# Cerebral Arterial Gas Embolism

D. Lindsie Cone, MD, UHM, FUHM

# Air / Gas Embolism
## *Cerebral Arterial Gas Embolism*

"Primary Training in Hyperbaric Medicine"
D. Lindsie Cone, MD

1

# Cerebral Arterial Gas Embolism
## *…Definition*

*The introduction of gaseous emboli into the cerebral arterial circulation.*

- In divers, it is not necessarily related to an excessive tissue gas burden.
- *Medicare: "Gas Embolism"
- *UHMS: "Air or Gas Embolism"

**Not specific to the brain/arterial circulation: supportive research is.*

2

# Cerebral Arterial Gas Embolism
## *…Etiology*

- Decompression
- Iatrogenic events
- Trauma

3

# Cerebral Arterial Gas Embolism
## *…Mechanism: Decompression-Induced*

*~ intratracheal pressures of 70-80mmHg*
*- Polack & Adams, 1932*

- Alveolar membrane failure
- A change in transpulmonary pressure of 70 – 80 mmHg is sufficient.
- Equivalent to an ascent from a depth of only ~1 meter of sea water.

4

# Cerebral Arterial Gas Embolism
## *…Mechanism: Decompression-Induced*

*Shallowest recorded depth involving pulmonary barotrauma-induced CAGE as a clinical diagnosis*

*- P.J. Benton, et al. 1996 Avia Space Environ Med: 67(1)*

- Helicopter escape training exercise
- Utilizing Short Term Air Supply System (STASS)

5

# Cerebral Arterial Gas Embolism
## *…Iatrogenic events*

- Cardiopulmonary bypass
  - Runnaway pump head
  - Trapped ventricular gas
  - Bubble oxygenator
  - Line disconnection
- Carotid endarterectomy
- Laparoscopic surgery
- Liver transplantation
- Transthoracic needle bx
- Central venous catheters
  - Insertion
  - Aspiration
- Mechanical ventilation
- Neurosurgery
- Dental implant surgery
- Nd:Yag laser surgery
- Thoracotomy

6

## Cerebral Arterial Gas Embolism

*…Iatrogenic events - continued*

- Balloon angioplasty
- Endometrium resection
- Closed wound suction kit
- Hysteroscopy
- Arthroscopy
- Transurethral prostate resection
- Hepatic protoenterostomy
- Peripheral venous catheter
- Knee arthrography
- Water jet dissector
- CPR
- Angioplasty
- Bronchoscopy
- Endoscopy
- Hip replacement
- Intra-aortic balloons
- Diagnostic monitoring
- Hemodialysis

7

## Cerebral Arterial Gas Embolism

*…Right to left shunting of bubbles*

*Patent foramen ovale*

*Thompson & Evans, 1930*
*Moorthy & Losasso, 1974*
*Verstappen et al, 1977*
*Gronert et al, 1979*

