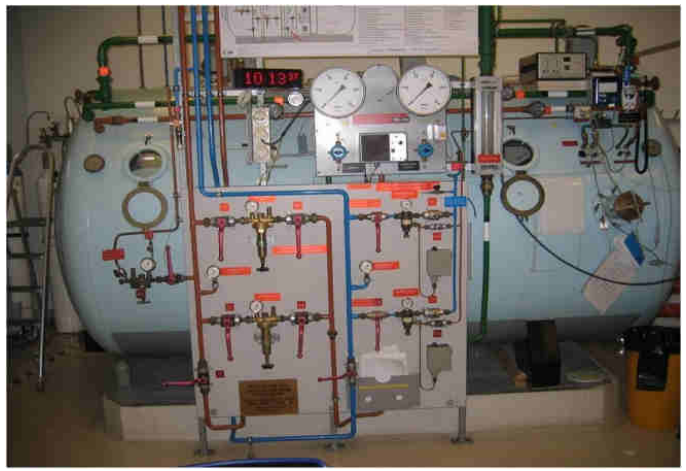
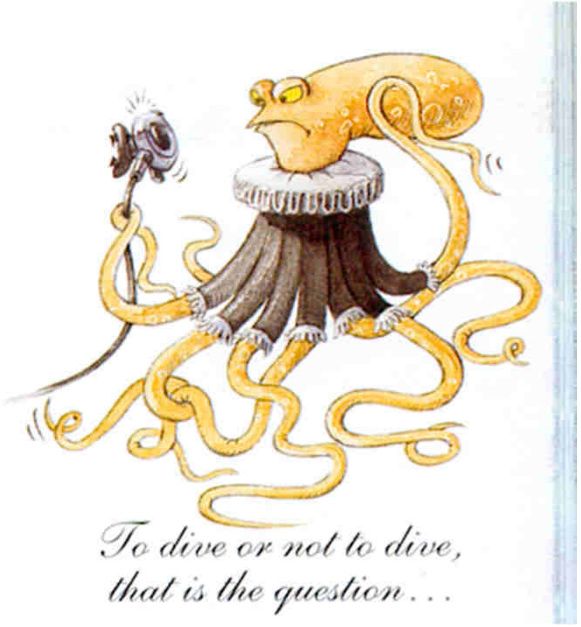
Bühlmann Symposium

Is diving a stress for pulmonary capillaries?

Francis Héritier
Service of Pneumology
Lausanne University Hospital and University of Lausanne
30.3.2019



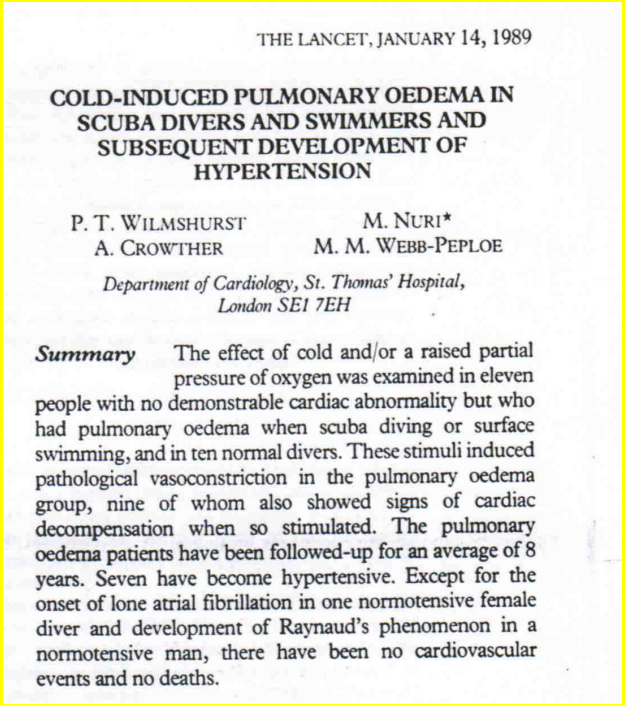
The first question I will try to answer today is not



but

Is diving a stress for pulmonary capillaries?

And the second: Could immersion pulmonary edema be explained by a capillary stress failure



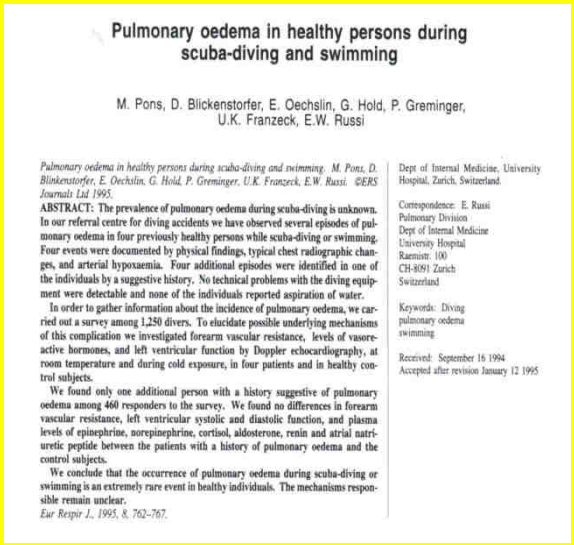
THE LANCET, JANUARY 14, 1989

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

Summary The effect of cold and/or a raised partial pressure of oxygen was examined in eleven people with no demonstrable cardiac abnormality but who had pulmonary oedema when scuba diving or surface swimming, and in ten normal divers. These stimuli induced pathological vasoconstriction in the pulmonary oedema group, nine of whom also showed signs of cardiac decompensation when so stimulated. The pulmonary oedema patients have been followed-up for an average of 8 years. Seven have become hypertensive. Except for the onset of lone atrial fibrillation in one normotensive female diver and development of Raynaud's phenomenon in a normotensive man, there have been no cardiovascular events and no deaths.



