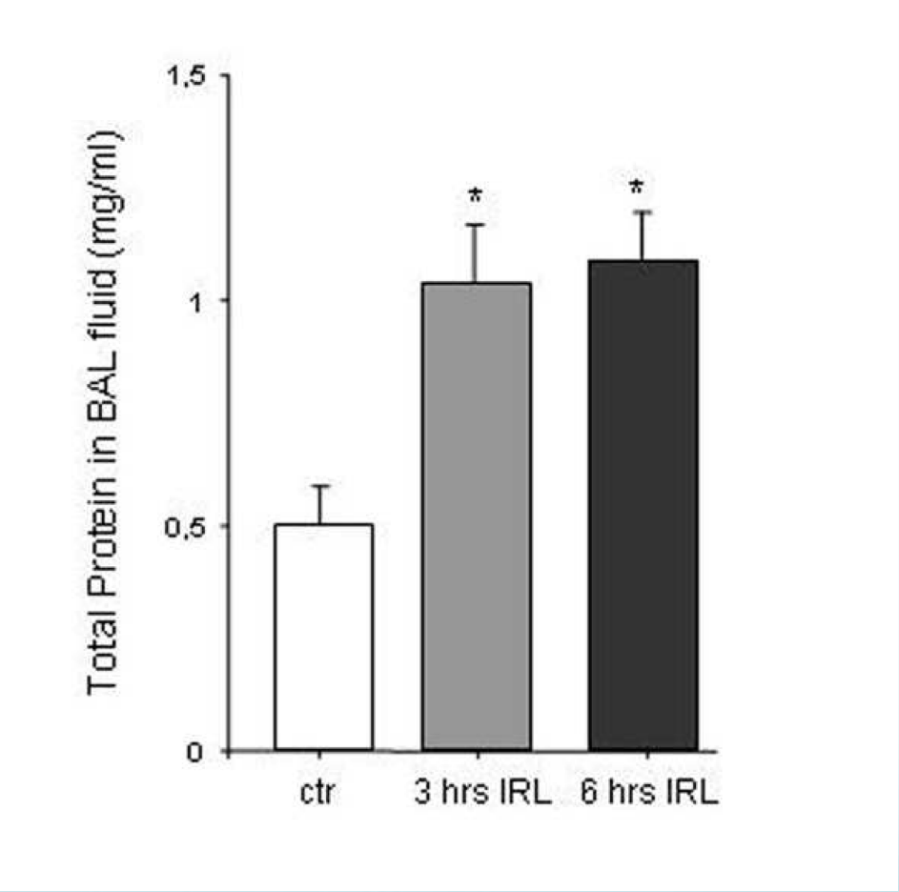
Negative Pressure Pulmonary Edema Following Bronchospasm Krodel DJ et al. *Chest.* 2011;140:1351-1354

Increased Inspiratory Resistance



Toumpanakis D, etal. Inspiratory resistive breathing induces acute lung injury. Am J Respir Crit Care Med. 2010;182:1129-36