*Pulmonary oxygen toxicity*

*Butler & Hills, 1981*

*Vasodilators*

*Butler & Hills, 1985*

*Arteriovenous shunts*

*Spencer & Oyama, 1971*

8

## Cerebral Arterial Gas Embolism

*…Right to left shunting of bubbles, continued*

*Bubble volume overload*

*Butler & Hills, 1985*
*Spencer & Oyama, 1971*

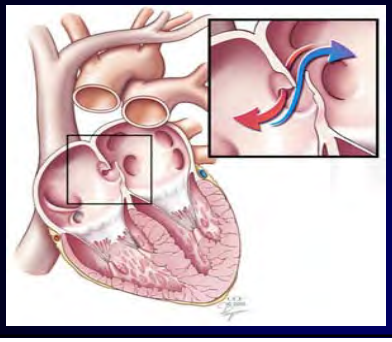
*Elevated pulmonary artery pressures*

*Verstappen et al, 1977*
*Gronert et al, 1979*

9

## Cerebral Arterial Gas Embolism

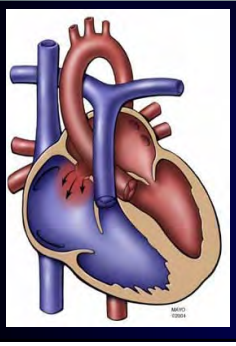
*…Patent foramen ovale*

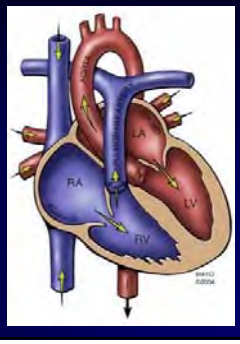


10

## Cerebral Arterial Gas Embolism

*…Patent foramen ovale: septum secundum*

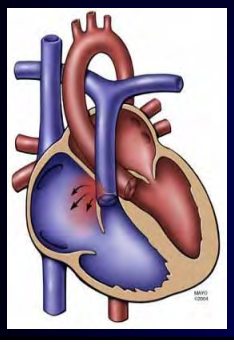


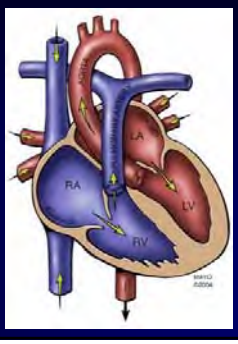



11

## Cerebral Arterial Gas Embolism

*…Patent foramen ovale: septum primum*

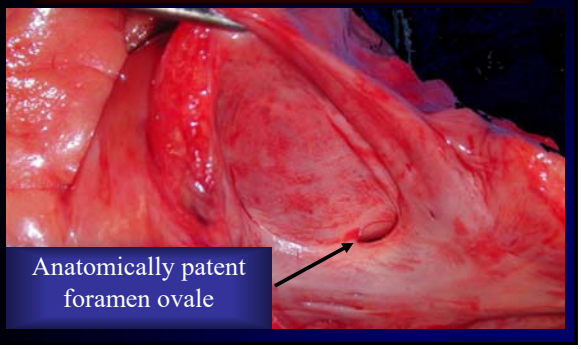





12

## Cerebral Arterial Gas Embolism

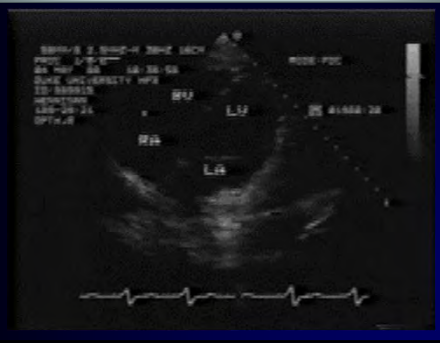
*…Patent foramen ovale*




13

## Cerebral Arterial Gas Embolism

*…Bubble Contrast Echocardiogram*




14

## Cerebral Arterial Gas Embolism

*…TEE evidence of transpulmonary PAE*

*Massive VGE associated with open brain surgery in the sitting position.*

*"Air continued to traverse the left atrium per TEE for 15 minutes after all venous entrainment had ceased."*

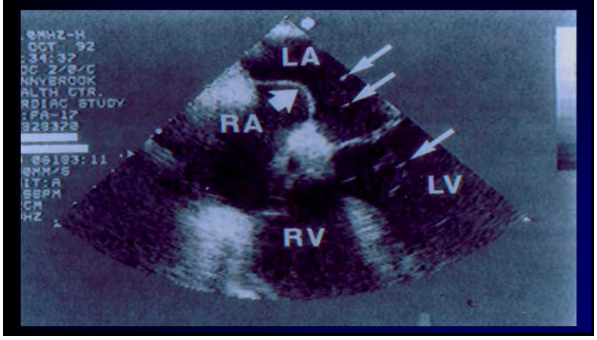
*- Bedell EA, et al. 1994 Anaesthesiol: 80(4)*