Pulmonary oedema in healthy persons during scuba-diving and swimming

M. Pons, D. Blickenstorfer, E. Oechslin, G. Hold, P. Greminger, U.K. Franzeck, E.W. Russi

Pulmonary oedema in healthy persons during scuba-diving and swimming. M. Pons, D. Blinkenstorfer, E. Oechslin, G. Hold, P. Greminger, U.K. Franzeck, E.W. Russi. ©ERS Journals Ltd 1995.

ABSTRACT: The prevalence of pulmonary oedema during scuba-diving is unknown. In our referral centre for diving accidents we have observed several episodes of pulmonary oedema in four previously healthy persons while scuba-diving or swimming. Four events were documented by physical findings, typical chest radiographic changes, and arterial hypoxaemia. Four additional episodes were identified in one of the individuals by a suggestive history. No technical problems with the diving equipment were detectable and none of the individuals reported aspiration of water.

In order to gather information about the incidence of pulmonary oedema, we carried out a survey among 1,250 divers. To elucidate possible underlying mechanisms of this complication we investigated forearm vascular resistance, levels of vasoreactive hormones, and left ventricular function by Doppler echocardiography, at room temperature and during cold exposure, in four patients and in healthy control subjects.

We found only one additional person with a history suggestive of pulmonary oedema among 460 responders to the survey. We found no differences in forearm vascular resistance, left ventricular systolic and diastolic function, and plasma levels of epinephrine, norepinephrine, cortisol, aldosterone, renin and atrial natriuretic peptide between the patients with a history of pulmonary oedema and the control subjects.

We conclude that the occurrence of pulmonary oedema during scuba-diving or swimming is an extremely rare event in healthy individuals. The mechanisms responsible remain unclear.

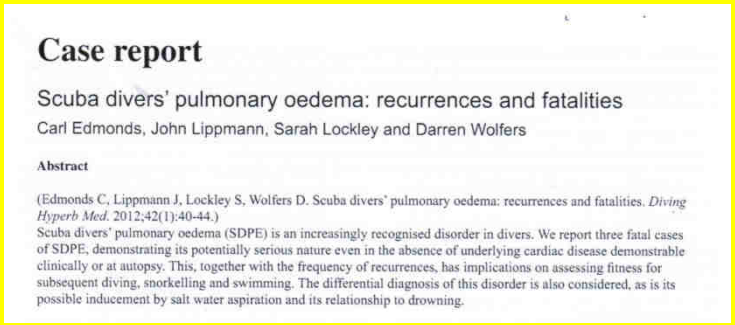
Eur Respir J., 1995, 8, 762–767.

Dept of Internal Medicine, University Hospital, Zurich, Switzerland.

Correspondence: E. Russi
Pulmonary Division
Dept of Internal Medicine
University Hospital
Raemistr. 100
CH-8091 Zurich
Switzerland

Keywords: Diving
pulmonary oedema
swimming

Received: September 16 1994
Accepted after revision January 12 1995



Case report

Scuba divers' pulmonary oedema: recurrences and fatalities

Carl Edmonds, John Lippmann, Sarah Lockley and Darren Wolfers

Abstract

(Edmonds C, Lippmann J, Lockley S, Wolfers D. Scuba divers' pulmonary oedema: recurrences and fatalities. *Diving Hyperb Med.* 2012;42(1):40-44.)
Scuba divers' pulmonary oedema (SDPE) is an increasingly recognised disorder in divers. We report three fatal cases of SDPE, demonstrating its potentially serious nature even in the absence of underlying cardiac disease demonstrable clinically or at autopsy. This, together with the frequency of recurrences, has implications on assessing fitness for subsequent diving, snorkelling and swimming. The differential diagnosis of this disorder is also considered, as is its possible inducement by salt water aspiration and its relationship to drowning.

Why swimming and scuba diving could be a stress for pulmonary capillaries?

- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

Comparison of pressures (mmHg) in the pulmonary and systemic circulations

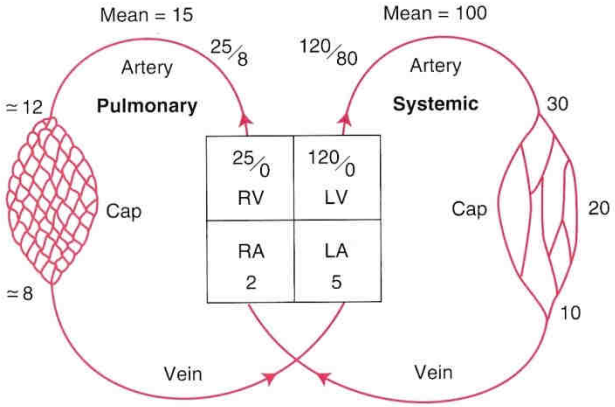
At rest, the pressures within the pulmonary circulation are remarkably low

Pulmonary circulation

Systolic pressure: 25

Diastolic pressure: 8

Mean pressure: 15



Systemic circulation

Systolic pressure : 120

Diastolic pressure : 80

Mean pressure : 100

Pulmonary artery wedge pressure < 15
(estimates the left atrial pressure)

