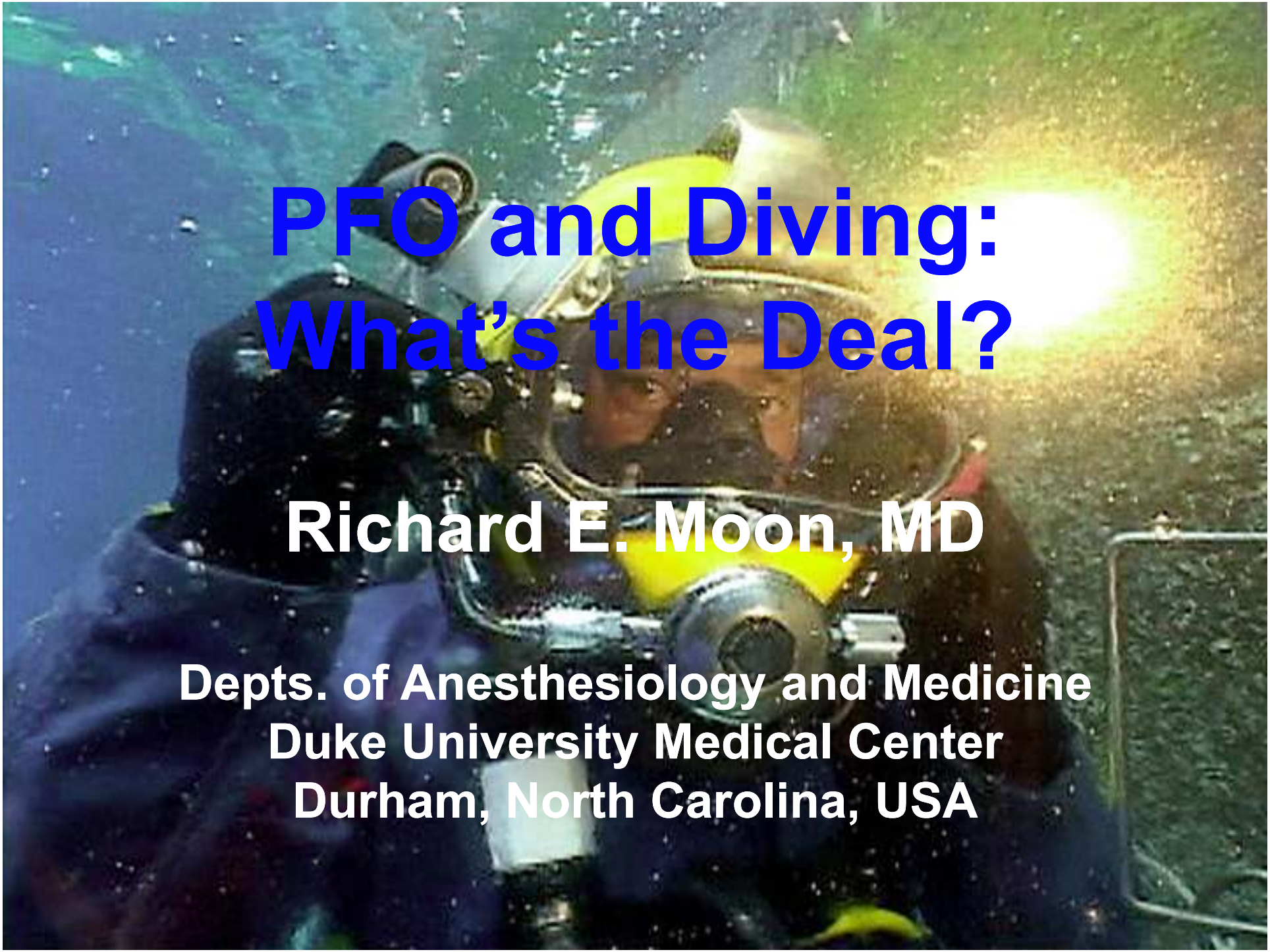
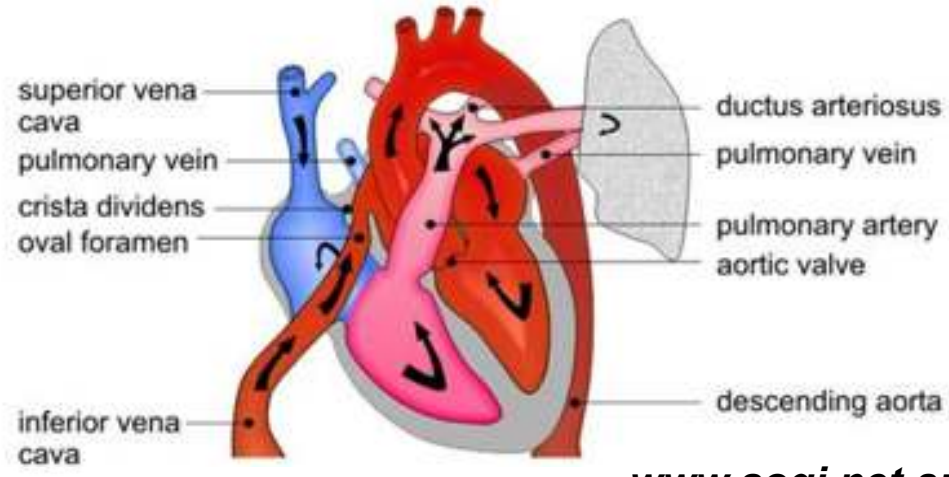


PFO and Diving: What's the Deal?

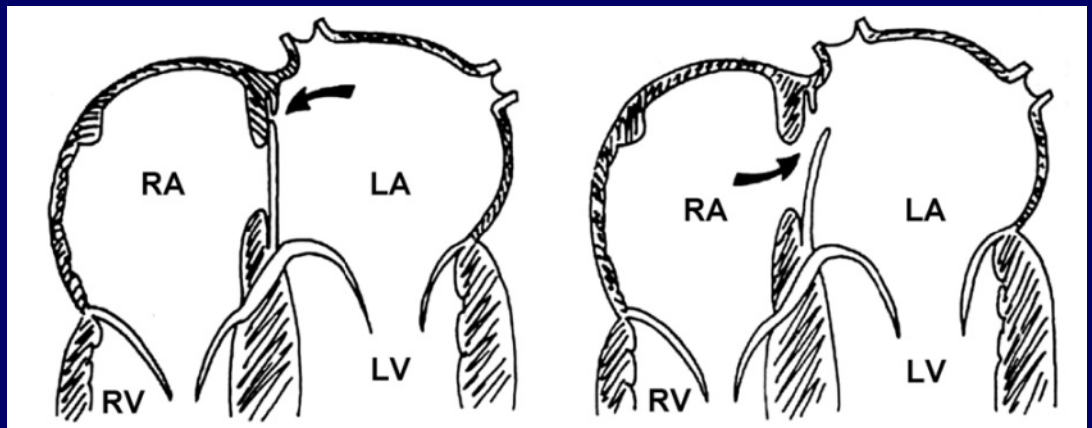
Richard E. Moon, MD

Depts. of Anesthesiology and Medicine
Duke University Medical Center
Durham, North Carolina, USA

Fetal-Adult Circulation

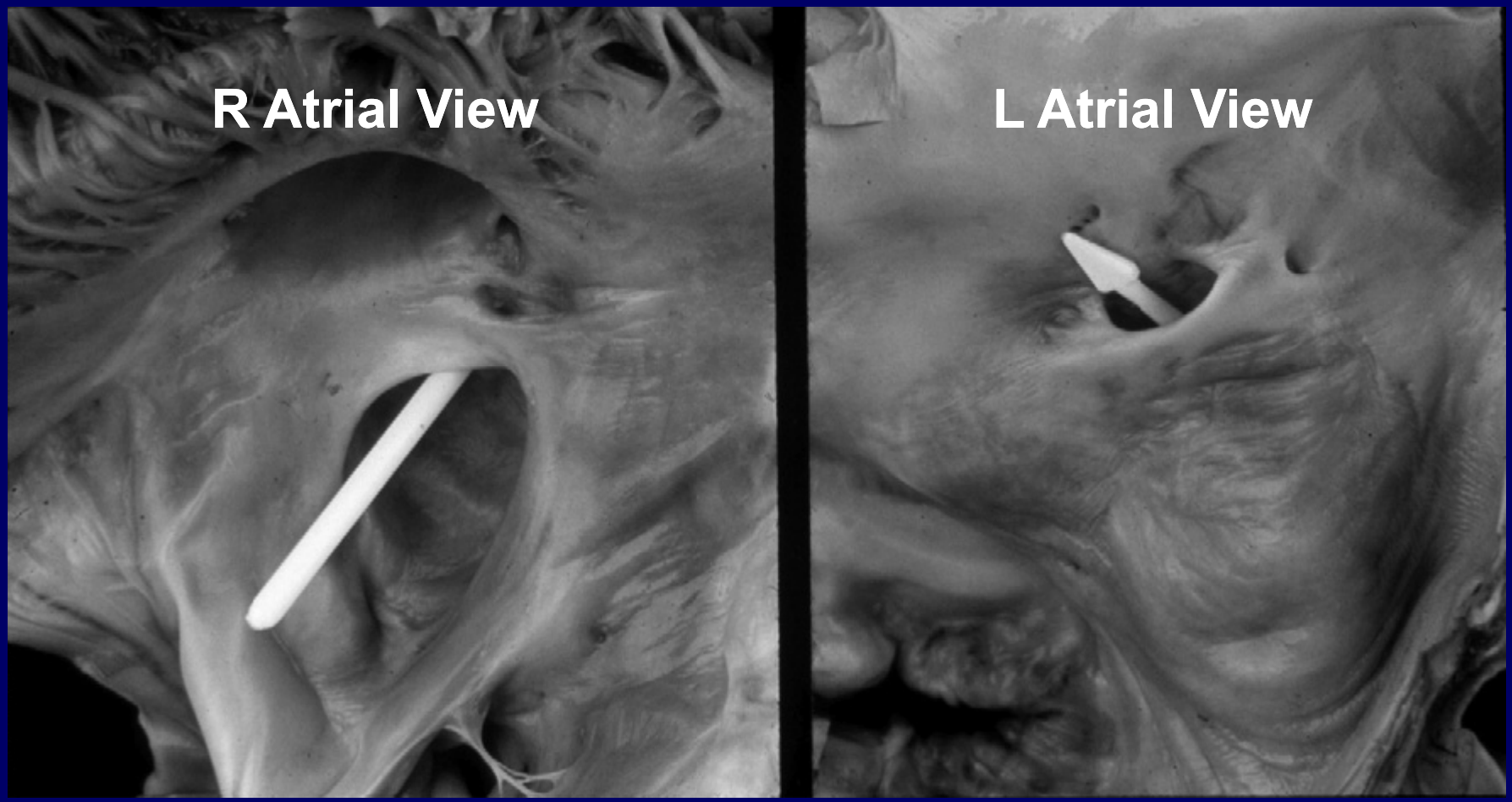


www.sogi.net.au



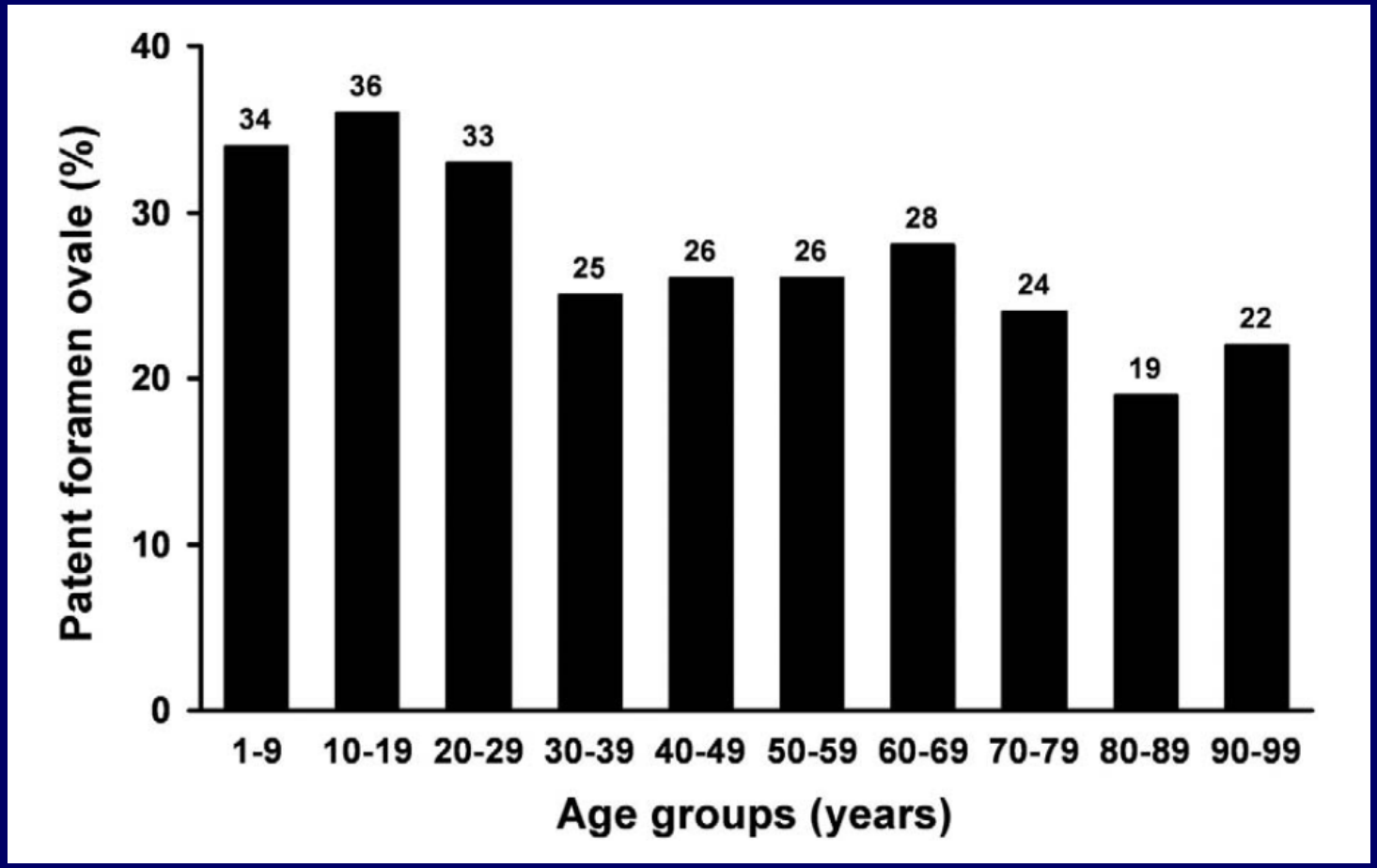
Holmes D, et al. *Curr Probl Cardiol* 2:49, 2004

Atrial Septal Aneurysm



Holmes DR. *Curr Probl Cardiol* 2:49, 2004

PFO Detected at Autopsy vs. Age



Data from Hagen PT, et al. *Mayo Clin Proc* 59:17, 1986
Fig. from *Curr Probl Cardiol* 2:49, 2004

Julius Cohnheim (1839-1884) and Paradoxical Thromboembolism

So habe ich noch kürzlich einen Fall von frischer, tödtlicher Embolie einer A. foss. Sylvii bei einer 35jährigen Frau zu beobachten Gelegenheit gehabt, wo Herzklappen, Aorta adscend., kurz alle in Betracht kommenden Arterien absolut intact waren, dagegen in den Venen der unteren Extremität sich eine ausgedehnte Thrombose fand. Sie werden glauben, dass ich zunächst entfernt nicht daran dachte, Beides in Zusammenhang mit einander zu bringen, bis ich bei genauerer Besichtigung des Herzens ein so grosses Foramen ovale auffand, dass ich mit Leichtigkeit drei Finger durch dasselbe hindurchbringen konnte. Jetzt konnte ich nicht länger die Möglichkeit von der Hand weisen, dass hier ein abgerissener Thrombus aus der V. cruralis bei der Passage durch das Herz aus dem rechten in den linken Vorhof und von da in die A. foss. Sylvii gerathen ist.