- PFO ruled out by negative findings on:
  - Multiple negative bubble contrast studies
  - Color flow doppler
  - Right-to-Left atrial septal bulging upon PEEP release

15

## Cerebral Arterial Gas Embolism

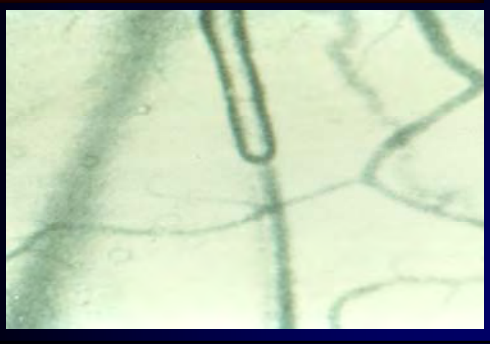
*…Septal displacement on PEEP release*




16

## Cerebral Arterial Gas Embolism

*…Vascular bubbles*



17

## Cerebral Arterial Gas Embolism

*…Spontaneous redistribution*

*Evidence and mechanism of spontaneous redistribution*

*- Gorman DF 1986 UBR; 13(3): 317-335*

- Bubble size less than 500 microns
  - Entrapment never occurred
  - Some evidence of vasoreactivity
- Bubble size greater than 5,000 microns
  - Entrapment and local circulatory arrest inevitable

18

## Cerebral Arterial Gas Embolism
*…Spontaneous redistribution, continued*

*Evidence and mechanism of spontaneous redistribution*

*- Gorman DF 1986 UBR; 13(3): 317-335*

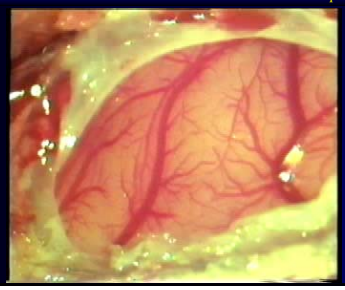
- Bubble size between 500 – 5,000 microns
  - Entrapment common but redistribution occurred within 3 minutes
  - Entrapment occurred most frequently in arterioles between 50 – 200 microns diameter.
  - Redistribution occurred only during the hypertensive period
  - Re-embolism occurred in 12% of observations

19

## Cerebral Arterial Gas Embolism
*…Spontaneous redistribution*

*Cerebral Arterial Gas in Rabbit Model*

*- Helps and Gorman*



20

## Cerebral Arterial Gas Embolism
*…Decompression induced CAGE*

*Clinical correlations to cerebral arterial gas*

*- Helps SC, Gorman DF 1990 Stroke; 21: 94-99*

- Five percent died
  - Permanent occlusion of pial vessels
- Thirty-five percent suffered sustained neurological injury
  - Temporary occlusion of pial vessels
- Sixty percent experienced spontaneous recovery of neurological function
  - Free transit of pial vessels

21

## Cerebral Arterial Gas Embolism
*…Decompression induced CAGE*

*Leukopenic animal model compared to controls*

*- Help SC, Gorman DF 1991 Stroke; 22: 351-354*

*It appears that decreases in both cerebral blood flow and brain function seen after embolism require the presence of leukocytes.*

22

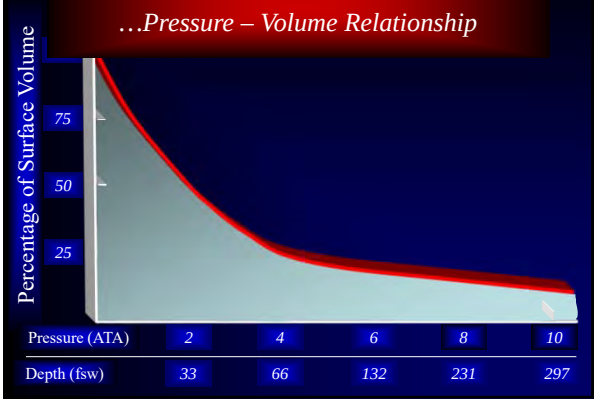
## Cerebral Arterial Gas Embolism
*…Decompression induced CAGE*