J.B. West 2001

Effect of cardiac output

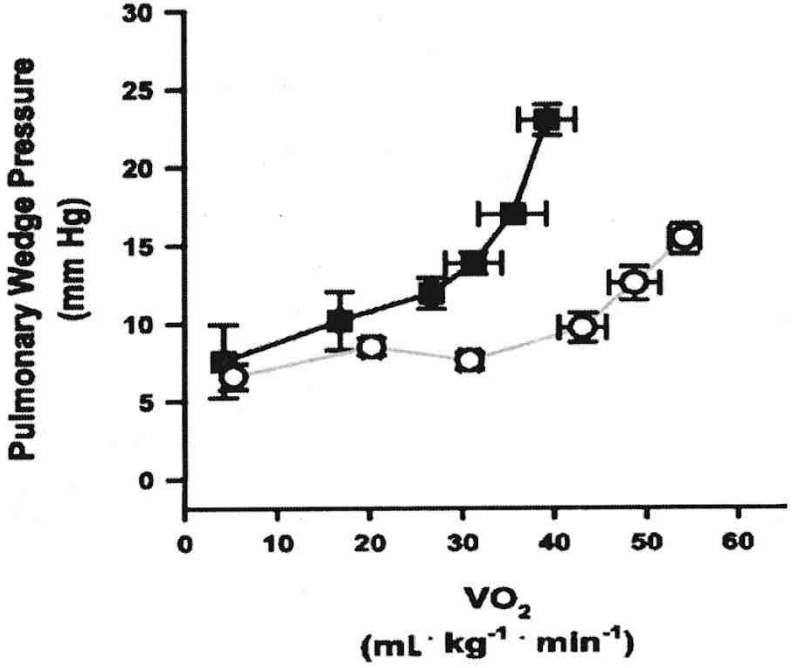
- The pulmonary circulation can adapt to large changes in cardiac output with only small increases in pulmonary arterial pressure

- These adaptations to increased flow occur
  - By passive dilatation of vessels
  - By recruitment of collapsed vessels

During heavy exercise

Bove A.A. MDCVJ 2016

- In standard individuals
  - An important limiting factor could be an increase of pulmonary venous pressure
  - As the left ventricle fails to relax adequately during diastole
- In high-capacity aerobic athletes
  - Diastolic relaxation of the left ventricle is greater
  - Low pulmonary venous pressure is preserved

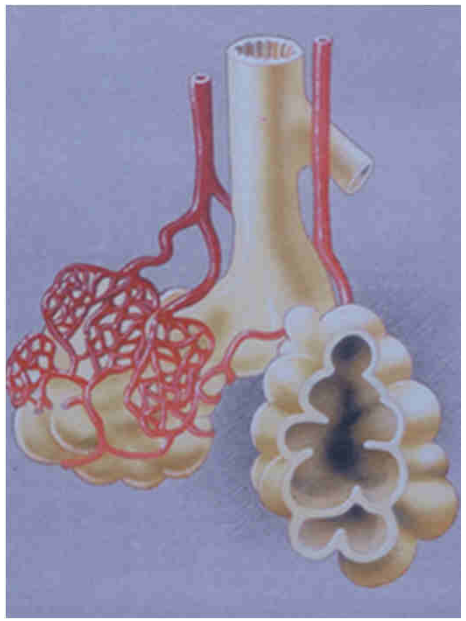


Squares: average-trained men
Circles: well trained men

Vulnerabilty of pulmonary capillaries during exercise

West JB. Exerc Sport Sci Rev 2004;32:24-30

During exercise,
pulmonary capillaries
have a dilemma



Their walls must be extremely thin for efficient gas exchange

but

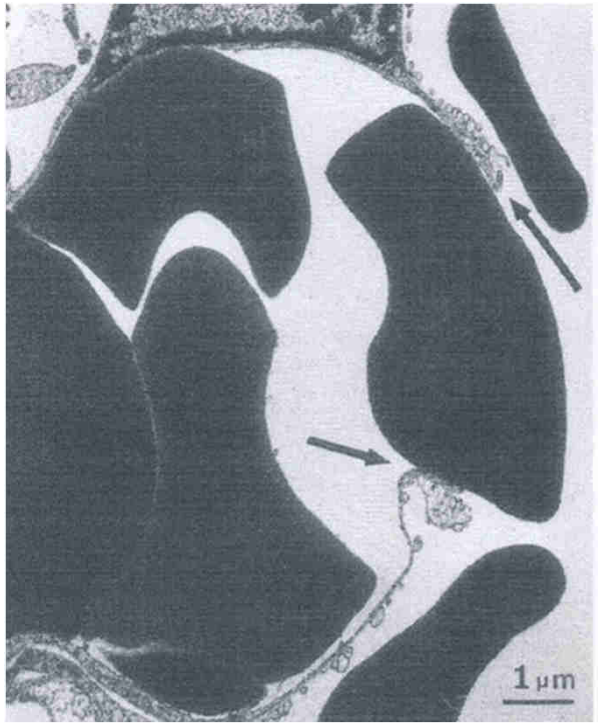
also immensely strong to resist the mechanical stresses that develop during heavy exercise

Stress failure of pulmonary capillaries

West J.B, Mathieu-Costello O. The Lancet 1992

- As the capillary pressure is gradually raised from normal to high levels (> 40 mmHg)
  - First stage: low permeability (hydrostatic) pulmonary oedema
  - Followed by a high-permeability type of oedema, or even frank haemorrhage

- Ultrastructural changes include disruption of:
  - Capillary endothelial cells
  - Alveolar epithelial cells
  - Sometimes all layers of the wall