"I just recently had a case of a deadly embolus in the middle cerebral artery, in a 35-year old woman. Her heart valves, ascending aorta and all arteries were intact. However, in the lower extremity a long drawn-out thrombus was found. And what I found next I never thought of, to put these two together, until I had a close look at the heart. I found a **very large foramen ovale** through which I could pass three fingers with ease. Now I could no longer ignore the fact that a **torn-off piece of thrombus arising from the femoral vein, while traveling through the heart, (passed) out of the right atrium into the left atrium and to the middle cerebral artery**"

Lippmann H, Raferty T. *Yale J Biol Med* 66:11, 1993

"Patency of the so-called 'Anatomically Open but Functionally Closed' Foramen Ovale"

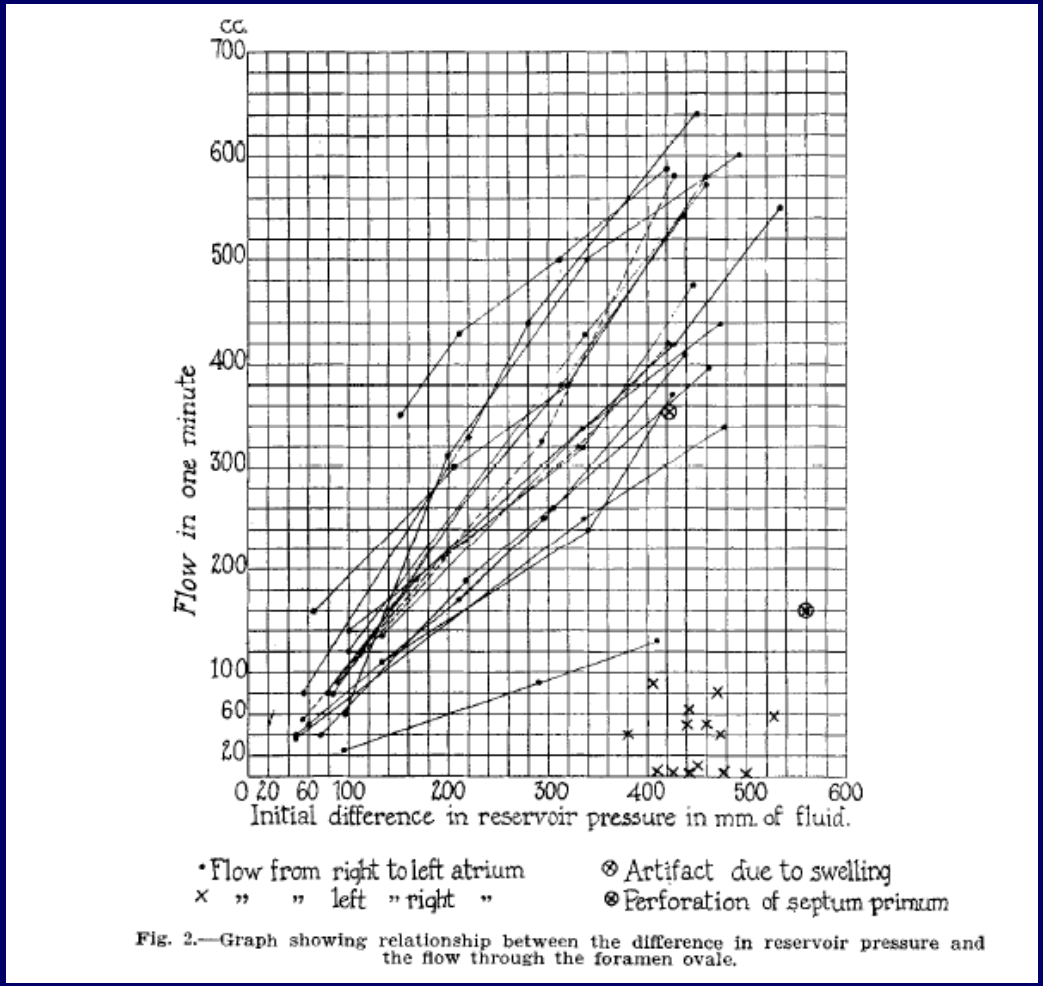
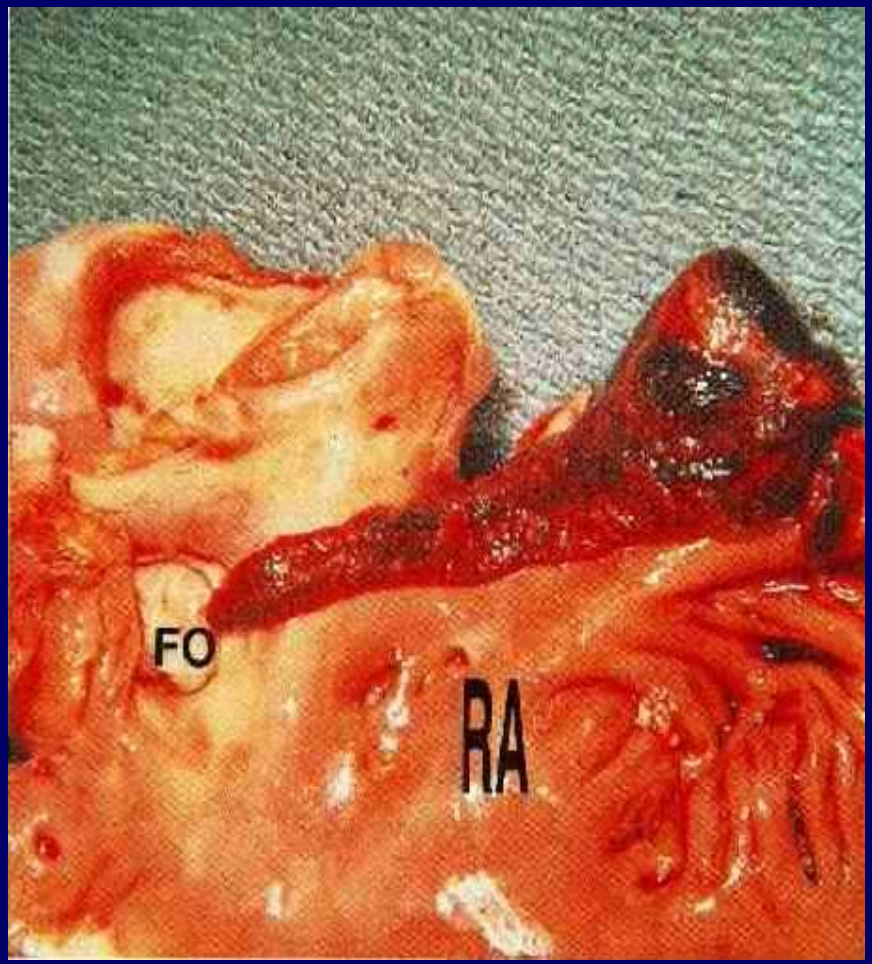


Fig. 2.—Graph showing relationship between the difference in reservoir pressure and the flow through the foramen ovale.

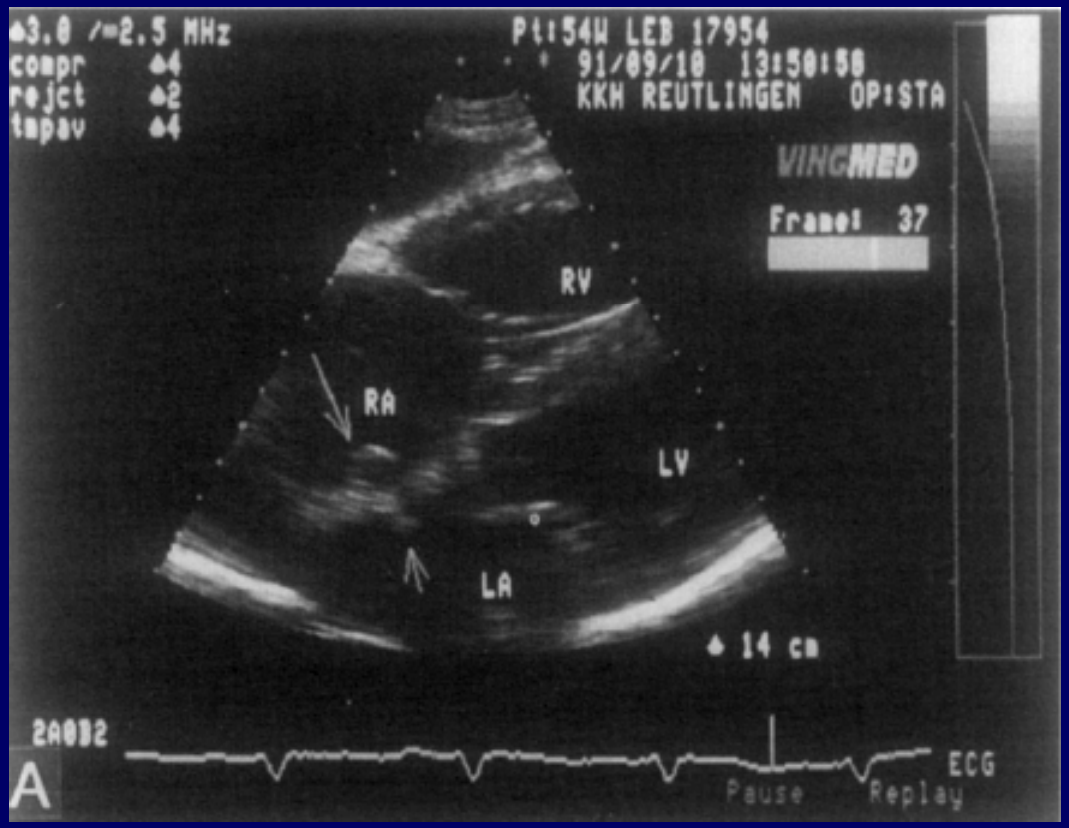
Gross P. Am *Heart J* 10:101, 1934

Paradoxical Thromboembolism



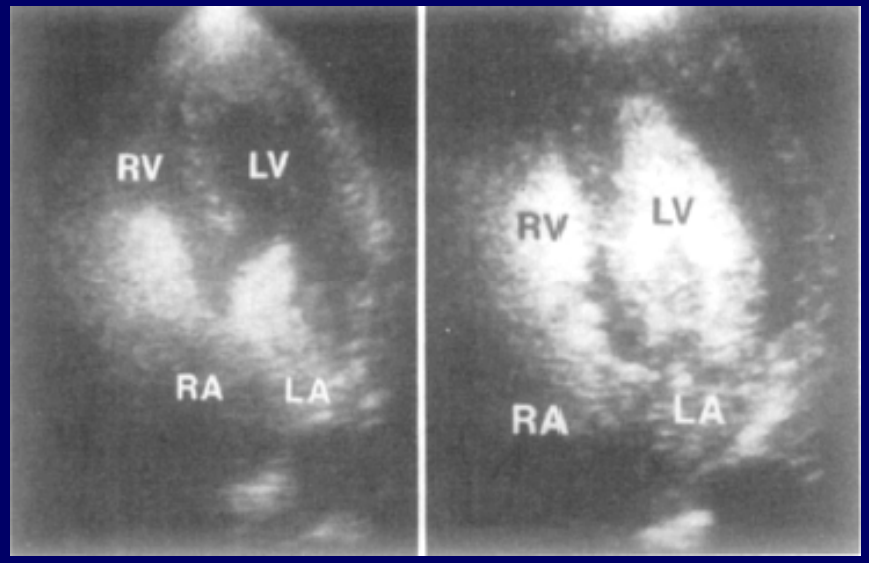
Silverman ME *N Engl J Med*, 329:930, 1993

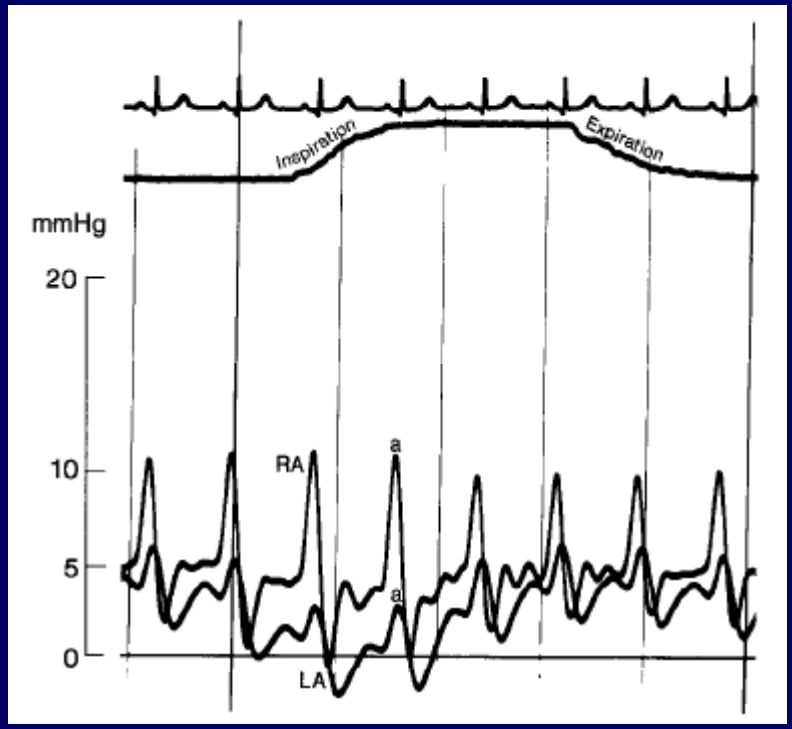
Thrombus Migration through a PFO in a 54 Year Old Female: TTE



Hust MH, et al. *Am Heart J* 129:620, 1995

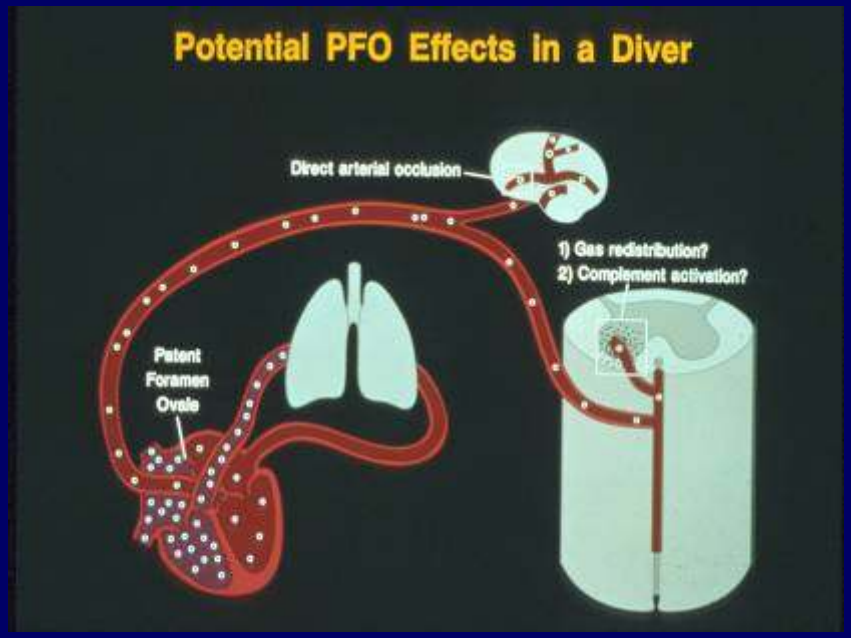
How do bubbles cross from right to left against a pressure gradient?