*Pressure and geometric proportions of bubbles*

*The danger of decompression-induced arterial gas embolism is greatest as the diver nears the surface.*

23

## Cerebral Arterial Gas Embolism
*…Pressure – Volume Relationship*




24

## Pressure Effects on Bubbles

| Depth in Feet | Pressure in ATA | Relative Volume (%) | Relative Diameter (%) | Relative Surface Area (%) |
|---|---|---|---|---|
| 0 | 1 | 100 | 100 | 100 |
| 33 | 2 | 50 | 79.4 | 63 |
| 66 | 3 | 33.3 | 69.4 | 48 |
| 99 | 4 | 25 | 63 | 39.7 |
| 132 | 5 | 20 | 58.6 | 34.3 |
| 165 | 6 | 16.7 | 55 | 30.3 |

25

## Cerebral Arterial Gas Embolism

*…Cause of death in divers*

| | |
|---|---|
| *Exhaustion, embolism, panic* | *205* |
| *Air embolism* | *123* |
| *Cave diving* | *113* |
| *Out of air at depth* | *60* |
| *Cardiovascular event* | *48* |
| *High waves or surf* | *37* |
| *Entrapped in kelp or weeds* | *26* |
| *Lost under ice* | *22* |

*~ NUADC 1976-1985*

26

## Cerebral Arterial Gas Embolism

*…Clinical significance*

*"Clinically significant cases of iatrogenic CAGE are under-diagnosed, under-treated, and under-reported"*

*- Tovar EA, et al. Ann. Thorac. Surg. 60, 1995*

27

## Cerebral Arterial Gas Embolism

*…Neuro-protection*

*Stroke and cognitive decline – previously considered infrequent, and a small price to pay for life saving/function improving surgery.*

*Recent systematic analysis: these complications are common; more than half such patients so disabled at discharge.*

*Newman MF, et al. NEJM 344:2001*

28

## Cerebral Arterial Gas Embolism

*…CPB as a source of embolization*

*Bubbles, per se, are injurious: it doesn't take a large volume to injure the brain.*

Off-pump CABG does result in a reduction in micro-emboli and cerebral hypoperfusion.

*- Diegeler A, et al. Ann. Thor. Surg; 69, 2000*

However, there is no difference in the degree of cognitive decline at 12 months between on-and off-pump procedures

*- Van Dijk D, et al. JAMA; 287 (11), 2002*

29

## Cerebral Arterial Gas Embolism

*…CPB as a source of embolization*

*"Perhaps the optimal approach to minimizing morbidity is to find effective neuro-protective agents"*

*Mark DB Newman MF JAMA : 287 (11) 2002*

*Most MEE's are probably gaseous*

*Stygall J, et al. Stroke; 31, 2000*

- A double opportunity for hyperbaric medicine?
  - ~ *treatment of a larger volume of patients*
  - ~ *preoperative neuro-protection*

30

## Cerebral Arterial Gas Embolism

*…Mechanical heart valves*

*"Most MEE's in mechanical heart valve patients are gaseous"*

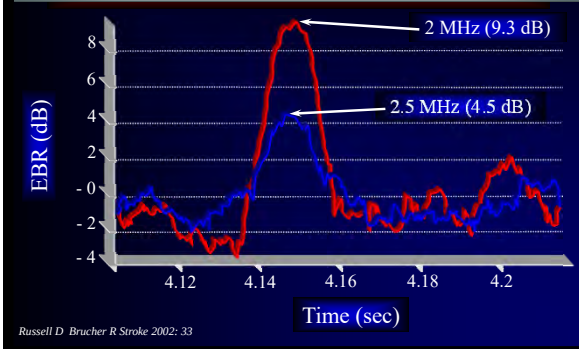
*- Russell D, Brucher R Stroke 33, 2002*