Exercice-Induced Pulmonary Edema

Increased pressure causing haemorrhage

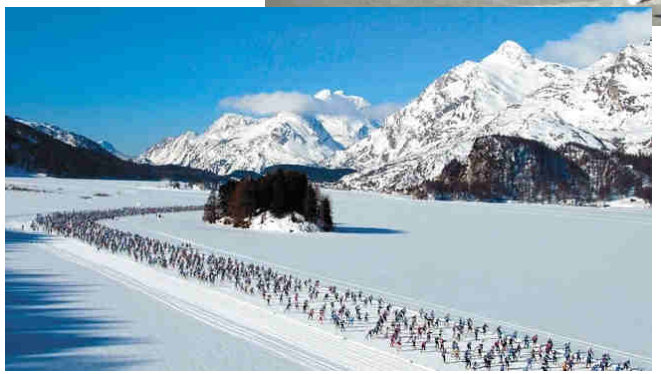
Whitwell KE, *Equine Vet J* 1984
Erickson BK, *Equine Vet J* 1990

- While galloping, racehorses develop enormously **high pulmonary vascular pressures**
- Mean pulmonary artery pressures
  - 80-120 mmHg
- Mean left atrial pressure
  - 70 mmHg
- VO2 max
  - 180 ml/min/kg
- All horses in training have evidence of alveolar bleeding, but < 5 % of the horses bleed through their noses

Does Exercise-Induced Pulmonary Edema exist in humans?

Bates ML, *Pulmonary Medicine* 2011

- Clinically relevant edema has been reported:
  - In a elite cyclist
  - Three runners (marathon, ultramarathon)
  - In a single individual after cross-country skiing



Why swimming and scuba diving could be a stress for pulmonary capillaries?

- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

When a diver is immersed in water up to the neck

- Body is exposed to
  - Atmospheric pressure

    +
  - Hydrostatic pressure

- Lungs are exposed to
  - Atmospheric pressure

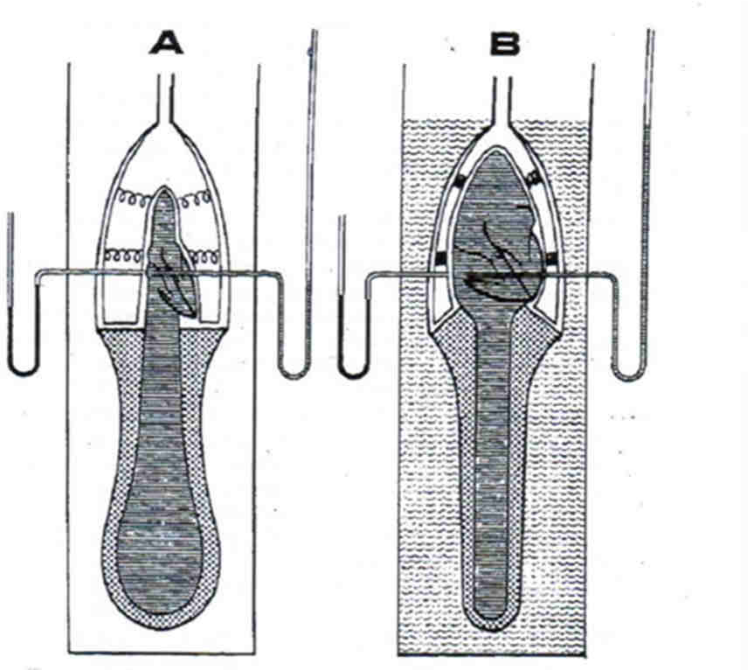
Degrees of negative pressure breathing at the surface

- Vertical head-out position
  - 20 cm H20

- Horizontal position (snorkeling)
  - 10 cm H2O

During head-out water immersion
Negative pressure breathing and hydrostatic pressure

- Effects on:
  - Lung volumes
  - Work of breathing
  - Cardiovascular regulation



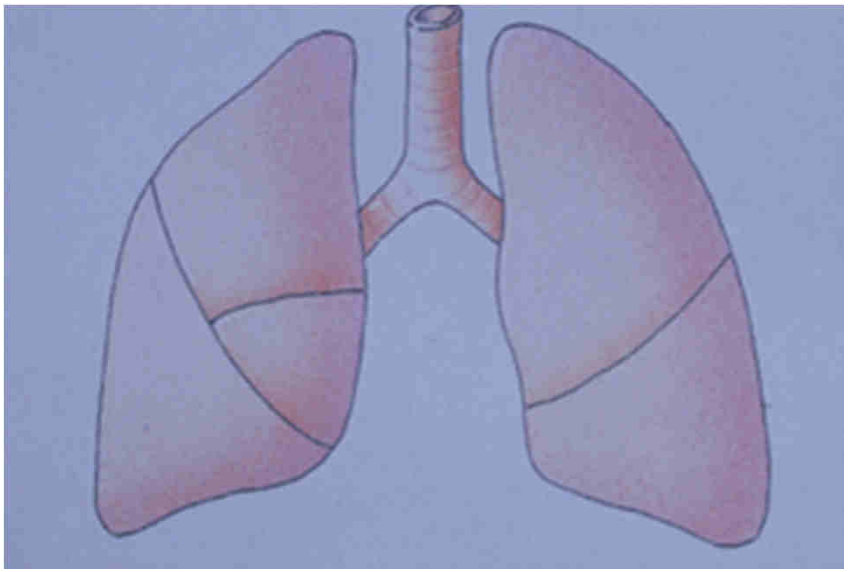
Non immersed

Immersion
Head above water

Mechanics of respiration during submersion in water (1)