Increased Inspiratory Resistance



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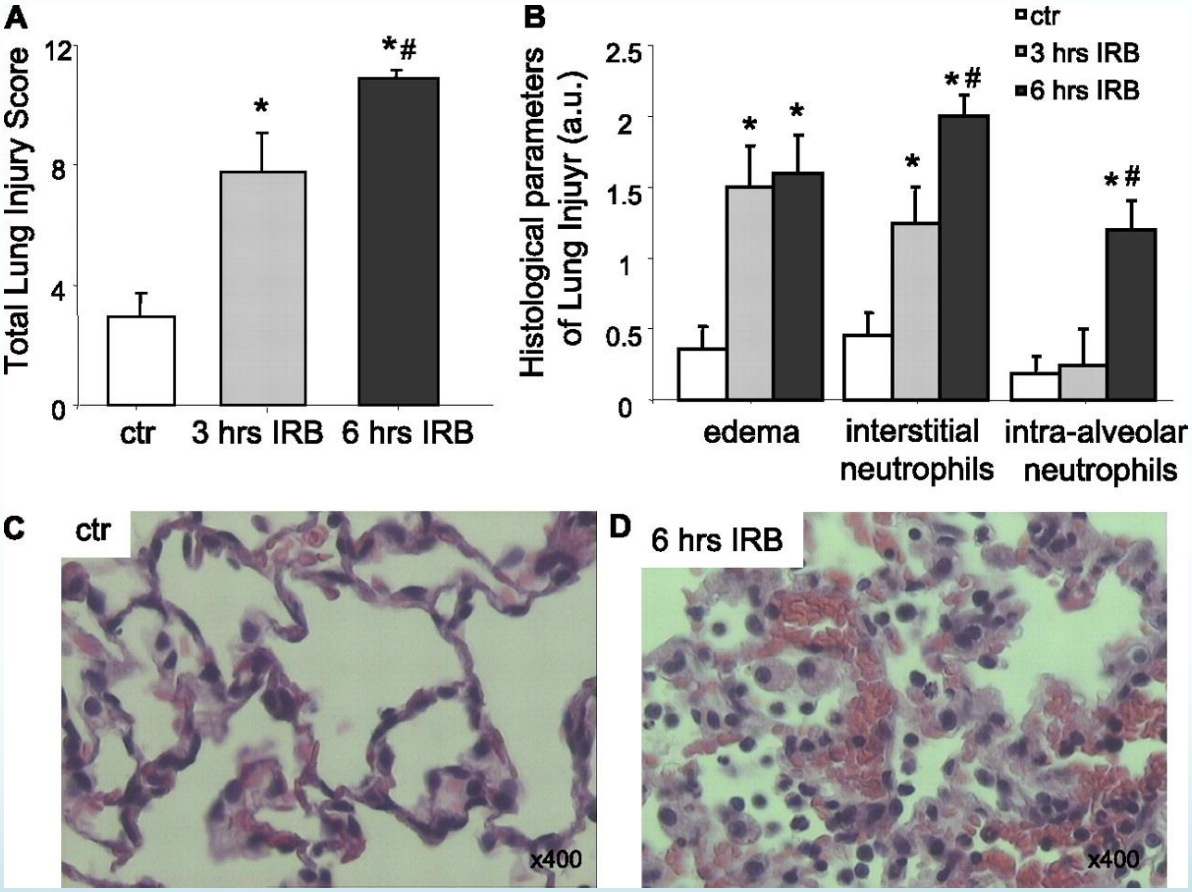
Increased Inspiratory Resistance



Toumpanakis D, etal. Inspiratory resistive breathing induces acute lung injury. Am J Respir Crit Care Med. 2010;182:1129-36

IPE/SIPE/EIPH/NPPE

- Fluid and blood leaking from capillaries into alveoli
- Increased Pulmonary Venous Pressure
  - Diastolic Dysfunction
  - Systolic Dysfunction (Tako-Tsubo)
  - Fluid Overload
  - Increased Afterload
  - High Cardiac output
- Decreased Intraalveolar Pressure
  - Increased Inhalation resistance
  - Vigorous chest expansion
- Increased Pulmonary Vascular Volume
  - Fluid overload
  - Immersion
  - Deep breath hold diving
- Increased lung susceptibility
  - Fewer lymphatics
  - Lower Lung Density
  - Weak capillaries (horses)

Prevention

- **Health evaluation**
- **Equipment evaluation**
- **Fluid volume regulation**
- **Minimize sudden onset of extreme exercise**
- **Maintain good physical conditioning**
- **Avoid cold exposure**
- **Medications**
  - **Diuretics banned in race horses**

What about Robert Boyle?