- 105 gas bubbles injected into a pig's cerebral circulation – 99 (94%) confirmed as gaseous, the balance as uncertain gaseous…none solid
- Right MCA microembolus in MHV patient identified as gaseous
- 433 of 514 emboli (84.2%) in 15 MHV pts. classed as gaseous,74 (14.4%) as solid, and 7(1.4%) uncertain solid or gas

31

## Cerebral Arterial Gas Embolism

*. . .In Vivo Porcine Analysis*



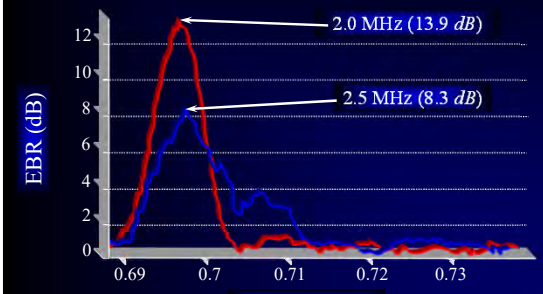

*Russell D Brucher R Stroke 2002: 33*

32

## Cerebral Arterial Gas Embolism

*…"Most microembolic events in mechanical heart valve patients are gaseous"*

*Human Subject*




*Russell D Brucher R Stroke 2002: 33*

33

## Cerebral Arterial Gas Embolism

*…Mechanical heart valves*

*"Most MEE's in carotid surgery pts. are solid"*

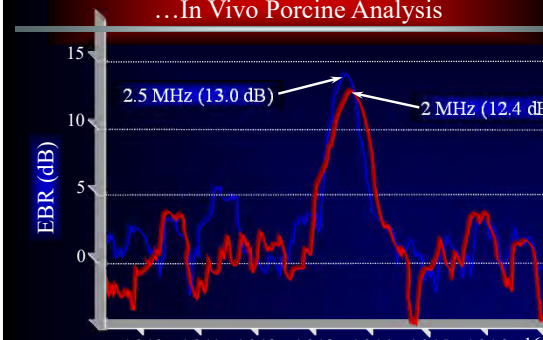
*- Russell D, Brucher R Stroke 33, 2002*

- 159 plastic microspheres injected into a pigs cerebral Circulation - 152 confirmed as solid (96%), the balance as uncertain solid …none as gaseous
- Right MCA microembolus in a carotid stenosis patient identified as solid
- (94%) of 52 emboli in 17 carotid stenosis patients classified as solid, balance as uncertain…none as gaseous

34

## Cerebral Arterial Gas Embolism

*…In Vivo Porcine Analysis*



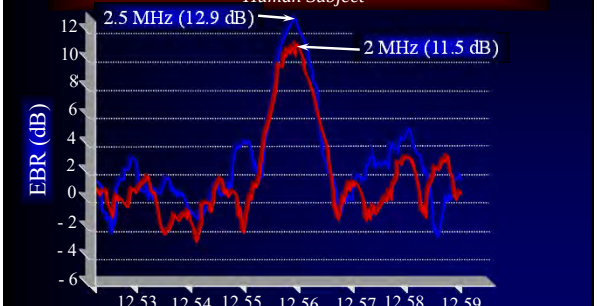

*Russell D Brucher R Stroke 2002: 33*

35

## Cerebral Arterial Gas Embolism

*…"Most microembolic events in carotid stenosis patients are solid"*

*Human Subject*




*Russell D Brucher R Stroke 2002: 33*

36

## Cerebral Arterial Gas Embolism

*…Incidence of decompression illness*

*US divers only, 1997*

- Divers Alert Network, 1999 Duke University Medical Center

| | |
|---|---|
| • Type I DCS | 222 |
| • Type II DCS | 598 |
| • CAGE | 68 |
| • No breakdown | 84 |
| Total | 972 |

37

## Cerebral Arterial Gas Embolism

*…Incidence during submarine escape training*

| | *# of Cases* | *CAGE* | *Deaths* |
|---|---|---|---|
| *RN* | *212,000* | *91* | *4* |
| *USN* | *250,000* | *44* | *8* |