S.H. Hong et al. J. Appl. Physiol.27:535-538.1969

- 4 subjects
- submersion in water to the neck



Mechanics of respiration during submersion in water (2)

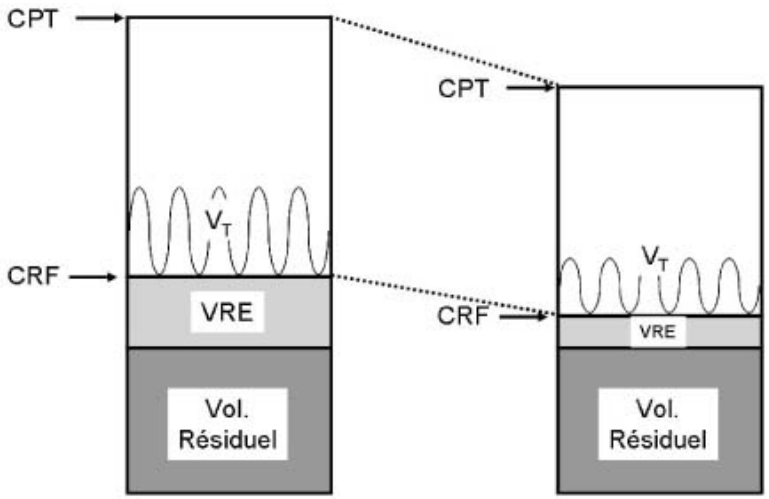
S.H. Hong et al. J. Appl. Physiol.27:535-538.1969

- ↓ Vital Capacity

  > 0.35 L

- ↓ Functional Residual Capacity

- ↑ total work of breathing



Non immersed

Immersion
Head above water

Mechanics of respiration during submersion in water (3)

S.H. Hong et al. J. Appl. Physiol.27:535-538.1969

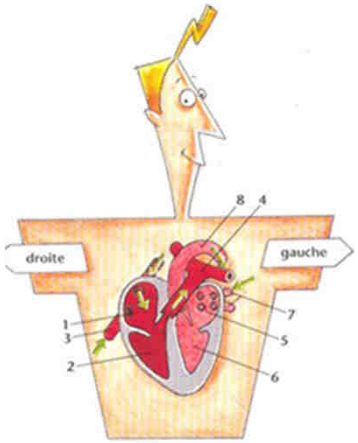
- Increased intrathoracic blood volume
  - 60 % of the reduction
- Hydrostatic pressure
  - counteracting the force of the inspiratory muscles
  - Craniad displacement of the diaphragm

Hemodynamic changes in man during immersion with the head above water (1)

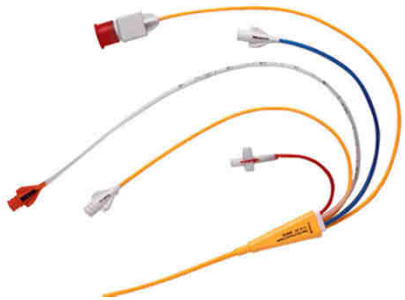
M. Arborelius et al. Aerospace Med. 43(6):592-598,1972

- 10 subjects sitting
  - in neutral temperatures in air (28°C)

  or
  - immersed with the head above water (35°C)



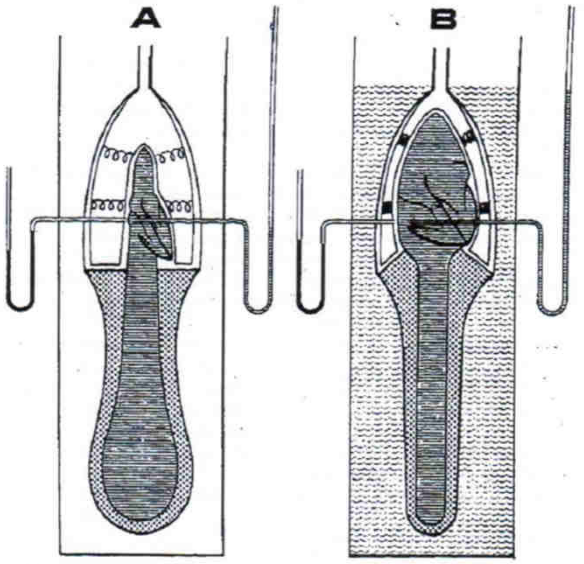
- Measurements of
  - cardiac output (dye dilution method)
  - right atrial pressure
  - brachial arterial pressure



Hemodynamic changes in man during immersion with the head above water (2)

M. Arborelius et al. Aerospace Med. 43(6):592-598,1972

- During immersion
  - **↑ cardiac output**
    - mean increase of 1.8l/min or **32%** ($p < 0.01$)
  - **↑ stroke volume**
    - mean increase of 26 ml or **35 %** ($p < 0.01$)
  - **Heart rate almost unchanged**
  - **↑ right atrial pressure**
    - mean increase of **18 mmHg** ($p < 0.001$)
  - **↑ central blood volume**
    - mean increase of **0.7 l** ($p < 0.01$)



Non immersed

Immersion
Head above water

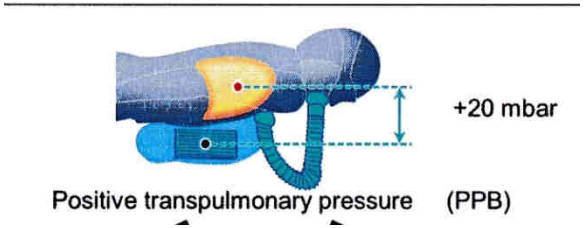
Why swimming and scuba diving could be a stress for pulmonary capillaries?