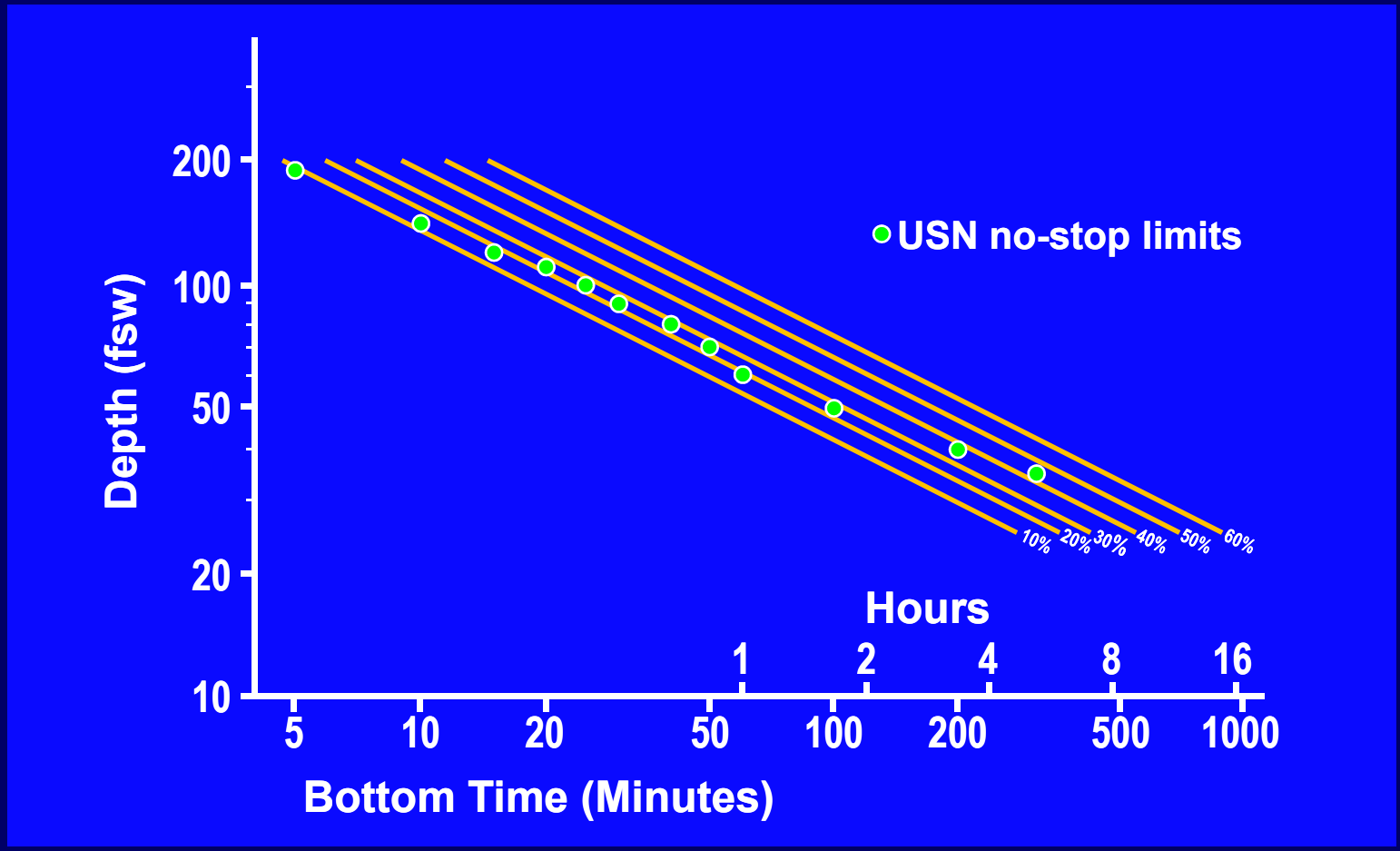


Strunk BL, et al. *Am J Cardiol* 60:413, 1987

Atrial Septal Defects and VGE

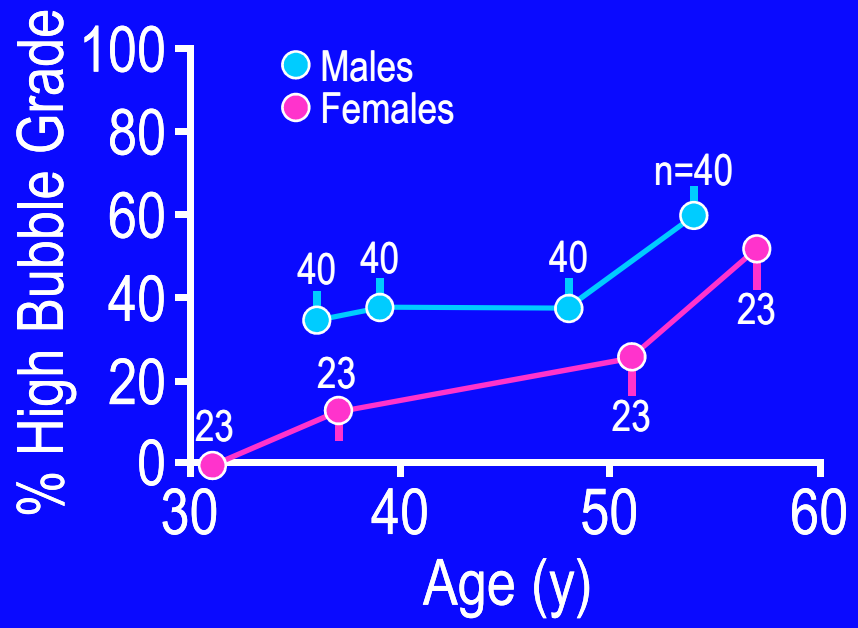


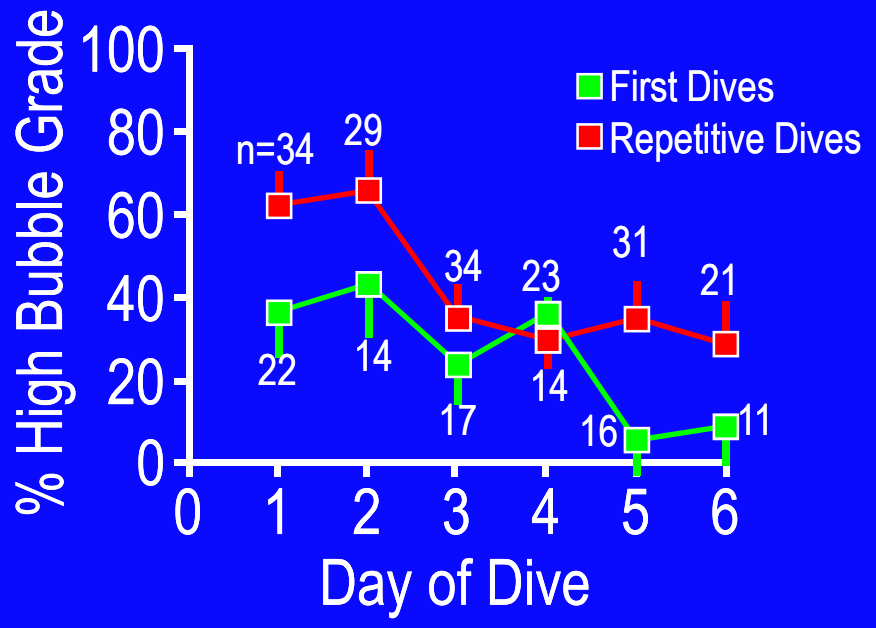
VGE and Hyperbaric Exposure



Spencer MP. *J Appl Physiol* 40:229, 1976

Maximum Depth and Multi-day Diving





Dunford RG, et al. *Undersea Hyperb Med* 29:247, 2002

PFO and Altitude DCS

- 50 year old male, BMI 32.8 kg/m^2, flight in the rear seat of a fighter jet, cabin altitude 35,500 ft, no O_2 pre-breathe. One prior flight-related episode of extreme fatigue, transient scotoma in the left eye and fleeting left temporal headache. 70 minutes after takeoff, severe stomach cramp followed by descent. Total flight time 101 minutes, 80 minutes at 35,500 ft. On the ground, patient unconscious and apneic. Died 11½ h post flight
- 34 year old male, BMI 34.9 kg/m^2, flight with cabin altitude 26,000 ft for 100 minutes, 29,000 ft for 4 minutes. Left sided numbness, unconscious on landing. O_2 administration, profound L side hemiparesis. Seizures, became moribund, died 6 hours after symptom onset

"The key to the development of the relatively large ischemic foci in the brain seems to be the presence of a patent foramen ovale in the heart"

Haymaker W, et al. *J Aviation Med* 27:2, 1956

DCI in a Patient with ASD

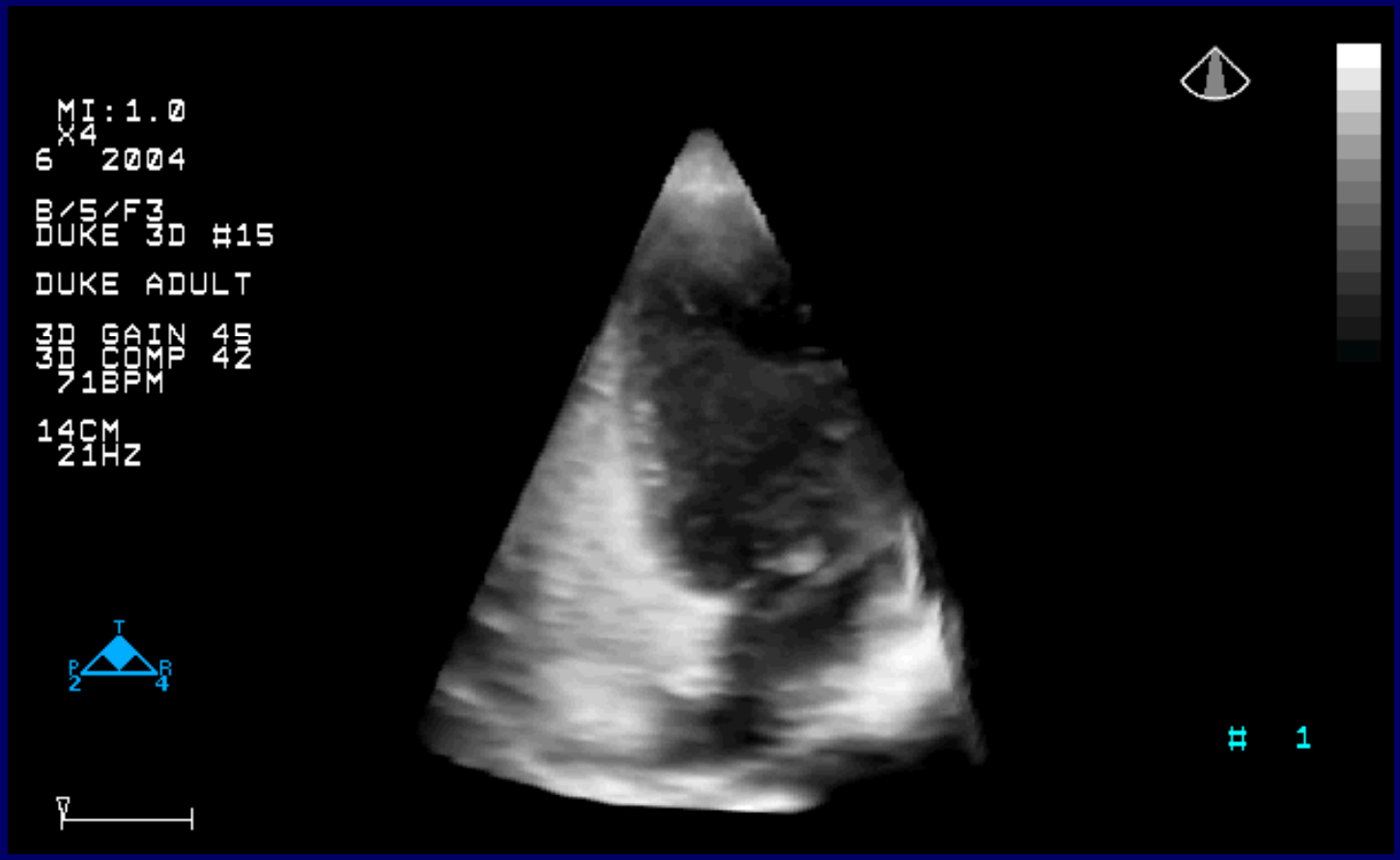
- Experienced recreational scuba diver made a dive to 38 m for 15 minutes
- 2 minutes after surfacing: abdominal pain, unilateral paresthesia, and dizziness, followed a few seconds later by loss of consciousness. All symptoms resolved over the next 30 minutes
- 6 hours later: progressive weakness and paresthesiae in both legs
- Next day: mixed motor and sensory paraplegia and slurred speech
- After recompression: mild paraparesis remained, which improved over the following year
- Fixed splitting of the second heart sound and a pulmonary systolic murmur. Cardiac catheterization: secundum atrial septal defect with pulmonary to systemic flow ratio 3:1. No right-to-left shunt supine breathing air. Valsalva maneuver, O_2 breathing, straight leg raising all produced bidirectional shunting

Wilmshurst PT, et al. *BMJ* 293:1277, 1986

Transthoracic Bubble Contrast Echo

Transthoracic Bubble Contrast Echo

Transthoracic 3-D Bubble Contrast Echo



PFO and Cryptogenic Stroke

PREVALENCE OF PATENT FORAMEN OVALE IN PATIENTS WITH STROKE

PH. LECHAT, M.D., PH.D., J.L. MAS, M.D., G. LASCAULT, M.D., PH. LORON, M.D., M. THEARD, M.D., M. KLIMCZAC, M.D., G. DROBINSKI, M.D., D. THOMAS, M.D., AND Y. GROSGOGEAT, M.D.

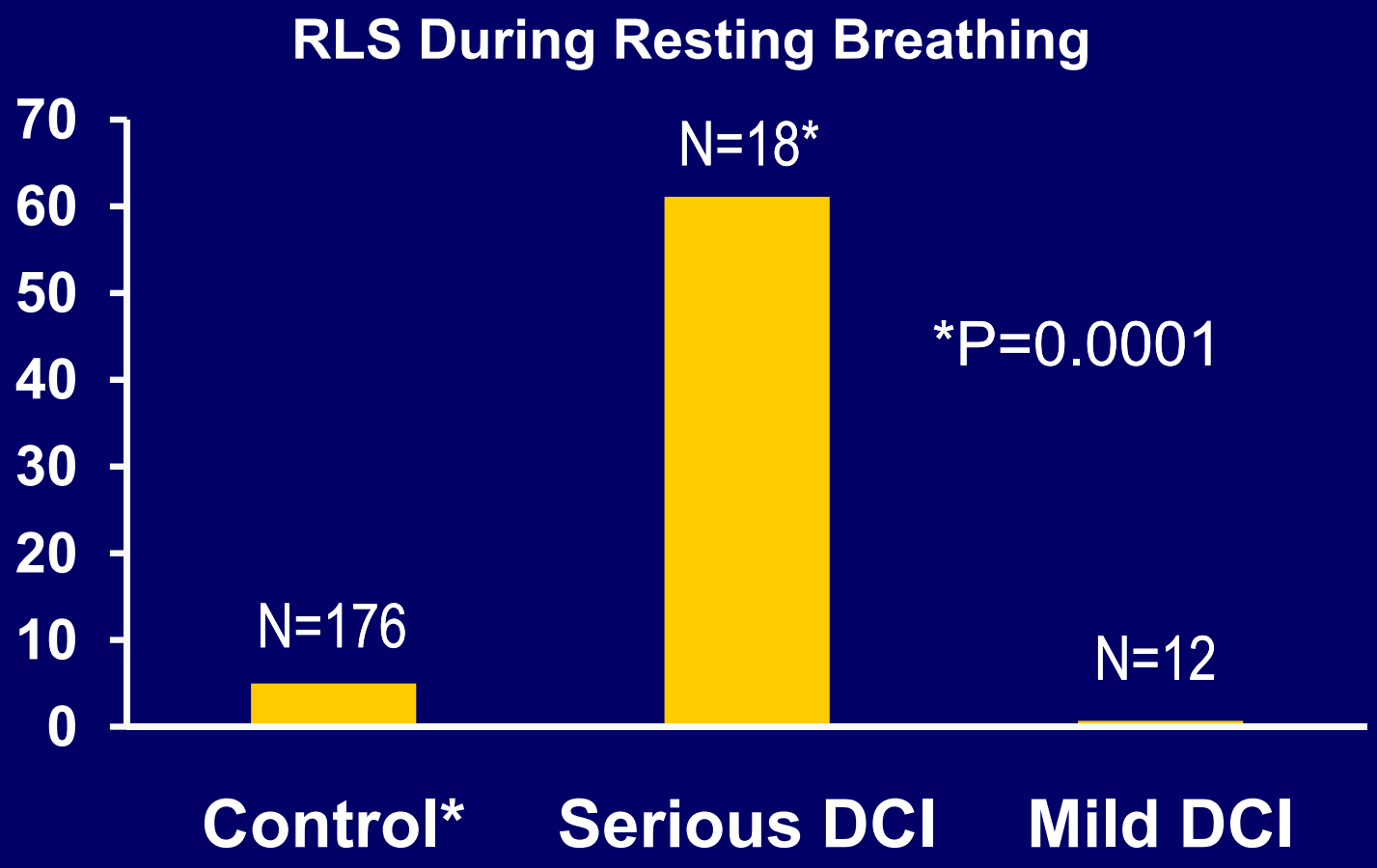
Abstract The cause of ischemic stroke in younger adults is undefined in as many as 35 percent of patients. We studied the prevalence of patent foramen ovale as detected by contrast echocardiography in a population of 60 adults under 55 years old with ischemic stroke and a normal cardiac examination. We compared the results with those in a control group of 100 patients.

The prevalence of patent foramen ovale was significantly higher in the patients with stroke (40 percent) than in the control group (10 percent, $P<0.001$). Among the patients with stroke, the prevalence of patent foramen ovale was 21 percent in 19 patients with an identifiable cause of their stroke, 40 percent in 15 patients with no identifiable cause but a risk factor for stroke, such as mitral-valve prolapse, migraine, or use of contraceptive agents, and 54 percent in 26 patients with no identifiable cause ($P<0.10$).

These results suggest that because of the high prevalence of clinically latent venous thrombosis, paradoxical embolism through a patent foramen ovale may be responsible for stroke more often than is usually suspected. (N Engl J Med 1988; 318:1148-52.)