$$r = KP$$

$$PV = K$$

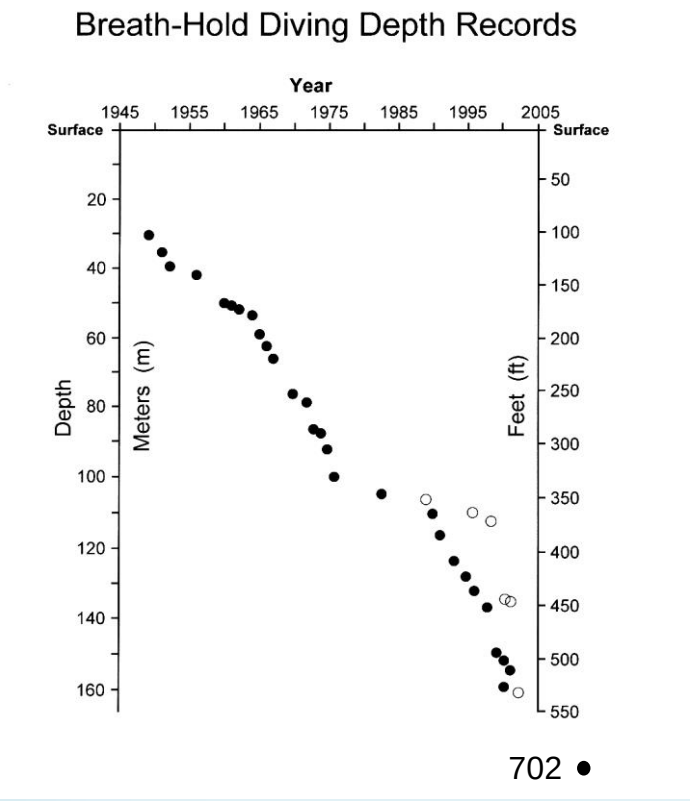
Robert Boyle

Robert Boyle (1627–91)

Born	25 January 1627 Lismore, County Waterford, Ireland
Died	31 December 1691 (aged 64) London, England
Fields	Physics, chemistry
Known for	Boyle's law, founder of modern chemistry
Influences	Galileo Galilei, Otto von Guericke, Francis Bacon, Samuel Hartlib[1]
Influenced	Isaac Newton; Is considered the founder of modern chemistry
Notable awards	Fellow of the Royal Society