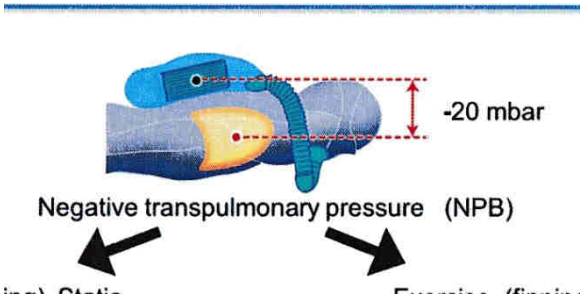
- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

The Key Roles of Negative Pressure Breathing and Exercise in the Development of Interstitial Pulmonary Edema in Professional Male SCUBA Divers (1)

Castagna et al. Sports Medicine-open (2018)4:1

- Sixteen professional male SCUBA divers were recruited
- Each diver completed four 30-min air-breathing dives in a 29°C freshwater pool, at shallow depth (1 m), using a closed-circuit rebreather
- The static conditions consisted in floating at rest, breathing:
  - with a positive pressure (rebreather attached anteriorly)
  - with a negative pressure (rebreather attached posteriorly)





The Key Roles of Negative Pressure Breathing and Exercise in the Development of Interstitial Pulmonary Edema in Professional Male SCUBA Divers (2)

Castagna et al. Sports Medicine-open (2018)4:1

- During exercise, subjects were asked to fin swim throughout the 30 min of immersion while maintaining a heart rate of 110 bpm
- Transthoracic echocardiography was performed immediately after exertion while still submerged
- Lung ultrasound was used to assess for the presence of extravascular lung water (EVLW)

The Key Roles of Negative Pressure Breathing and Exercise in the Development of Interstitial Pulmonary Edema in Professional Male SCUBA Divers (3)

Castagna et al. Sports Medicine-open (2018)4:1

- SCUBA diving at rest caused a moderate rise in venous return, right heart preload, vascular pulmonary congestion
- Exercise combined with positive pressure breathing increased the cardiovascular effects (changes in the right heart) and triggered significant extravascular lungs water accumulation
- These effects, during exercise, were substantially amplified by negative pressure breathing

Why swimming and scuba diving could be a stress for pulmonary capillaries?

- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

Cardiovascular responses to ice-cold showers

W.R. Keatinge et al. J. Appl. Physiol.19(6):1145-1150,1964

- 22 male volunteers aged 20 – 40 yrs
- Ice – cold showers (0 – 2.5 C) over the chest for 2 min at 6 liters / min
  - Large increases in systolic and diastolic arterial pressures and pulse rate
  - Increase in cardiac output
  - Hyperventilation
  - Peripheral venoconstriction
- Changes related to sympathetic nervous reflexes

Why swimming and scuba diving could be a stress for pulmonary capillaries?

- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

Effect of hyperbaric oxygen on limb circulation

Bird A.D, Telfer A.B.M. The Lancet 1965

- The mean reduction in forearm blood-flow on changing from air to oxygen at one atmosphere was 11 %
- At two atmospheres, the mean reduction was 19%

Why swimming and scuba diving could be a stress for pulmonary capillaries?

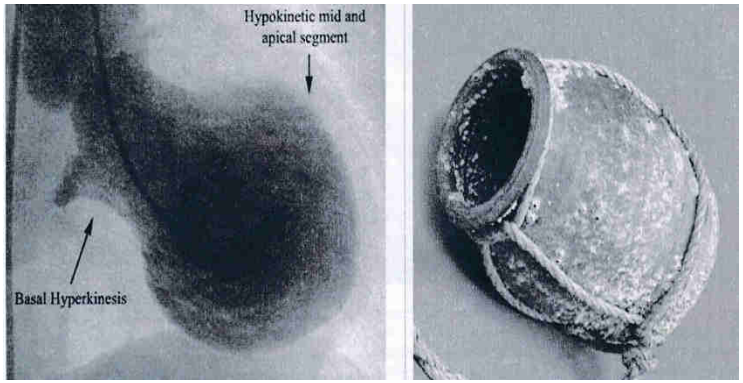
- Immersion
- Sustained fin swimming
- Malfunctioning SCUBA regulator
- Hypothermia
- Hyperoxia
- Wetsuit
- Psychological stress

SCIENTIFIC LETTER

Pulmonary oedema induced by emotional stress, by sexual intercourse, and by exertion in a cold environment in people without evidence of heart disease

P T Wilmshurst

Heart 2004;**90**:806–807. doi: 10.1136/hrt.2002.005595



Stress-induced cardiomyopathy

Takotsubo

The Journal of Emergency Medicine, Vol. 50, No. 2, pp. 277–280, 2016

0736-4679/$ - see front matter

ELSEVIER

http://dx.doi.org/10.1016/j.jemermed.2015.09.045

Selected Topics: Sports Medicine

CrossMark

STRESS CARDIOMYOPATHY CAUSED BY DIVING: CASE REPORT AND REVIEW OF THE LITERATURE

Aurangzeb Baber, MD, Sanjeev U. Nair, MD, Sumit Duggal, MD, Salman Bhatti, MD, and Deborah W. Sundlof, DO

Cardiology Division, Lehigh Valley Health Network, Allentown, Pennsylvania
Corresponding Address: Aurangzeb Baber, MD, Cardiology Division, Lehigh Valley Health Network, 1250 South Cedar Crest Boulevard, Suite 300, Allentown, PA 18103

Cold-induced pulmonary oedema in SCUBA divers and swimmers (1)