Lechat Ph. *N Engl J Med*, 318:1148, 1988

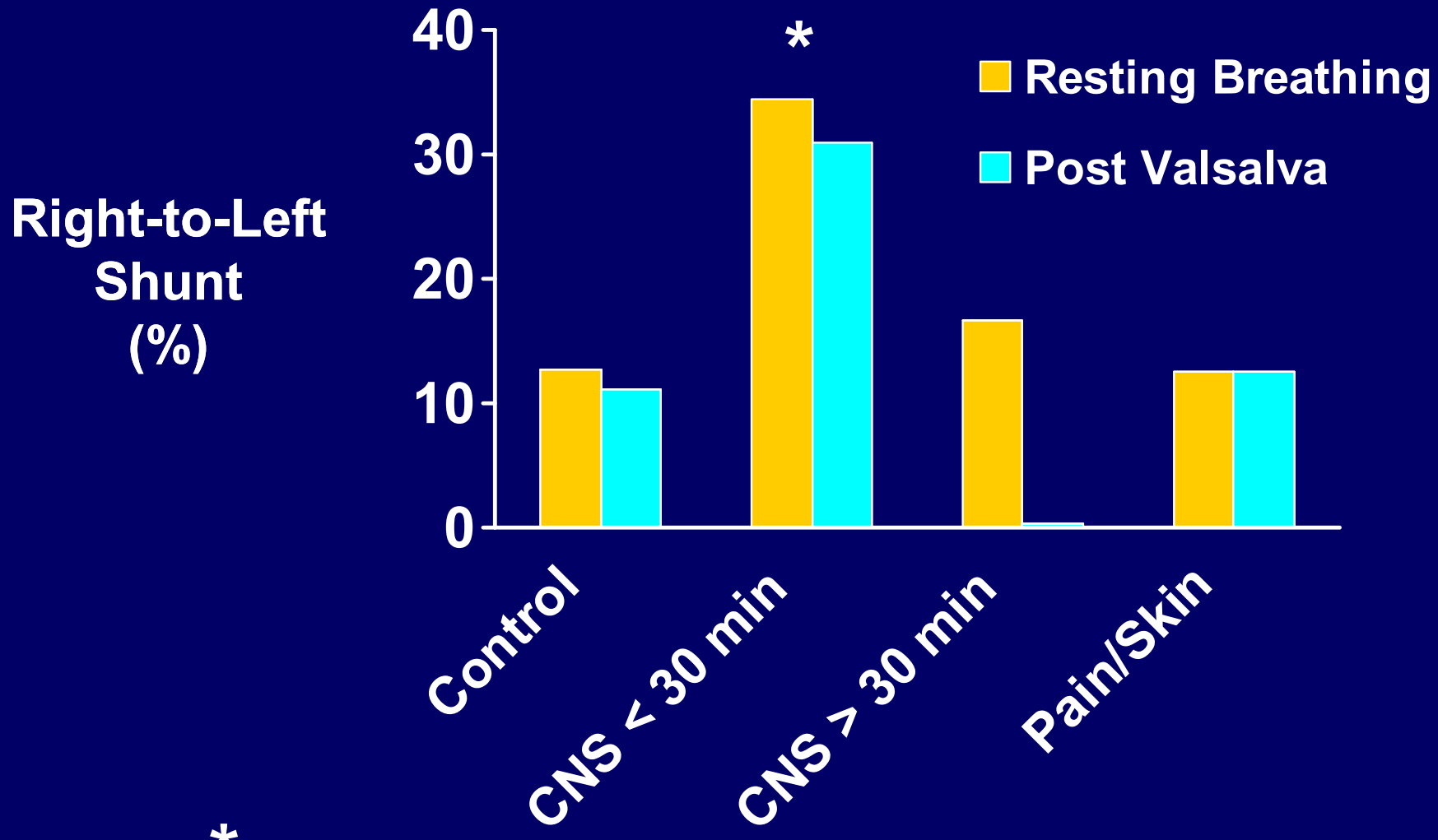
PFO by TTE in DCS



* Lynch JJ, et al. Am J Cardiol 53:1478, 1984
Lechat PH, et al. N Eng J Med 318:1148, 1988

Moon RE, et al *Lancet* 1:513, 1989

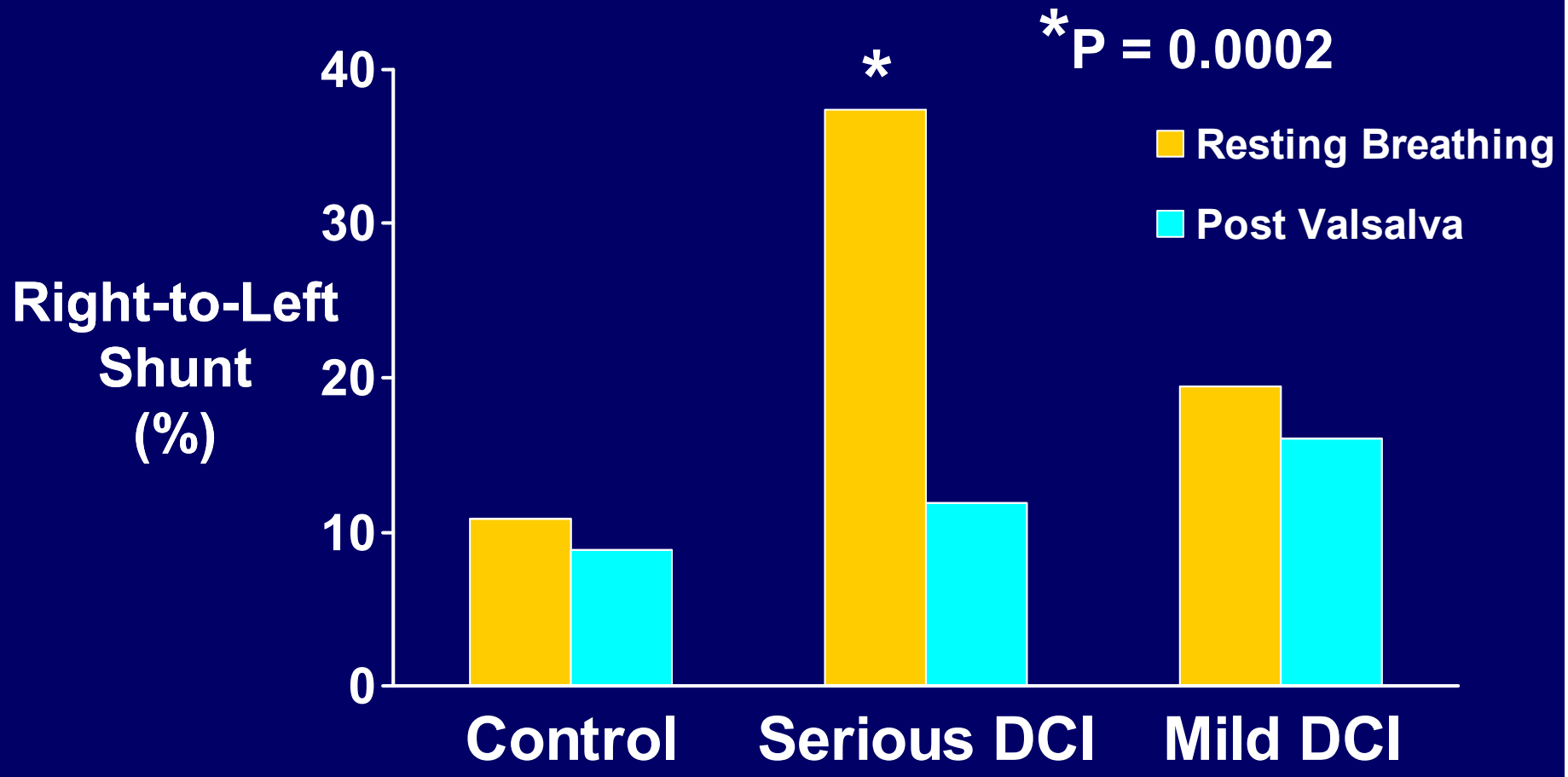
PFO by TTE and DCS



*P < 0.001

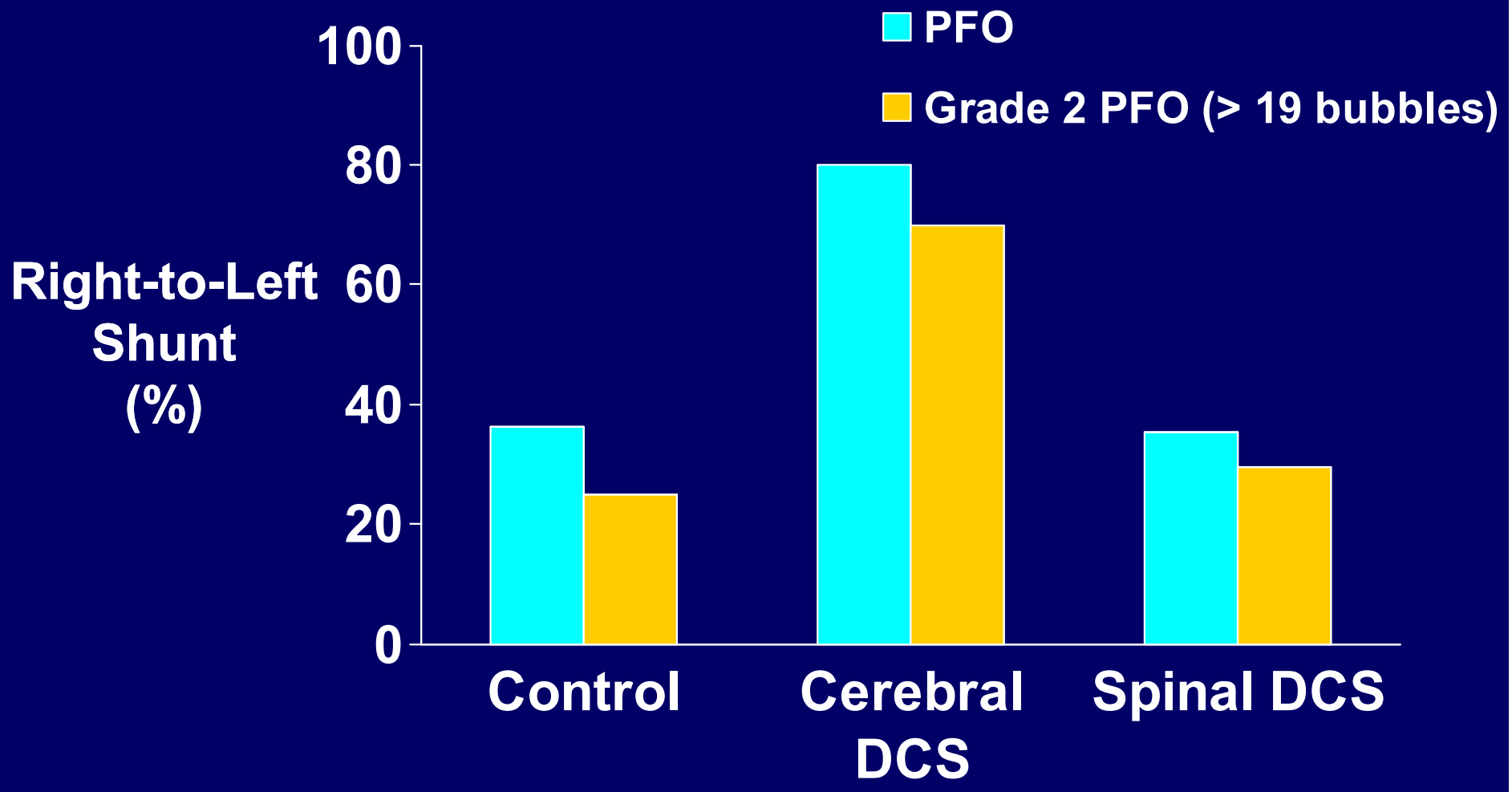
Wilmshurst et al *Lancet* 2:1302, 1989

PFO by TTE in DCI



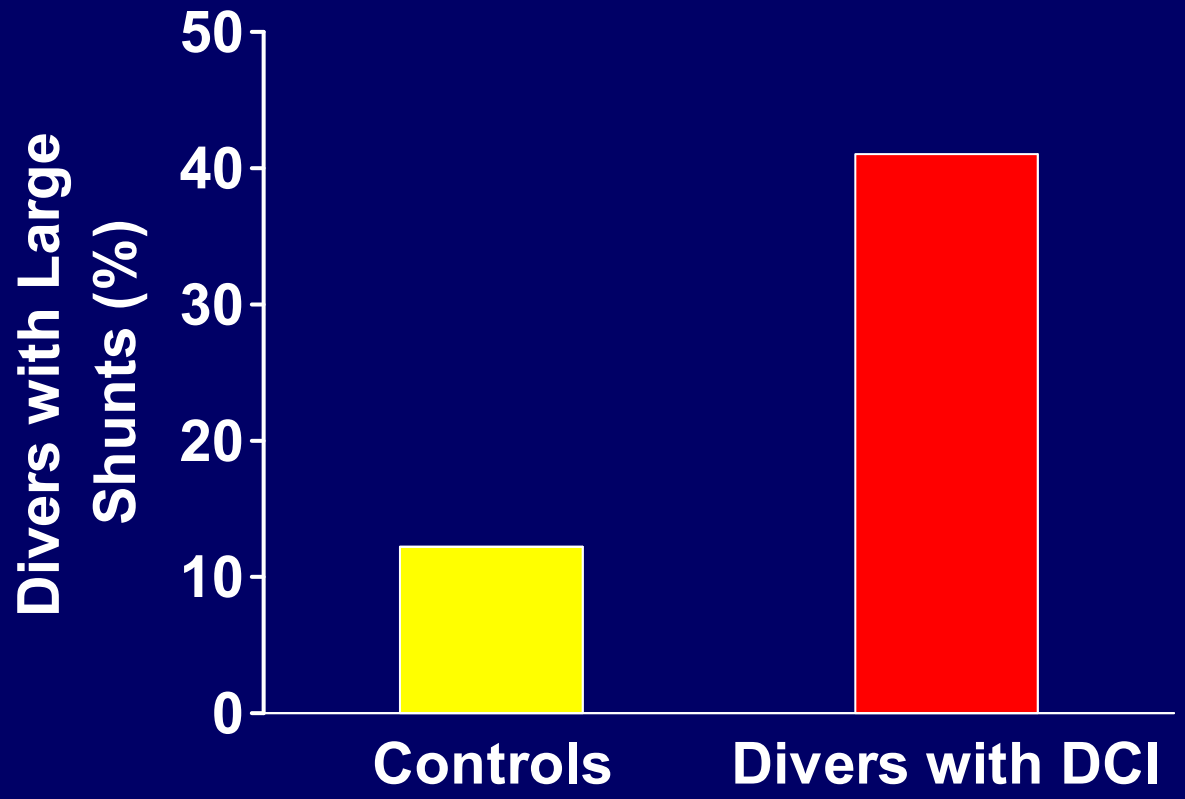
Moon et al *Undersea Hyperb Med* 18(Suppl):A1, 1991

PFO by TEE and DCS



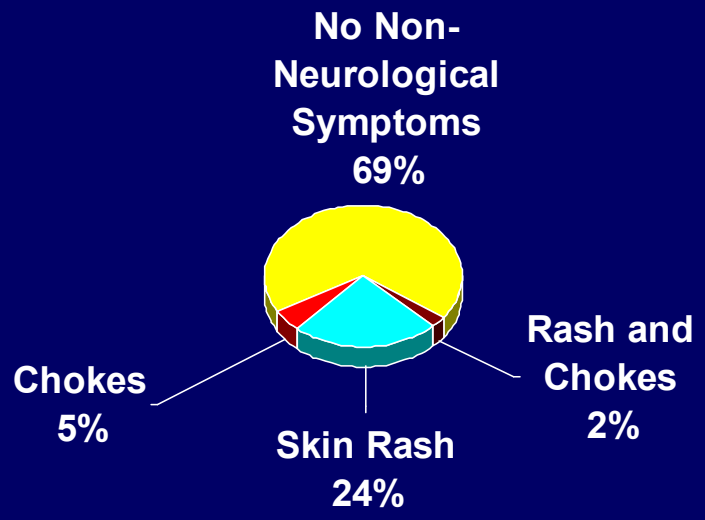
Germonpré et al *J Appl Physiol* 84:1622, 1998

Analysis of 100 Divers with Neurological DCI, 123 Control Divers



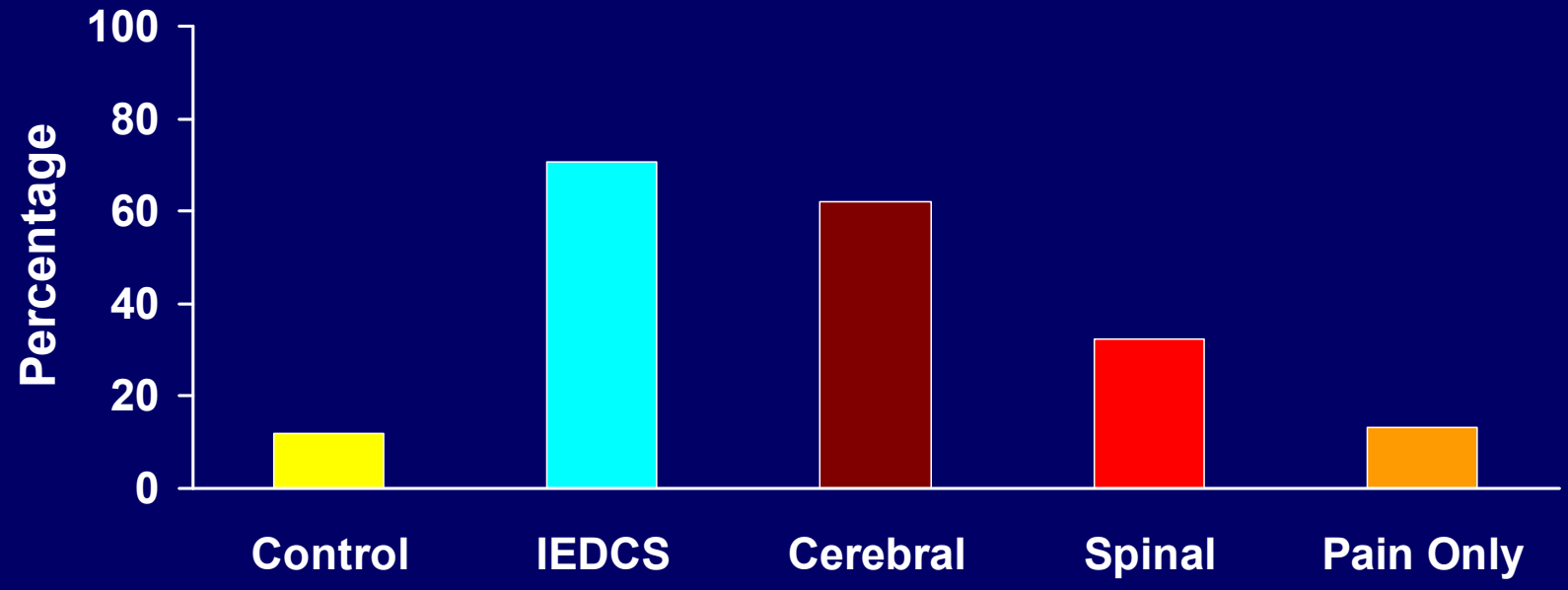
Wilmshurst & Bryson *Clin Sci* 99:65, 2000