Free Diving

Lung Injury with Breath hold Diving

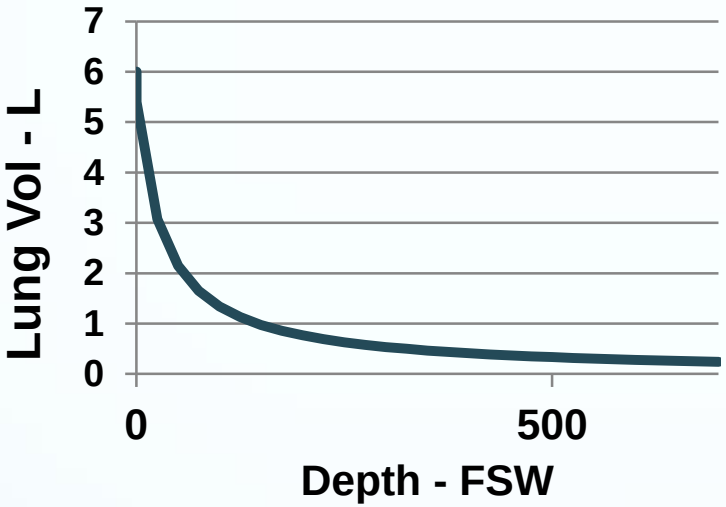


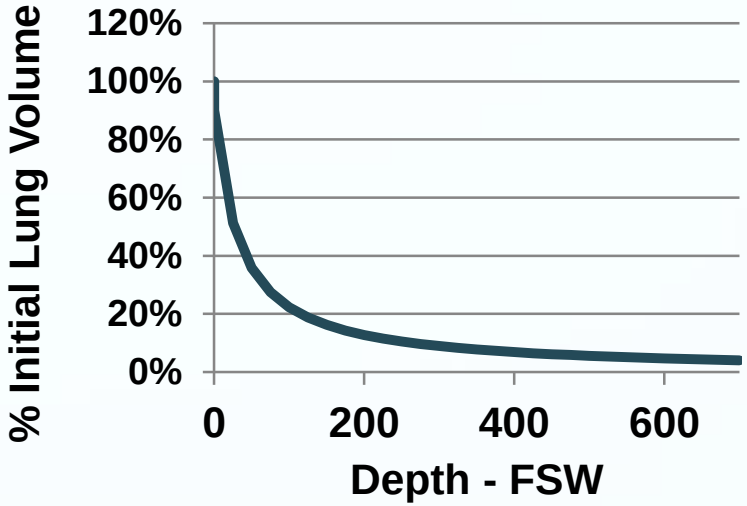
Free Diver Dies Trying to Break World Record

Oct. 17 2002

Champion free diver Audrey Mestre took a single breath, then dove 561 feet to try to try to break a world record. But the 28-year-old French woman did not make it back up alive.

Lung Volume vs. Depth





214 m = 22.4 ATA
6/22.4 = 0.268L
= 4.5% of TLC

Breath Hold Pulmonary edema

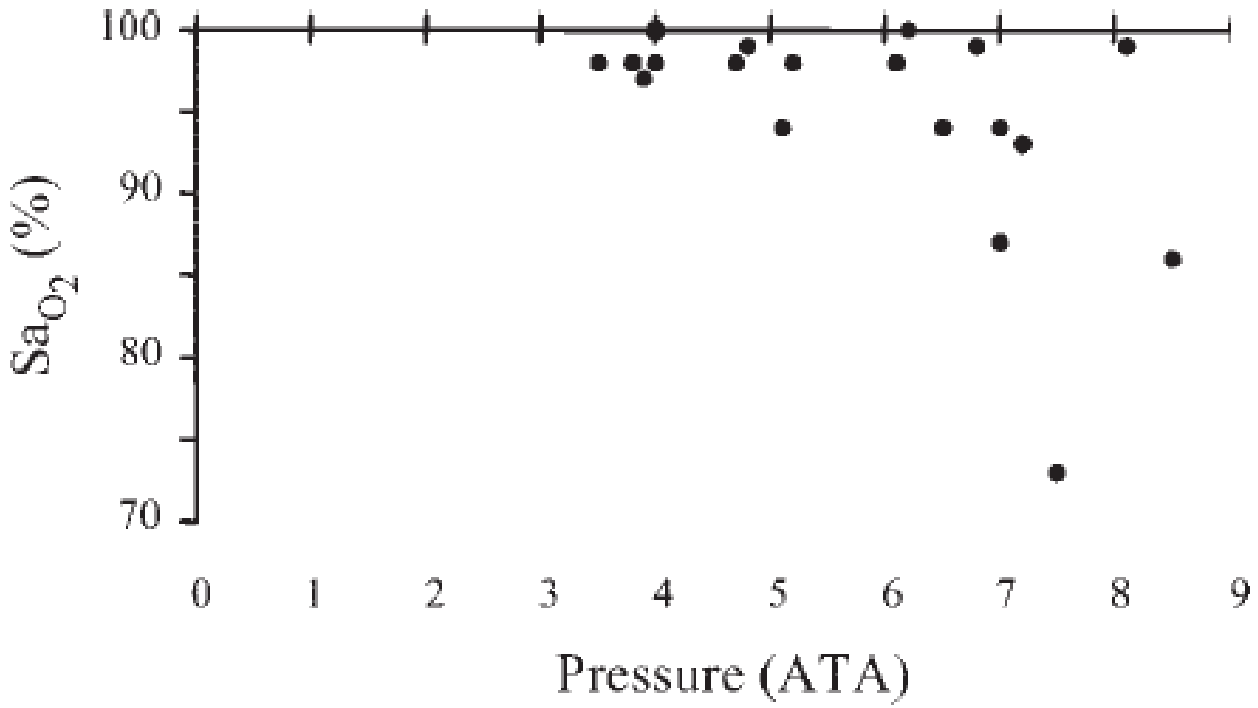
	FVC, liters	FEV_1, liters
Control	6.1 (1.2)	4.6 (0.9)
Post-DYN	6.0 (1.2)	4.6 (0.9)
Post-DIVE	5.5 (1.2)	4.0 (1.1)
	$P < 0.01$	$P < 0.01$