*Presentation in 91 cases of CAGE*

| | |
|---|---|
| • Coma | 35% |
| • Stupor | 23% |
| • Focal or hemi paresis | 20% |
| • Somatic sensory changes | 12% |
| • Visual disturbances | 9% |
| • Collapse, without coma | 8% |

*- Ah-See AK, Proc. VI Int. Cong. HBO 1977*

38

## Cerebral Arterial Gas Embolism

*…Relapse In Decompression-Induced CAGE*

*While prompt recompression produces immediate relief in most cases, approximately 20% will later develop focal neurological deficits.*

*- Hallenbeck J, 1977*

*One third of those immediately recompressed relapsed within 20 minutes to several hours.*

*- Pearson RR, 1982*

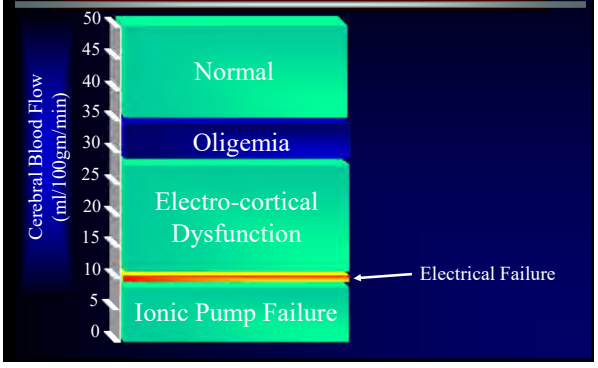
*In 89 cases recompressed with prompt clearing of deficits, 27 (30%) suffered a relapse, or new signs/symptoms during latter stages of treatment.*

*- Ah-See AK, 1977*

39

## Cerebral Arterial Gas Embolism

*…Neurological Response to Decreased Blood Flow*




40

## Cerebral Arterial Gas Embolism

*…Comparison Of Tables 6A & 6; USN experience*

Retrospective review of 2 yrs. prior to (6A) and 2 yrs. after (6) revision 3 of the USN Diving Manual.

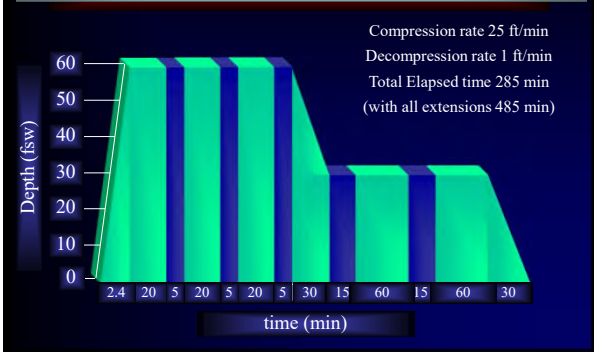
| Pre-Revision (30) | Post-Revision (13) |
|---|---|
| • 53% (16) treatment on TT 6A | • 100% treatment on TT 6 |
| • 75% complete relief within 30 minutes @ 6 ATA | • 54% complete relief during 1st $O_2$ cycle |
| • 88% complete relief prior to ascent to 1 ATA | • 85% complete relief prior to ascent to 1 ATA |
| • 10% (3) with treatment delay >1hr. | • 23% (3) with treatment delay >1hr. |
| • 10% recurrence | • 0% recurrence |

Howsare C, *et al*. UHM 24 (S147), 1997

41

## Cerebral Arterial Gas Embolism

*…Treatment: USN Table 6*




42

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies - Positioning*

*Modified Trendelenburg no longer recommended*

*-Dukta AJ, UHMS Workshop # 41, 1990*

- Considered likely to compound neurological pathology, by increasing venous return and decreasing cerebral perfusion
- Maintain patient in the supine, or coma, position
- Advise not to strain or valsalva maneuvers