Analysis of 41 Divers with Neurological DCI and Large Right-to-Left Shunt



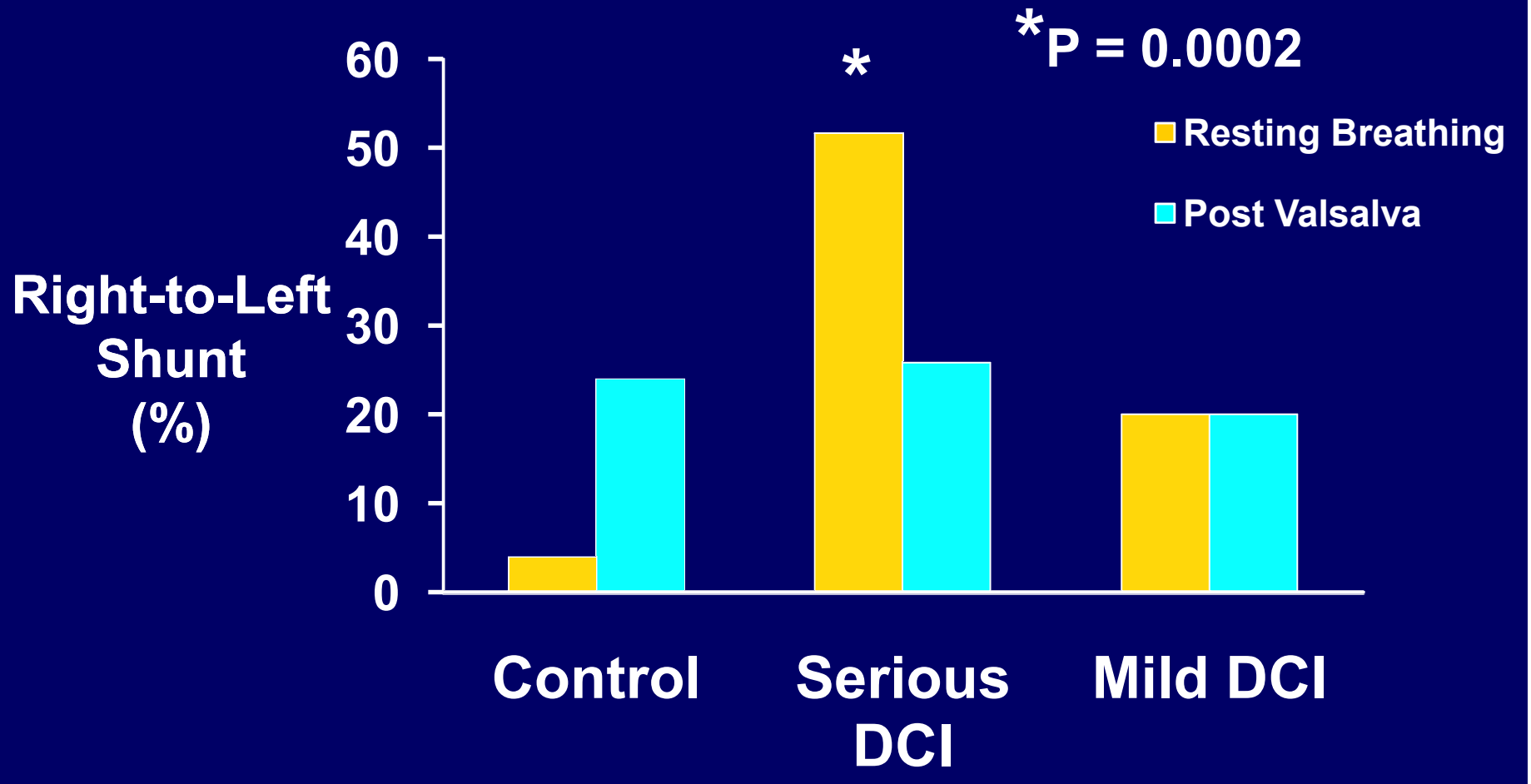
Wilmshurst & Bryson *Clin Sci* 99:65, 2000

Prevalence of Right-to-Left Shunt Detectable via TCD in 101 Cases of DCI, 101 Controls



Cantais, et al *Crit Care Med* 31:84, 2003

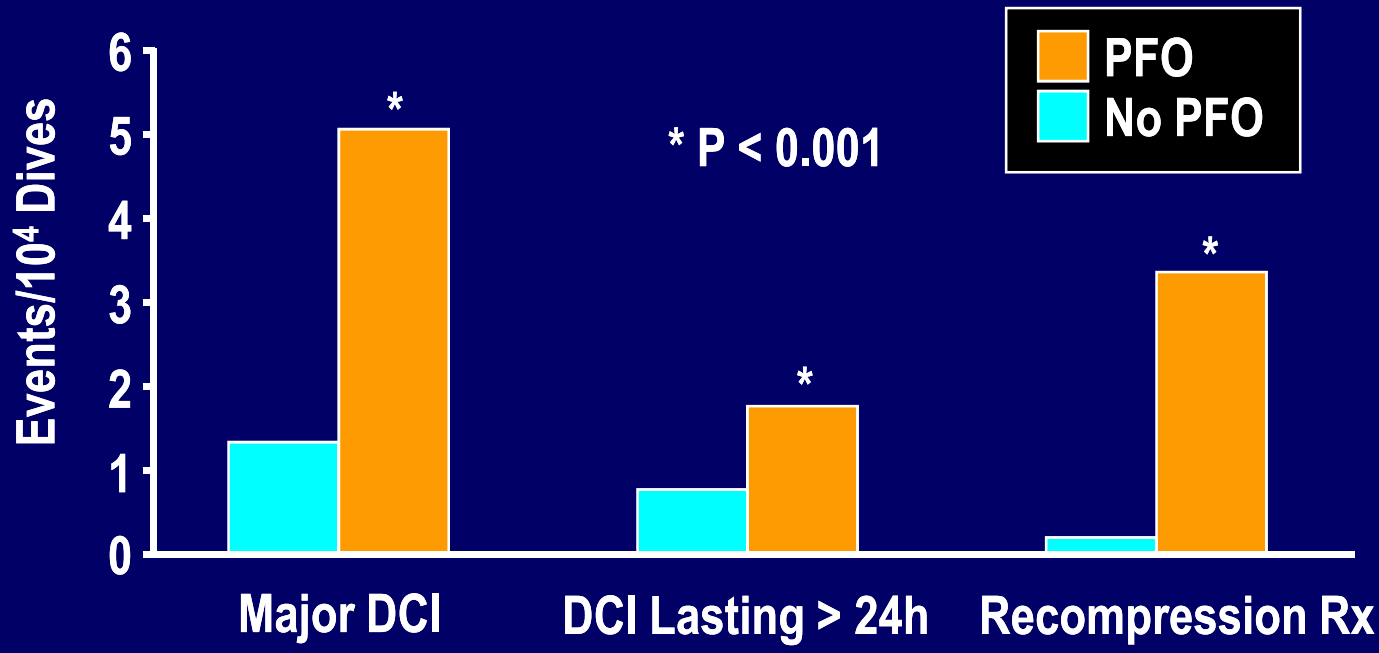
PFO by TEE in DCI



TTE sensitivity 80% (95% CI 70.3,89.7)
TTE specificity 96.8% (95% CI 92.5,100)

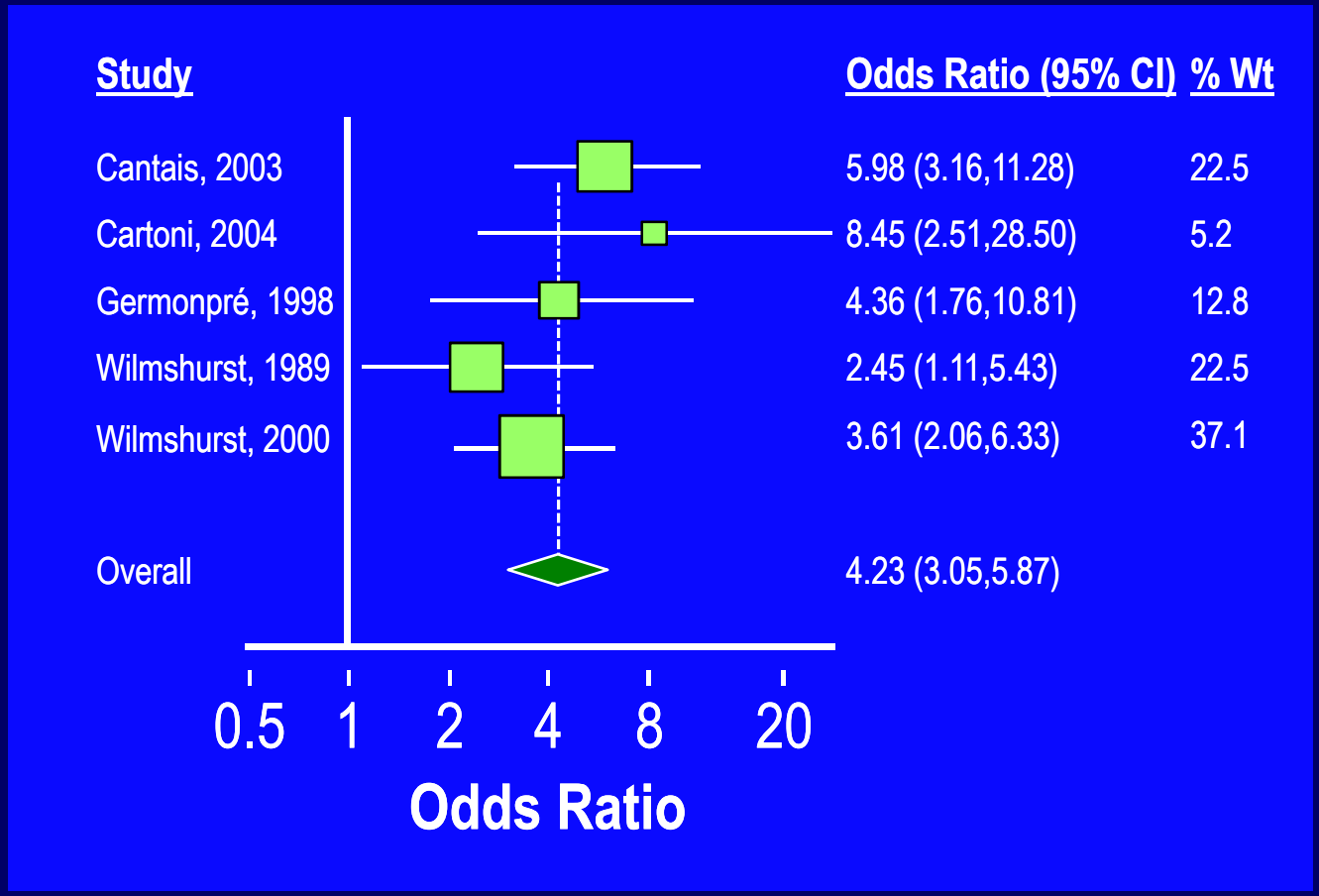
Cartoni D, et al. *Am J Cardiol* 94:270, 2004

Prevalence of Events in 230 Divers With or Without PFO



Torti, et al *Eur Heart J* 25:1014, 2004

PFO and DCS: Meta-Analysis



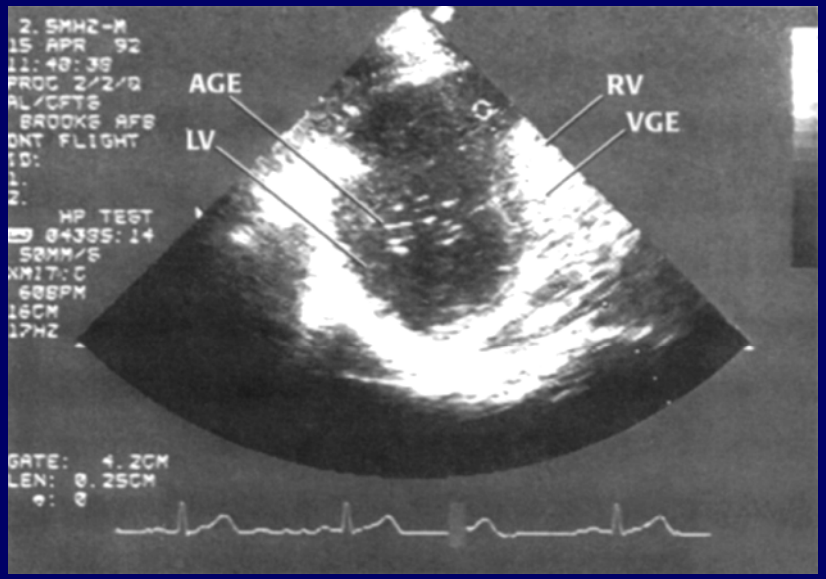
Lairez O, et al. *Clin J Sport Med* 19:231, 2009

LV Gas Embolism in Altitude DCS

- 369 human altitude exposures to 15,000-35,000 ft
- 6 cases of LV bubbles
- 5 of 6 cases became symptomatic simultaneously with AGE onset: joint pain and skin mottling; no cerebral manifestations
- 5 subjects tested for PFO:

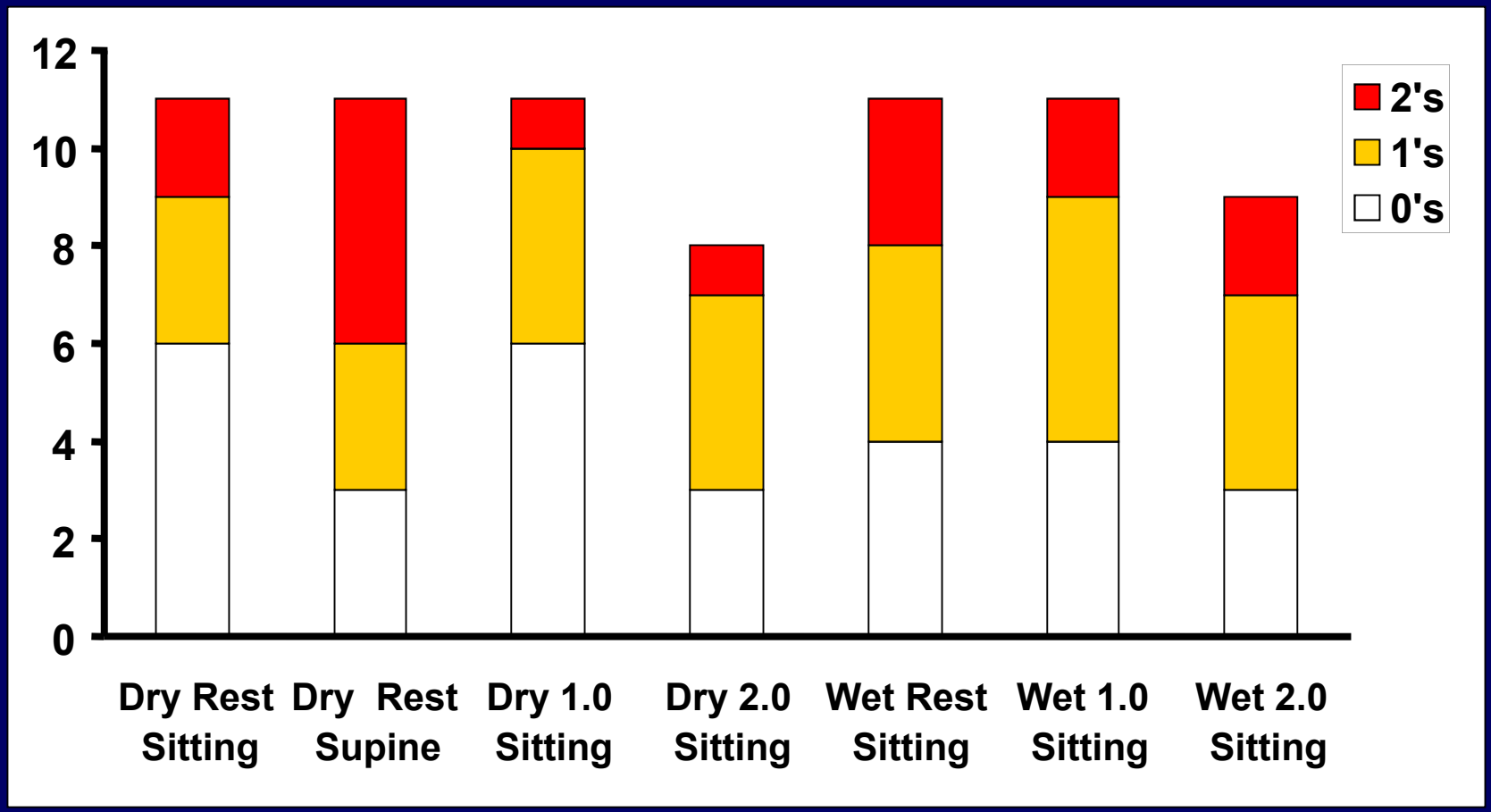
  3 TEE: 2 positive

  2 TTE: 0 positive



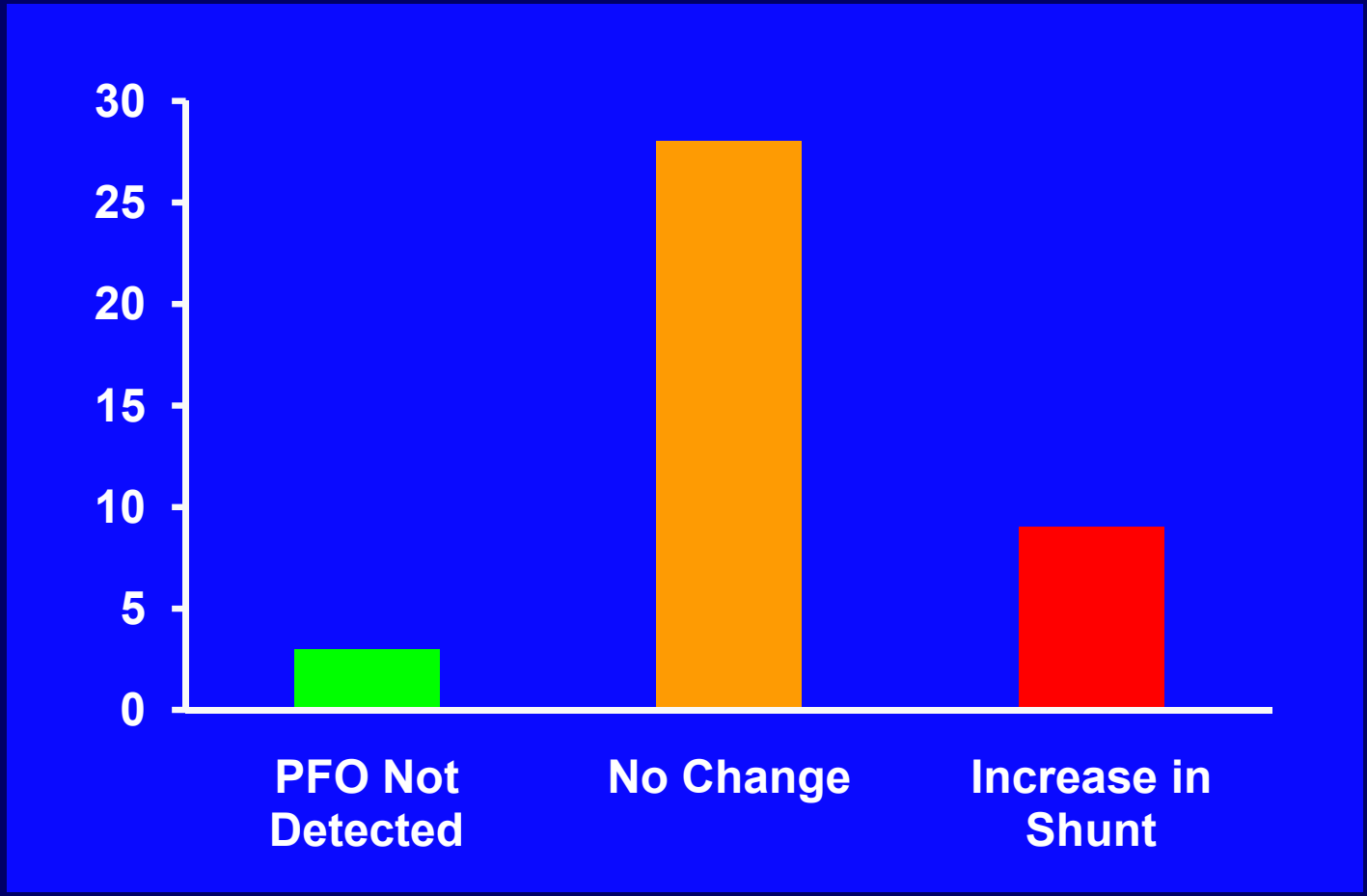
Pilmanis AA, et al. *Aviat Space Environ Med* 67:1092, 1996

Does exercise or immersion affect right-to-left shunt through a PFO?



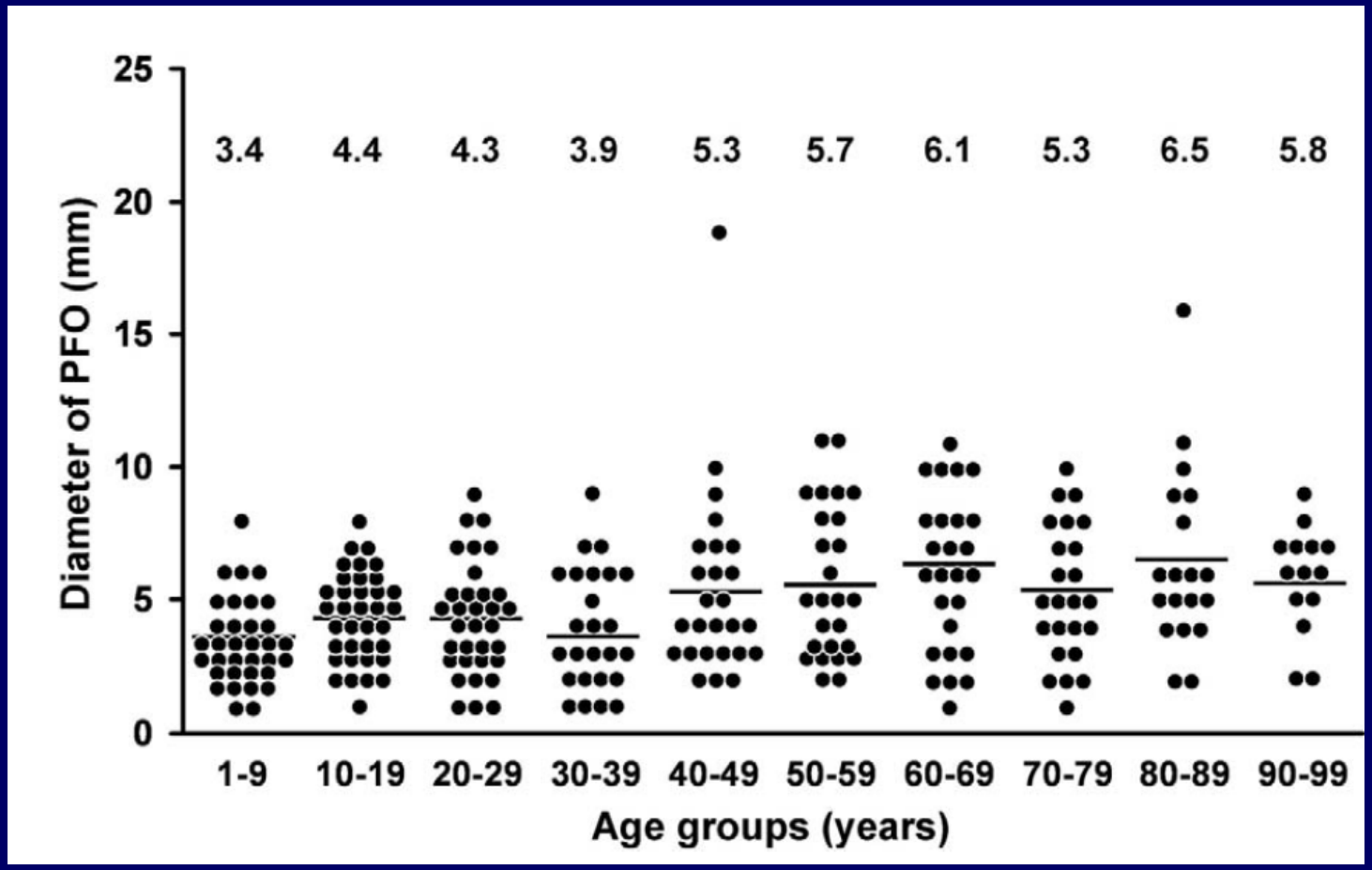
Dear G De L. *Undersea Hyperb Med* 20(Suppl):82, 1993

Change (6-8 y) in PFO in Scuba Divers



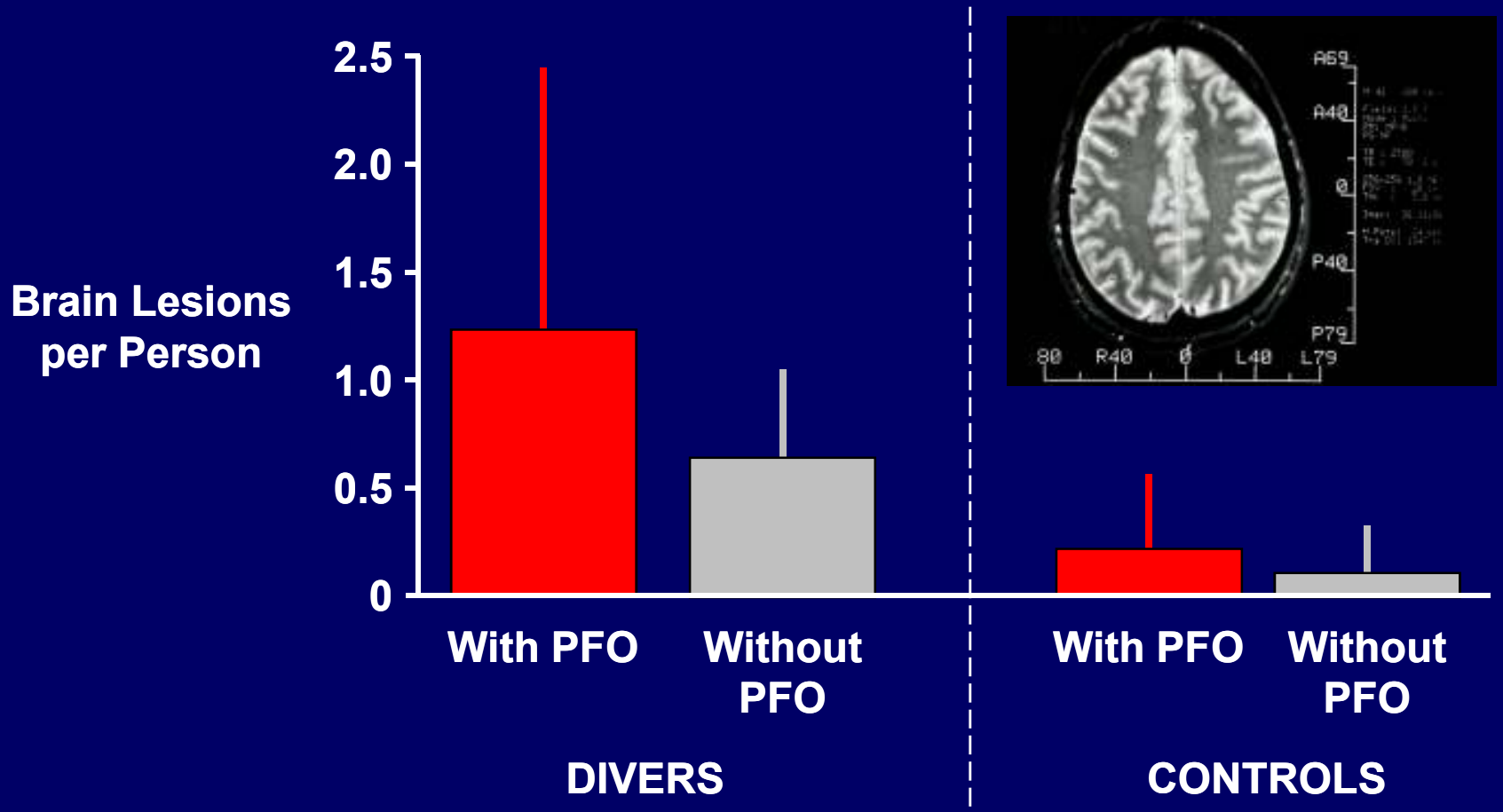
Germonpre P, et al. *Am J Cardiol* 95:912, 2005

PFO size tends to increase with age



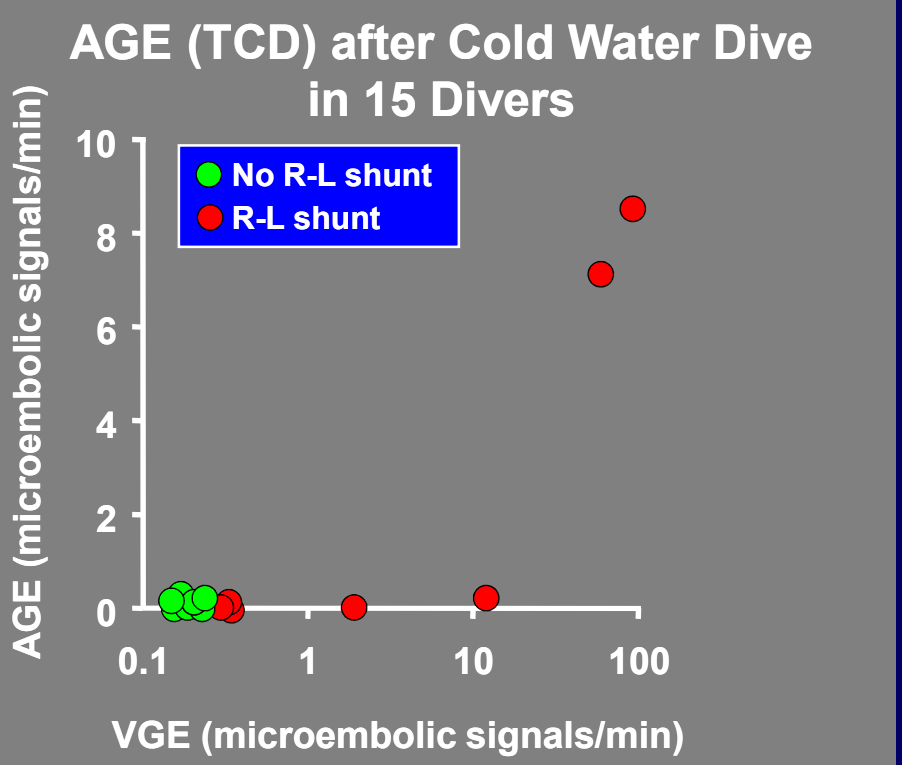
Data from Hagen PT, et al. *Mayo Clin Proc* 59:17, 1986
Fig. from *Curr Probl Cardiol* 2:49, 2004

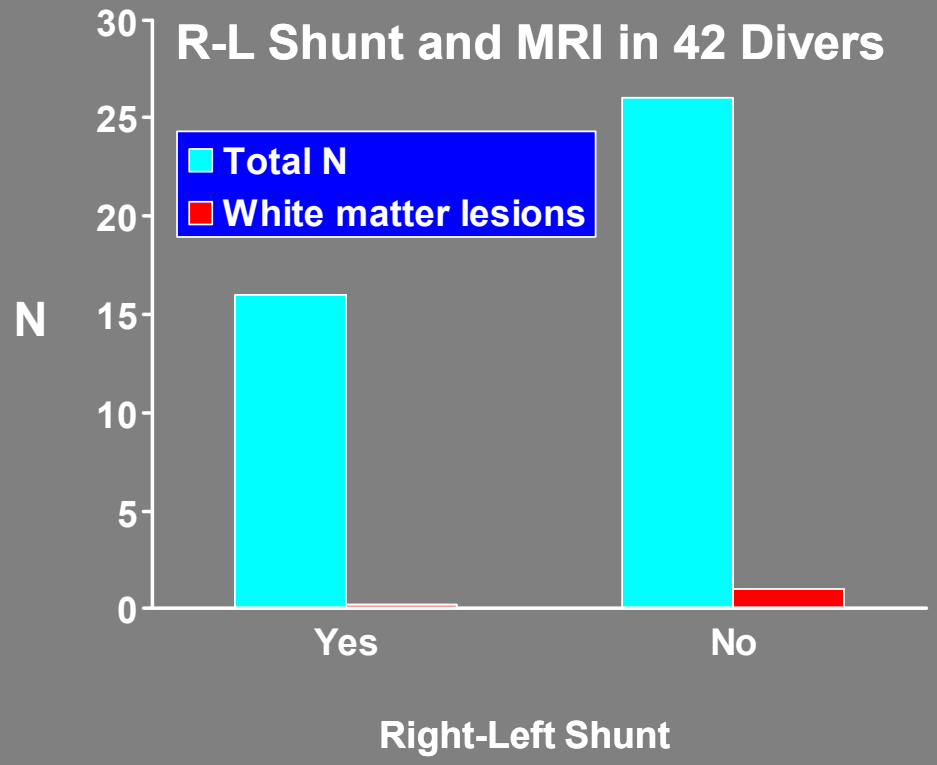
PFO and Brain Lesions on MRI



Schwerzmann, et al *Ann Intern Med* 134:21, 2001

PFO and Brain Lesions on MRI in Recreational Divers





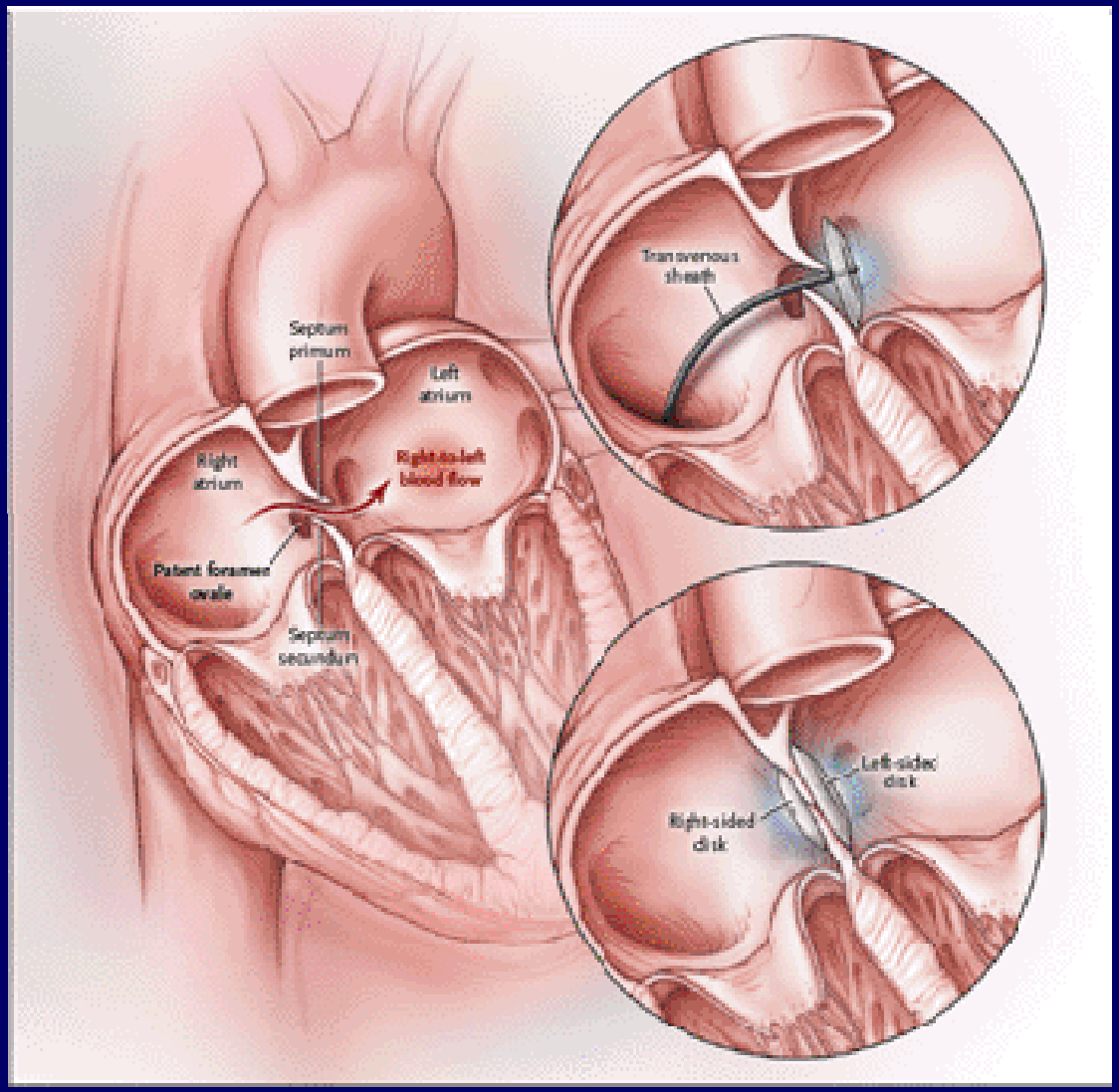
Gerriets T, et al *Aviat Space Environ Med* 74:1058, 2003