19 Divers in BH dive competition.
Mean Age 31 (17-42)
Mean depth 48m (25-75)
9/19 – previous PE symptoms
Dyspnea 2/19
Chest pain 5/19
Hemoptysis 3/19
Rales 4/19

Liner et al. *J Appl Physiol* 2008;104: 986

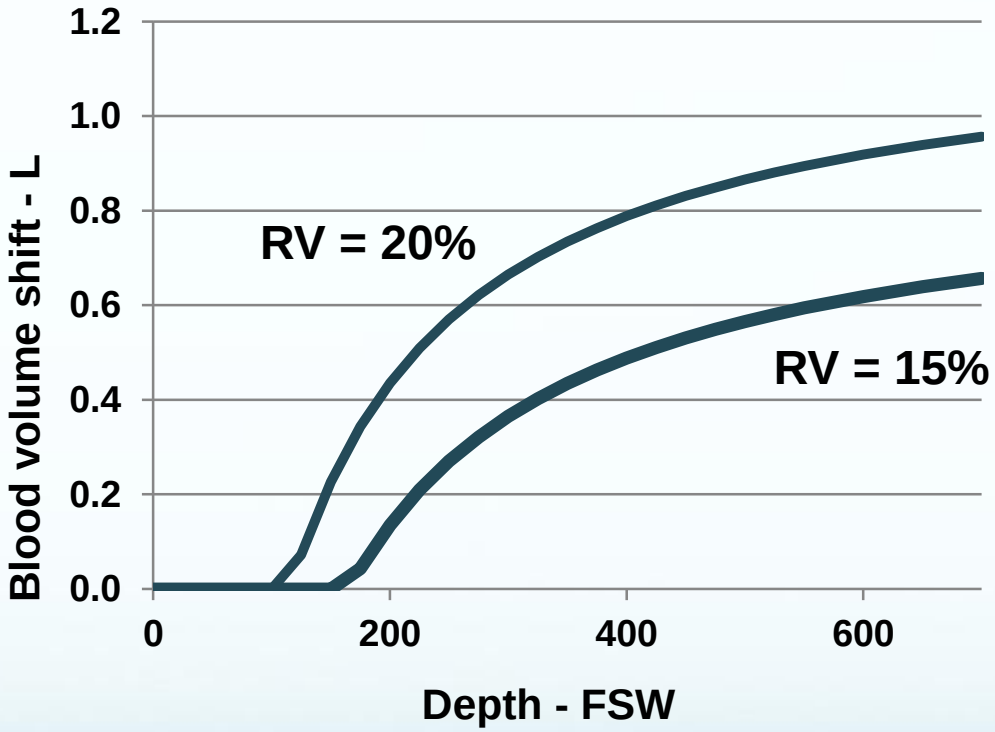
Breath Hold Pulmonary edema

Post Dive