P.T. Wilmshurst et al. Lancet 1989;1:62-65

- 11 divers (age: 45.6 yrs ± 2.6) with up to 7 episodes of pulmonary oedema when in water
- All divers had had many years of trouble-free diving before the first episode
- Pulmonary oedema occurred while the patients were scuba diving and breathing air
- 2 had also had similar episodes while swimming at the surface

Cold-induced pulmonary oedema in SCUBA divers and swimmers (2)

P.T. Wilmshurst et al. Lancet 1989;1:62-65

- In all cases the diver became dyspnoeic at depth, without having undertaken excessive exertion
- Symptoms:
  - Cough (n = 11)
  - Expectoration of froth (n = 7)
  - Haemoptysis (n = 6)
  - Syncope (n = 2)
  - Orthopnoea on leaving the water (n = 11)
- None recalled water inhalation
- Diagnosis made by a physician or a cardiologist (basal crepitations, chest X-ray, third heart sound, or history alone)

Cold-induced pulmonary oedema in SCUBA divers and swimmers (3)

P.T. Wilmshurst et al. Lancet 1989;1:62-65

- These 11 “abnornal divers were compared with 10 divers with a similar length of diving experience but no cardiorespiratory symptoms during:
  - Exercise
  - Cold–packing of head and neck in towels soaked in ice-cold water
  - Oxygen-breathing (67 % oxygen, 33 % nitrogen)
  - Ice and oxygen
- Measurements:
  - Mean blood pressure
  - Forearm blood flow (venous occlusion plethysmograph)
  - Forearm vascular resistance

Cold-induced pulmonary oedema in SCUBA divers and swimmers (4)

P.T. Wilmshurst et al. Lancet 1989;1:62-65

- During pressor interventions (cold, oxygen, ice and oxygen)
  - **Blood pressure**
    - **Higher** after each intervention **in the abnormal divers** ($p < 0.05$)
  - **Forearm blood flow**
    - ↓ in both groups but **more in the abnormal divers** ($p < 0.05$)
  - **Vascular resistance**
    - ↑ in both groups but **much more in the abnormal divers** ($p < 0.05$)

- During the cold pressor test and/or combination of ice and oxygen
  - 9 / 11 abnormal divers had **clinical evidence of cardiac decompensation**

Pulmonary oedema in healthy persons during scuba-diving and swimming

M. Pons et al. Eur Respir J.,1995,8,762-767

- Comparison between 5 “abnormal” divers (episodes of pulmonary oedema whilst diving or swimming) and 6 volunteers

- Cold packing of head and neck with towels soaked in iced water for 3 min.

- No differences between the two groups in:
  - forearm vascular resistance
  - left ventricular systolic and diastolic function
  - plasma levels of epinephrine, norepinephrine, cortisol, aldosterone, renin and atrial natriuretic peptide

- The mechanisms of pulmonary oedema occurring during scuba-diving and swimming remain unknown and speculative

Swimming-Induced Pulmonary Edema

Y.Adir et al.Chest 2004;126:394-399

- 70 cases of *swimming-induced pulmonary edema* (SIPE) in young healthy male subjects participating in a fitness-training program
- Swimming time trial over 2.4 to 3.6 kilometers in the open sea
- Wearing a bathing suit, using swim fins
- Average water temperature 20^{o}C

Aqua jogging-induced pulmonary oedema

M. Wenger and E.W. Russi

ABSTRACT: The present study reports the case of a 43-yr-old very sporty male, who developed shortness of breath and expectorated bloody froth during aqua jogging. Pulmonary oedema was diagnosed clinically and by computed tomography of the chest. The patient made a full recovery and his echocardiography was entirely normal.

Pulmonary oedema occurring in healthy scuba-divers and swimmers has been reported previously. However, this is the first case where pulmonary oedema was observed during aqua jogging.

Eur Respir J 2007;30:1231-1232

Deaths in triathletes: immersion pulmonary oedema as a possible cause

Moon R.E. et al. *BMJ Open Sport Exerc Med* 2016

- Left ventricular hypertrophy – a marker of SIPO susceptibility- was present in a greater than the expected proportion of triathletes who died during the swim portion

Swimming-Induced Pulmonary Edema Risk Reduction With Sildenafil (1)