PFO and Paradoxical Systemic Embolization: Summary of 145 Published References

Patent foramen ovale and paradoxical systemic embolism: a bibliographic review

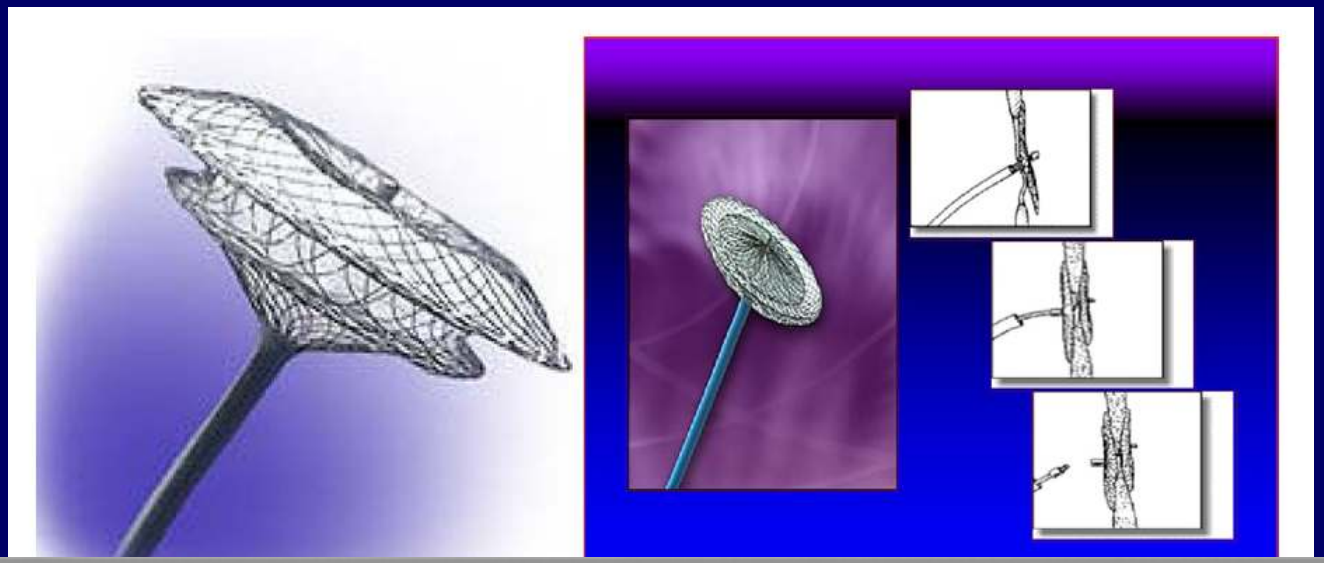
Foster PP, Boriek AM, Butler BD. *Aviat Space Environ Med* 74:(6, suppl): B1-B61, 2003

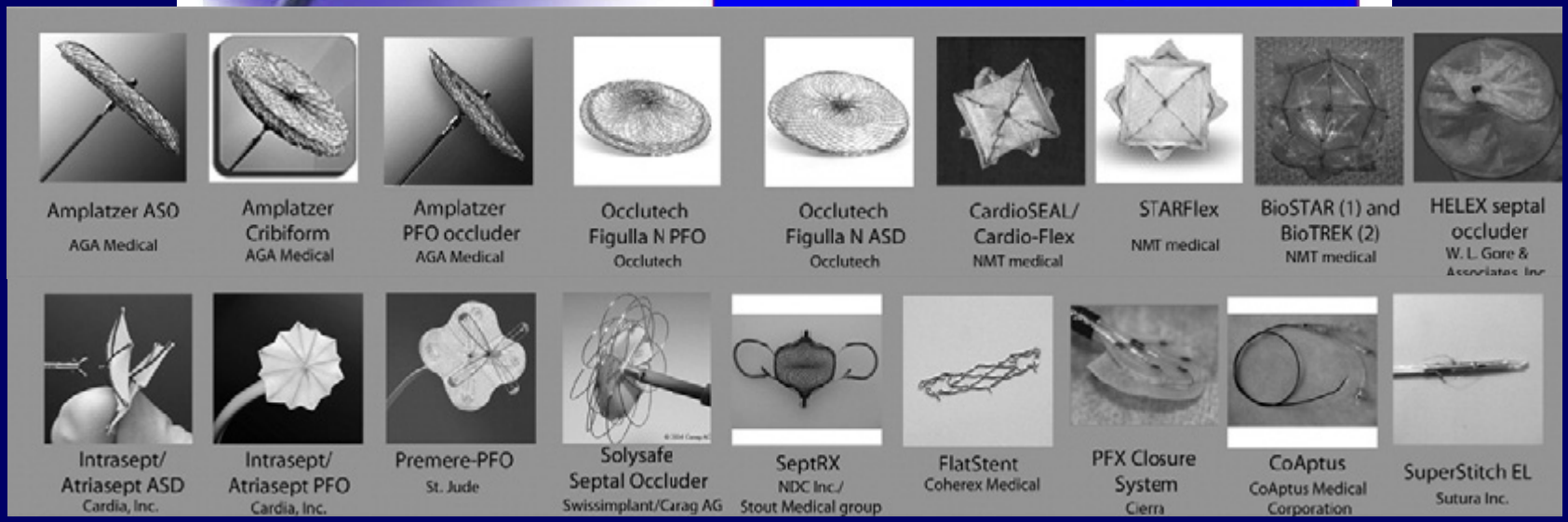
Transvenous Closure of PFO



Kizer JR, Devereux RB. *N Engl J Med* 353:2361, 2005

Transvenous Occluding Devices





Holmes D, et al. *Curr Probl Cardiol* 2:49, 2004

Closure of PFO in Divers with DCI

- 7 divers (ages 18-60 y, F=1): 3 professional, 4 amateur
- 6 divers: 3 spinal cord DCI, 3 cerebral DCI
- One diver: 2 separate episodes of cerebral DCI
- One diver also experienced skin bends
- All episodes occurred within 30 min of surfacing
- PFTs, chest radiographs all normal. All had resting R-L shunt; one inter-atrial aneurysm
- One of the divers (38 year old male) had small CVA unrelated to diving with full recovery in 4 days. No risk factors
- Post insertion of occluder: one trivial R-L shunt with Valsalva, 6 no shunt
- All returned to diving, with no DCI over 3-12 month followup

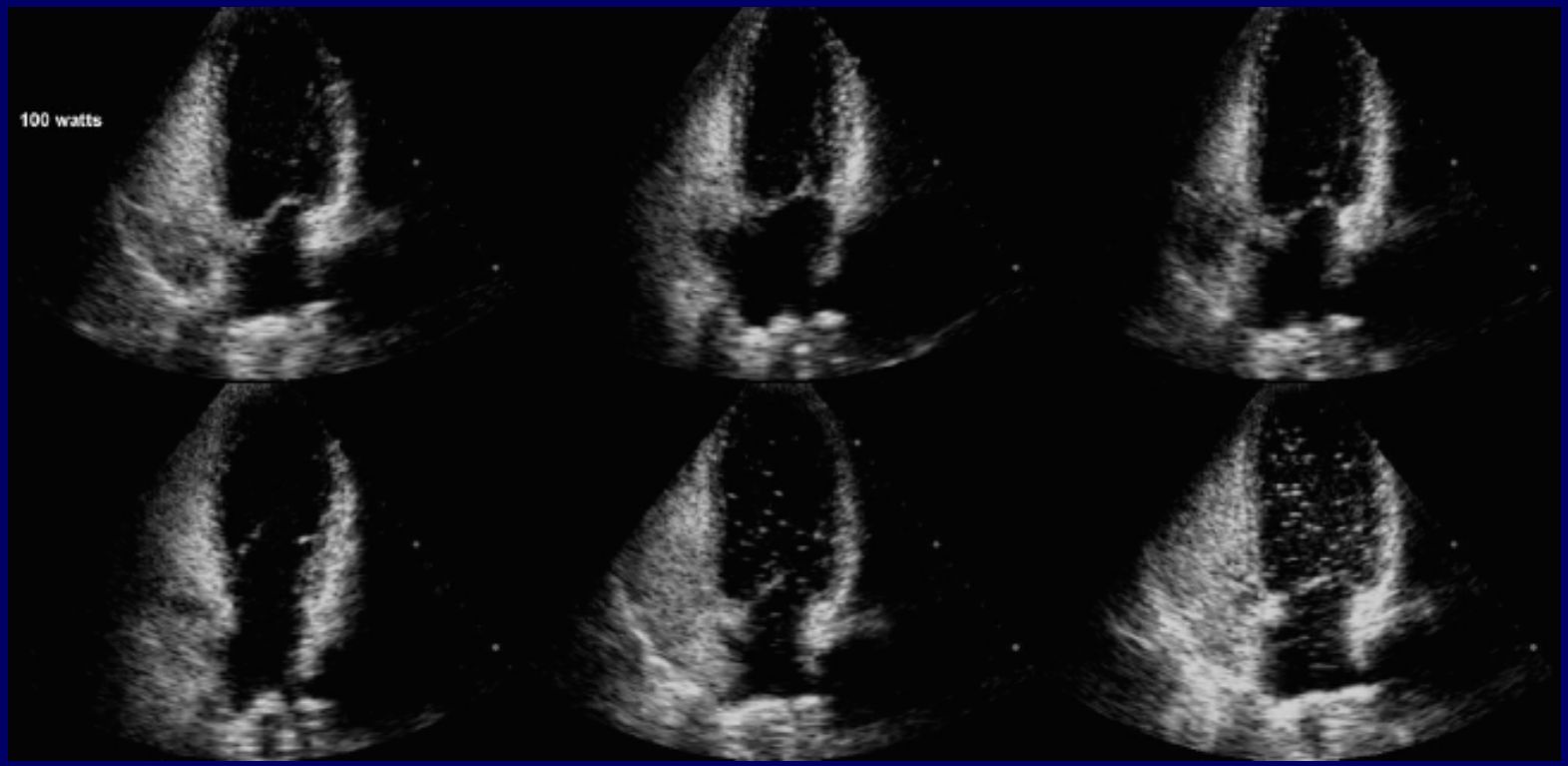
Walsh KP, et al. *Heart* 81:257, 1999

Closure of PFO in Divers with DCI

- 29 divers (F=11): 28 PFOs, 1 ASD
- 23 have resumed diving, including 7 as professional divers
- 2,536 dives since closure procedures. 18 have dived deeper than 30 m, 13 deeper than 40 m, and 8 deeper than 50 m
- Follow-up 9-32 months
- No recurrence of DCI

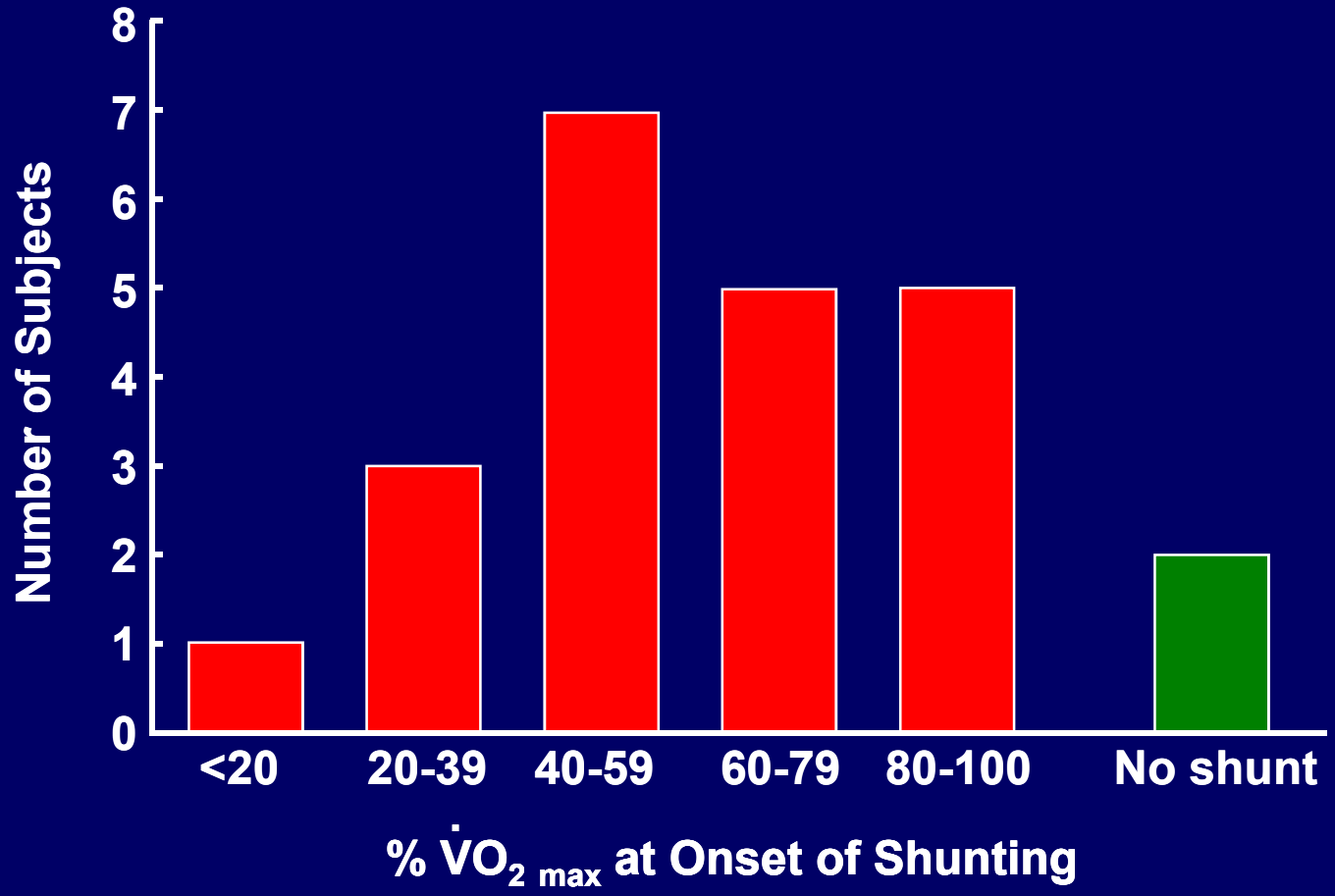
Wilmshurst PT, et al. *Lancet 356:*1648, 2000

Transpulmonary Shunt in 28 Year Old Female at 40% $\dot{V}O_{2\ max}$



Eldridge MW. *J Appl Physiol* 97:797, 2004

Transpulmonary Shunt During Exercise



Eldridge MW. *J Appl Physiol* 97:797, 2004

The Conventional Wisdom

- PFO precipitates DCI by facilitating arterialization of VGE
- Appropriate methods of reducing the impact of a PFO on diving safety
  - Screening out divers with PFO
  - Repairing PFO
  - Reducing VGE by choice of depth-time/breathing gas

Problems with the Conventional Wisdom

- The conventional wisdom (PFO: VGE→AGE →DCI) may be wrong
  - PFO is common
  - VGE is common
  - Serious DCI is rare