43

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – Surface Oxygen*

*100% oxygen may relieve some symptoms and may reduce likelihood of others developing*

- *Corrects any hypoxemia*
- *Enhances inert gas elimination*
- *Reduces size of embolic gas*
- *Prophylaxes against DCS*
- *Treats established DCS*

44

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – Anti-platelet Drugs*

*There are more arguments against its use (aggravates inner ear or spinal cord hemorrhage; increases risk of dysbaric osteonecrosis)*

- Limited evidence that agents such as aspirin modify platelet action upon decompression
- *Aspirin "prophylaxis" in professional drivers!*

45

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – Fluid Resuscitation*

*Frequently indicated, particularly in acute setting*

*-Moon RE Sheffield PJ, Aviat. Space Environ. Med. 68, 1997*

- *Hemo-concentration*
- *Platelet and PMNL accumulation/clumping*
- *Endothelial injury*
- Glucose-free agents, unless hypoglycemia present

46

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – Lidocaine*

*"There is sufficient evidence to justify lidocaine in clinical settings where DCI is highly likely"*

*- Mitchell SJ, 2001*

- Neuroprotection thought to be afforded through several pathways:
  - *modulates leukocyte activity*
  - *anti-inflammatory properties*
  - *reduces cerebral metabolism*
  - *decelerates ischemic ion shifts*
  - *reduces intracranial pressure*

Mitchell SJ, *et al*. Ann. Thoracic Surg. 67, 1999 Francis J, SPUMS Journal; 32 (2), 2002

47

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – Steroids*

*Data supporting reduction of edema and modification of inflammatory responses comes from traumatic and vascular brain injuries, not DCI*

- Moon RE, SPUMS Journal, 2000

- Widespread acceptance in neuronal cases despite little convincing evidence

48

## Cerebral Arterial Gas Embolism

*…Adjunctive Therapies – NSAIDS*

*Data supporting reduction of edema and modification of inflammatory responses comes from traumatic and vascular brain injuries, not DCI*

- Moon RE, SPUMS Journal, 2000

Large *(180pts)* RCT found that Tenoxicam, 20mg daily x 7, significantly reduced number of tx's necessary; no difference in outcomes.

*- Bennett MH, et al. UHM ASM #29,2002*

49

## Cerebral Arterial Gas Embolism

*…The spontaneously "recovered" diver*

- Relapse is common, and unpredictable
- Suppression of evolution of concurrent DCS
- Antagonism of leukocyte-mediated I-R injury
- Protection/treatment of simultaneous embolism elsewhere
- Limiting/resolving cytotoxic and vasogenic edema
- Protection against cerebral infarcts

*- Clarke D, et al. Aviat. Space Environ Med; 73, 2002*

50

## Cerebral Arterial Gas Embolism

*…Delayed treatment*

*Excellent Clinical Outcome In Delayed Hyperbaric Treatment Of CAGE*

- 23 hours - *L. Lau, 1991*
- 24 hours - *J. Mader, 1979*
- 30 hours - *C. Armon, 1991*
- 42 hours - *E. Massey, 1990*
- 52 hours - *C.Wherrett, 2002*
- 60 hours - *H. Bitterman, 1993*

51

## Cerebral Arterial Gas Embolism

*…Cerebral Infarcts*

CT's of untreated cerebral arterial gas embolism have demonstrated areas of brain infarct, even in patients with apparent complete clinical recovery