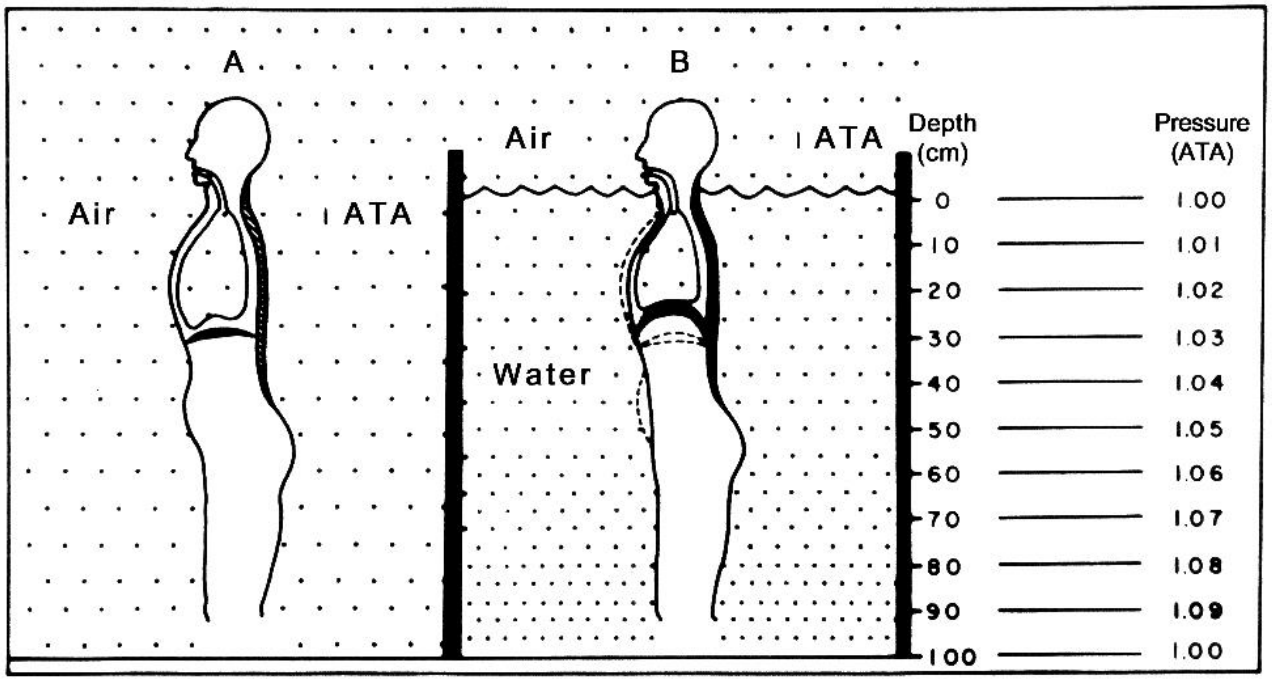


Liner et al. *J Appl Physiol* 2008;104:986

Lung Dynamics

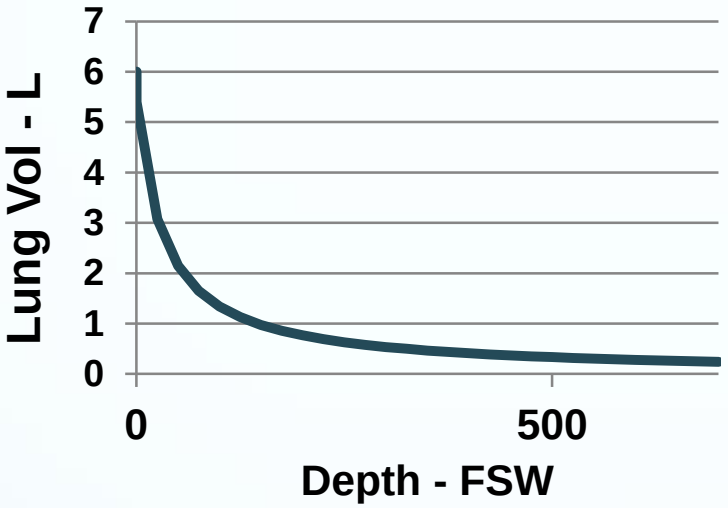


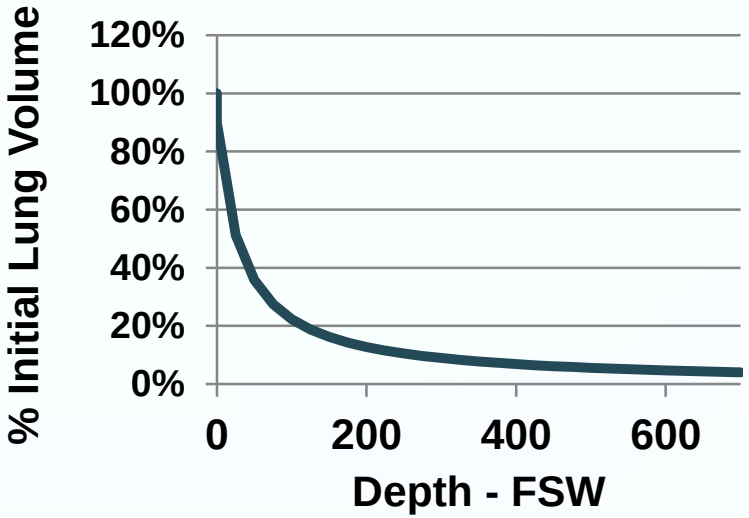
Immersion



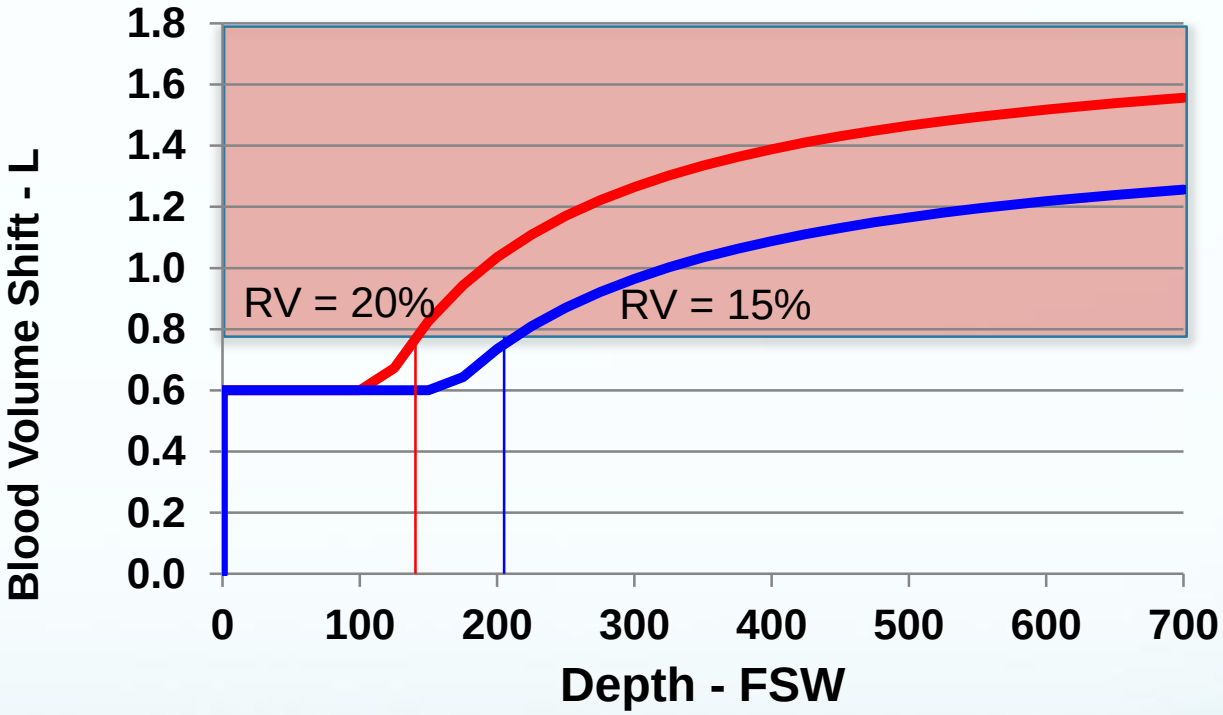
Ferrigno, M. Breath Hold diving. In Bove AA Diving Medicine 4th ed. Elsevier 2004

Immersion Effects





Depth + Immersion



Conclusion

- **Mechanisms of lung Capillary stress with deep BH diving are similar to those present in SIPE/IPE**
- **Divers should be educated about factors that can cause lung injury not related to Arterial Gas Embolism**
- **Avoid deep BH dives**