R.E. Moon et al.
Circulation.2016;133:988-996

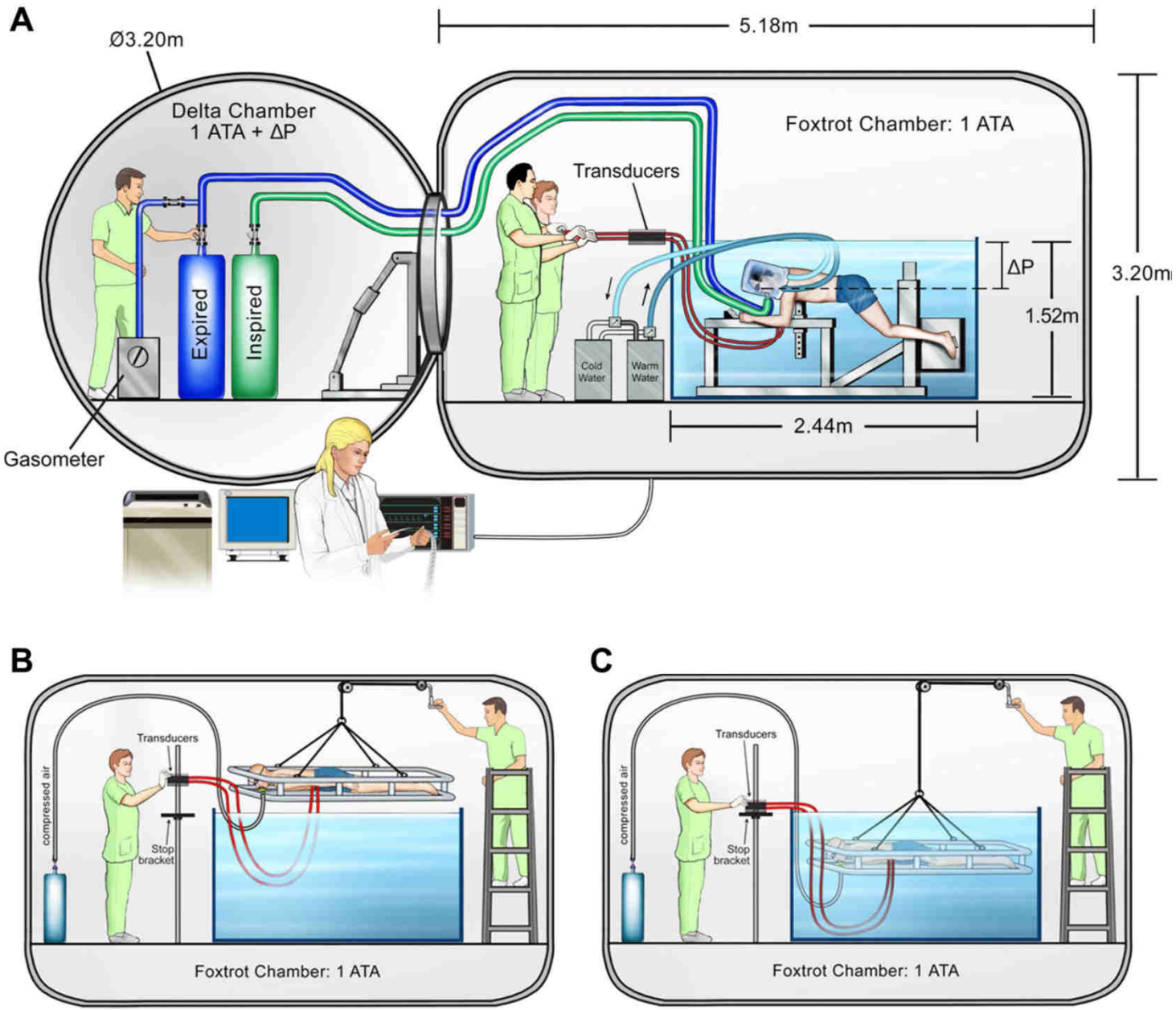
- 10 subjects with a history of SIPE (mean age 42 y)

vs

- 20 control subjects (mean age 36 y)

- Radial artery, pulmonary artery catheters
- Moderate cycle ergometer exercise (6-7 minutes) while submersed in 20° C water

- SIPE-susceptible subjects repeated the exercise 150 minutes after oral administration of 50 mg sildenafil


A
Ø3.20m
5.18m
Delta Chamber
1 ATA + ΔP
Foxtrot Chamber: 1 ATA
Transducers
Expired
Inspired
Cold Water
Warm Water
ΔP
1.52m
3.20m
2.44m
Gasometer
B
Transducers
compressed air
Stop bracket
Foxtrot Chamber: 1 ATA
C
Transducers
compressed air
Stop bracket
Foxtrot Chamber: 1 ATA

Swimming-Induced Pulmonary Edema Risk Reduction With Sildenafil (2)

R.E. Moon et al.
Circulation.2016;133:988-996

- Mean pulmonary pressure (CO:13.8 L/min)
  - Controls
    - 22 mmHg
  - SIPE-susceptible subjects
    - 34 mmHg (*P*=0.004)
- Pulmonary artery wedge pressure
  - Controls
    - 11 mmHg
  - SIPE-susceptible subjects
    - 19 mmHg (*P*=0.028)
- After sildenafil, no statistically significant differences in MPAP and PAWP between the two groups.

Swimming and scuba diving induced pulmonary edema (*SIPE*)

Effects of swimming and scuba diving

- Immersion
  - → central blood pooling
  - ↑ right atrial pressure
  - ↑ cardiac preload
  - ↓ vital capacity
- Hypothermia
  - → arterial constriction
  - → venous constriction
  - ↑ cardiac preload
  - ↑ cardiac afterload
- Hyperoxia
  - → arterial constriction
  - ↑ cardiac afterload
- Sustained fin swimming
  - ↑ cardiac output
  - ↑ ventilation (L/min)
  - ↑ work of breathing
  - ↑ large airway pressure swings
- Wetsuit
  - → impairment of ventilatory mechanics
  - ↓ vital capacity
- Malfunctioning SCUBA regulator
  - ↑ negative intrathoracic inspiratory pressures
- Psychological stress
  - ↑ sympathetic activation

Swimming and scuba diving induced pulmonary edema (*SIPE*)

Mechanisms in susceptible individuals

- Abnormal vascular reactivity

  P.T. Wilmshurst et al. Lancet 1989;1:62-65

- Hypertension frequently observed

  E. Gempp et al. Int J Cardiol 2014;172:528-529

- Reversible myocardial dysfunction

  E. Gempp et al. Am J Cardiol 2013;111:1655-1659

- ↑ pulmonary artery pressure and pulmonary artery wedge pressure
- ↓ pulmonary vascular pressures after sildenafil (selective inhibitor of phosphodiesterase-5)

  R.E. Moon et al.Circulation.2016;133:988-996


EUREKA !