Project Dive Exploration 1995-2008

- 10,722 divers:137,451 dives
- 41 DCS cases (0.03% of dives, 1/3,352)
- 1998-2004: 822 of 2,438 DCI cases (34%) in recreational divers motor, cerebral, balance, mental status, vision, auditory
- Estimated serious DCI risk 0.01% of recreational dives

Dr. Petar Denoble, personal communication

Problems with the Conventional Wisdom

- The conventional wisdom (PFO: VGE→AGE →DCI) may be wrong
  - PFO is common
  - VGE is common
  - Serious DCI is rare
- Repair of PFOs using transvenous occluding devices is not totally benign

Complications of Transvenous PFO Closure (%)

Overall	**8.2 ± 0.8**
Technical	**5.0 ± 0.6**
Bleeding	3.4 ± 0.5
Acute posthemorrhagic anemia	0.5 ± 0.1
Other technical	1.7 ± 0.3
Mechanical failure of instrument or apparatus during procedure	<0.5
Mechanical complication of cardiac device	0.7 ± 0.2
Infection and inflammatory reaction	<0.5
Other complications of internal prosthetic device 996.7 0.9 ± 0.2	
Vascular surgery	<0.5
Systemic	**3.7 ± 0.4**
Cardiac	1.6 ± 0.2

Opotowski AR, et al. *Am Heart J* 157:867, 2009

Incidence of Thrombus Formation on the CardioSEAL and the Amplatzer Interatrial Closure Devices

Hitoshi Anzai, MD, John Child, MD, Barbara Natterson, MD, Janine Krivokapich, MD, Michael C. Fishbein, MD, Vicki K. Chan, BS, and Jonathan M. Tobis, MD

Transcatheter closure for atrial septal defect (ASD) and patent foramen ovale (PFO) is a promising alternative to surgical closure or anticoagulant therapy. A potential complication is thrombus formation on the device after implantation. From February 2001 to June 2003, 66 patients with atrial communication were treated successfully with the Amplatzer device (16 septal and 20 PFO occluders) or the CardioSEAL device (30). Patients were discharged on antiplatelet medication (aspirin and clopidogrel) and/or anticoagulation. Fifty patients (76%) had transesophageal echocardiography (TEE) 1 month after device implantation (28 ± 10 days). No patient experienced a thromboembolic episode during follow-up. TEE revealed that thrombus formation occurred more frequently on the CardioSEAL device (5 of 23 patients; 22%) than on the Amplatzer device (0 of 27 patients; 0%) ($p = 0.02$). Although thrombus disappeared or markedly diminished after additional anticoagulation therapy in 3 patients, 1 patient had surgical explantation of the device due to progressive increase in the size of thrombus with hypermobility despite intensive anticoagulation therapy. There was no variable associated with the presence of thrombus formation on the occluder other than the use of the CardioSEAL device. One month after insertion, the CardioSEAL device is more likely to have thrombus present than the Amplatzer device.

(Am J Cardiol 2004;93:426–431)

Late Aortic Insufficiency after PFO Closure

- 240 consecutive patients with percutaneous closure of ASD or PFO from 2001-2006
- TEE before implantation, 3, 6 and 12 months after closure
- Sufficient closure without residual shunt in 89% of patients with ASD, 92% of patients with PFO
- Long-term follow-up disclosed newly developed or worsened aortic valve regurgitation (AR) in 10% of patients with PFO, possibly due to overgrowth of the device by tissue, causing changes in inter-atrial septal geometry, traction on the root of the noncoronary aortic cusp

Schoen SP, et al. *Heart* 94:844, 2008

Problems with the Conventional Wisdom

- The conventional wisdom (PFO: VGE→AGE →DCI) may be wrong
  - PFO is common
  - VGE is common
  - Serious DCI is rare
- Repair of PFOs using transvenous occluding devices is not totally benign
- Decompression tables have been designed and tested in populations that include those with a PFO

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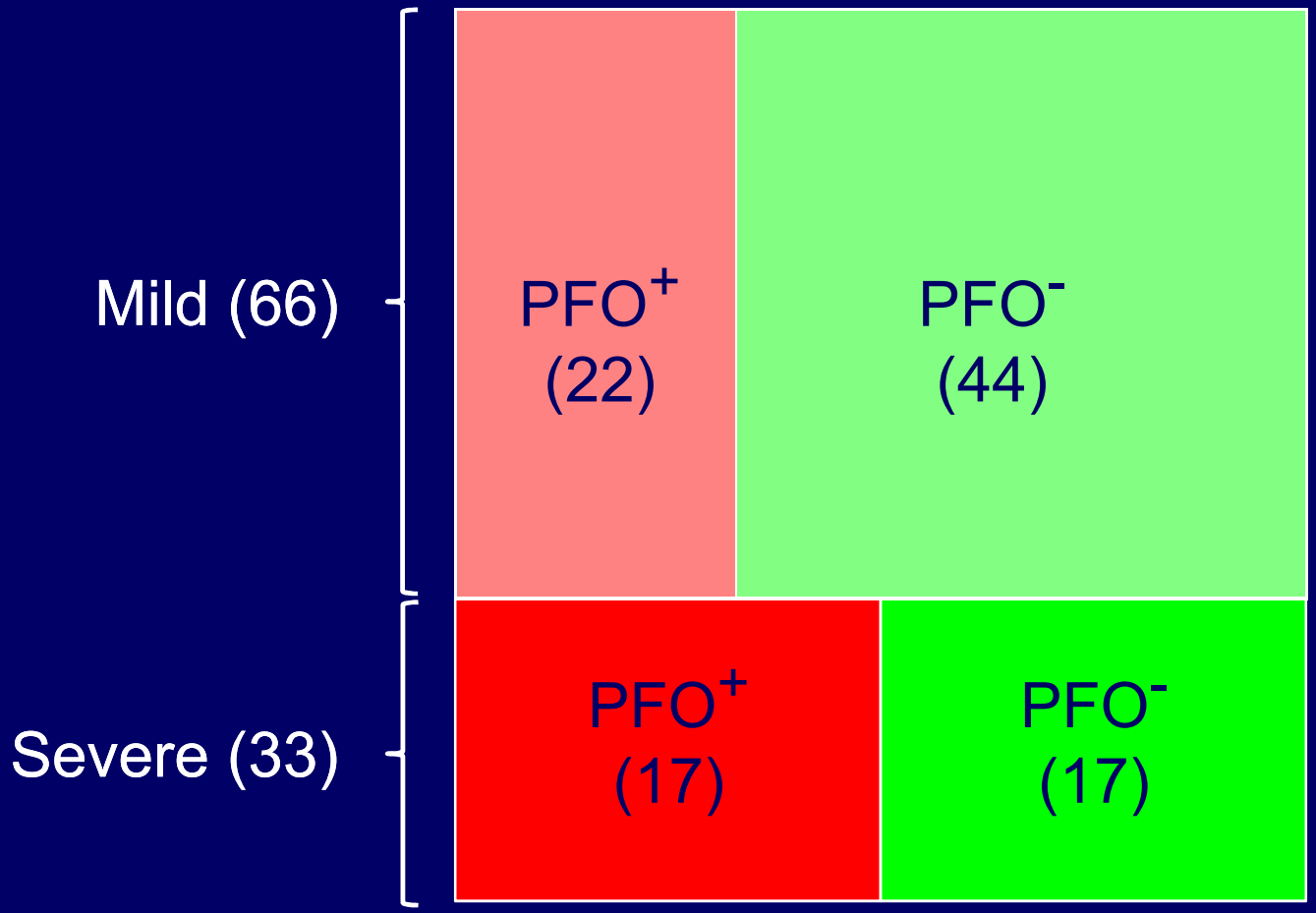
100 DCS Cases



PFO^{+}=39; PFO^{-}= 61

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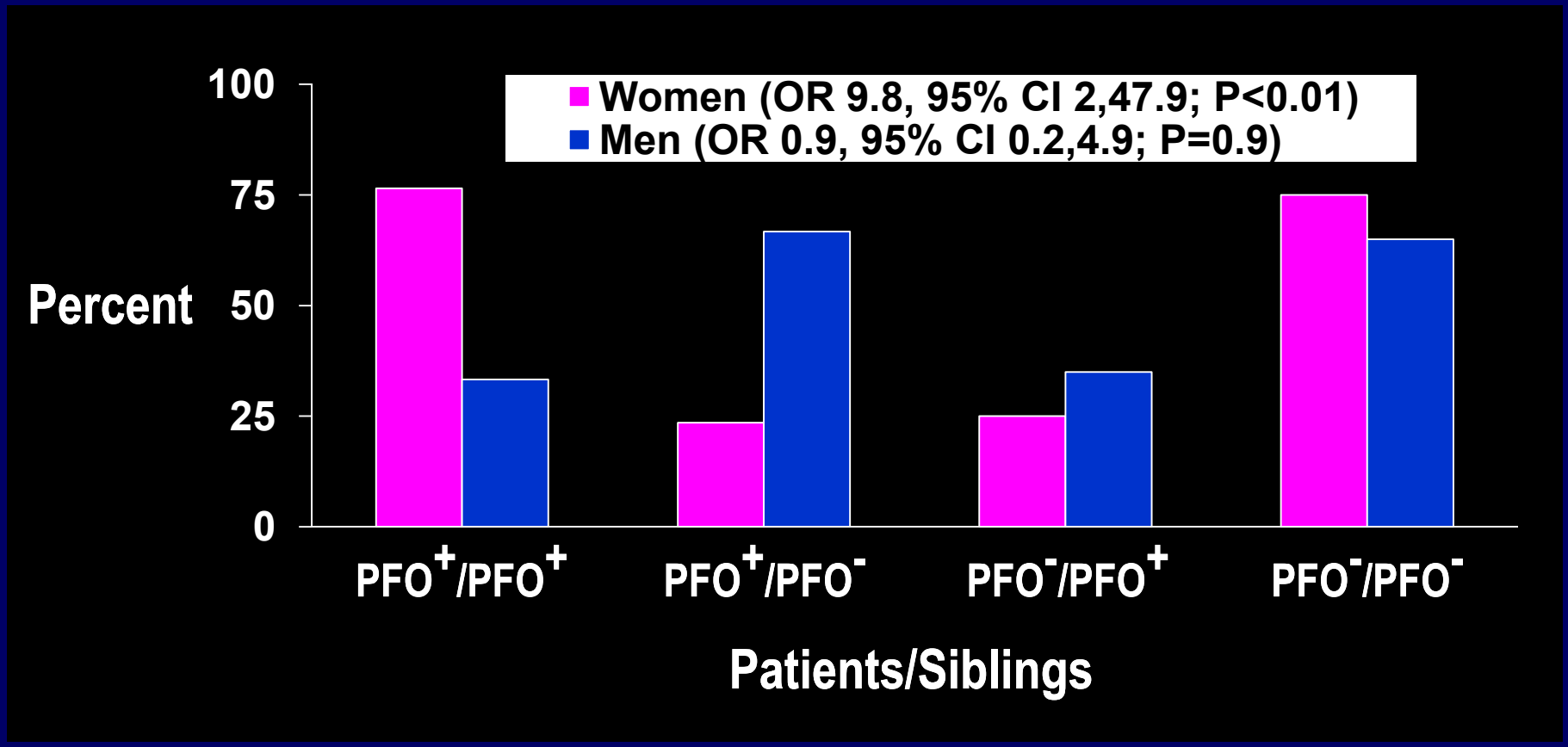
- Screening for a rare but treatable disorder by looking for a common anomaly is inefficient (e.g. screening for renal artery stenosis by doing renal arteriograms on all hypertensives)
- Perhaps PFO is simply a marker of susceptibility to DCI. If so, treating PFO, screening divers with PFO, eliminating VGE may be useless

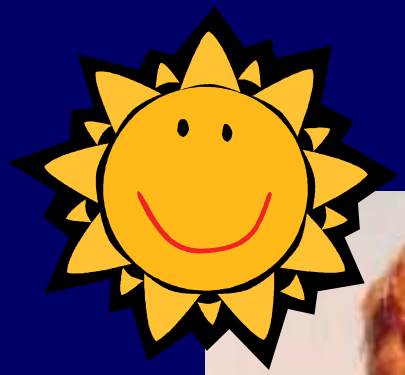
PFO Inheritance



Arquizan C, et al. *Stroke* 32:1563, 2001

Risk Factor: Redhead

Redheads and Sunburn



“Fixing” the risk factor may not alter the risk

Patent Foramen Ovale Closure Devices: Thoughts from the Circulatory Device Advisory Panel

"PFOs occur in almost 30% of the general population. PFOs are more common in patients who have strokes or transient ischemic attacks (TIAs). However, no RCT has found that the closure of PFOs reduces the incidence of stroke or death"

Somberg J. *Am J Cardiol* 100:905, 2007

Conclusions (1)

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- Data to suggest that PFO closure prevents DCI are incomplete

Conclusions (2)

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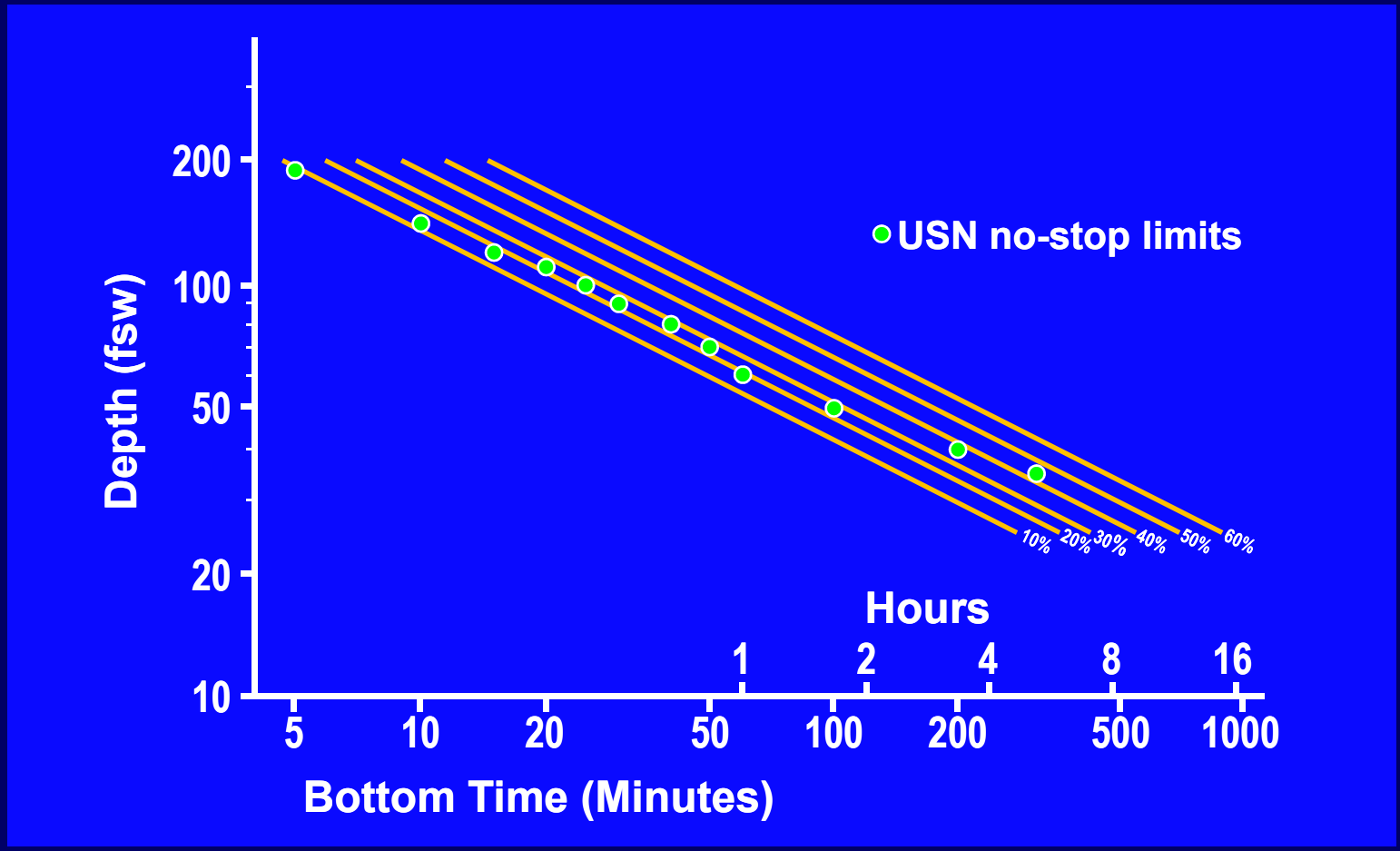
VGE and Hyperbaric Exposure



Spencer MP. *J Appl Physiol* 40:229, 1976

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- Don’t focus risk factor research exclusively on PFO. There are probably many other “better” physiological risk factors (demographics, genetics, proteomics, environmental factors)

Risk Factors for DCS in Tunnel Workers

- 932 men with 12 shifts or more at maximum working pressure of ≥1 bar in a compressed air tunneling project in Hong Kong
- 356 men (38.2%) had one or more DCS episodes
- Logistic regression used to predict DCS^+ group

Factor	P
Maximum working pressure	<0.001
# Exposures	<0.01
Past # DCS episodes	<0.05
Job type ('1'=miner, '0'=others)	<0.01
BMI	<0.01

Lam TH, Yau KP. *Undersea Biomed Res* 16:283, 1989