Kearns PT, *West J. Med.*:140:615-617, 1984

Warren LP, *Am J Radiol.*;151:1003-1008, 1988

52

## Cerebral Arterial Gas Embolism

*…Treatment outcomes*

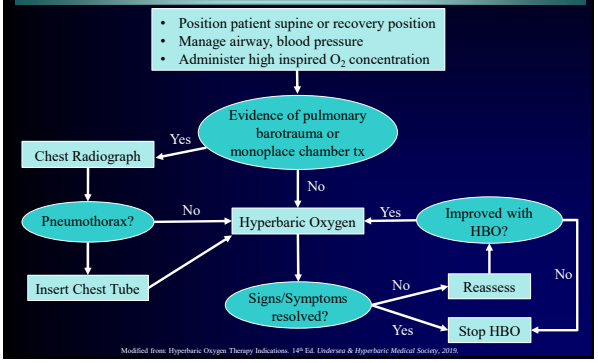
| *Outcome* | *HBO* | *NO HBO* |
|---|---|---|
| *Full Recovery* | *346 (84.24%)* | *74 (24.7%)* |
| *Residual* | *45 (10.9%)* | *63 (21.9%)* |
| *Death* | *20 (4.9%)* | *151 (52.4%)* |
| *Total* | *411 (100%)* | *288 (100%)* |

Dutka AJ, *UHMS Critical Review*, 1991

53

## Cerebral Arterial Gas Embolism

*…Treatment Flowchart*




54

## REFERENCES


- Ah-See AK: **Review of arterial air embolism in submarine escape.** Proceed. Sixth Int. Congress Hyperbaric Medicine. 1977; Aberdeen University Press 349-351.
- Armon C, et *al.*: **Hyperbaric treatment of cerebral air embolism sustained during an open-heart surgical procedure.** May Clinic Proceedings 1991;66:565-571
- Bedell EA, *et al.*: **Paradoxic air embolism during venous air embolism: transesophageal echo-cardiographic evidence of transpulmonary air passage.** Anesthesiology 1994;80(4):947-950
- Bennett MH, *et al*: **Adjunctive treatment of decompression illness with a non-steroidal anti-inflammatory drug (Tenoxicam) reduces compression requirement (Abstract).** Undersea Hyper Med 2002;29(2)S:29.
- Benton PJ, et *al.*: **Arterial gas embolism following a 1-meter ascent during helicopter escape training: a case report.** Aviation, Space and Environmental Medicine 1996;67(1):63-64
- Bitterman H, *et al*: **Delayed hyperbaric treatment of cerebral air embolism.** Israel Journal Medical Science 1993;29(1):22-26
- Butler BD, *et al*: **Effect of Excessive Oxygen Upon the Capability of the Lungs to Filter Gas Emboli.** Proceedings: 7th Symposium on Underwater Physiology 1981. Undersea & Hyperbaric Medical Society.
- Butler BD, *et al*: **Transpulmonary passage of venous air emboli.** J. Applied Physiology 1985;59(2):543-547.
- Clarke D, *et al*: **Pulmonary barotrauma-induced cerebral arterial gas embolism with spontaneous recovery: commentary on the rationale for therapeutic compression.** Aviat Space Environ Med 2002;73(2):139-146.
- Diegeler A, *et al*: **Neuromonitoring and neurocognitive outcome in off-pump versus conventional coronary bypass operation.** Ann Thorac Surg 2000;69:1162-1166.
- Divers Alert Network: **1999 Report on decompression illness and diving fatalities.** DAN Box 2823, Duke University Medical Center, Durham, North Carolina.
- Dutka AJ: **Air or gas embolism.** In Hyperbaric Oxygen Therapy: A Critial Review. Eds. EM Camporesi and AC Barker 1991:1-10.
- Dutka AJ: **Diving Accident Management Proceedings.** 41st UHMS Workshop 1990. Undersea and Hyperbaric Medical Society.
- Francis J: **A randomised prospective trial of lignocaine in the management of acute neurological decompression illness – an update.** SPUMS J 2002;32(2):97-105.
- Gorman DF, *et al*: **Cerebral Vasoreactivity and Arterial Gas Embolism.** UBR 1986;13(3):317-335.
- Gronert GA et al: **Paradoxical Air Embolism From a Patent Foramen Ovale.** Anesthesiology 1979;50:548-549.
- Hallenbeck JM, *et al*: **Impaired microvascular perfusion and secondary deterioration in dysbaric cerebral air embolism.** 13th Ums Workshop on Arterial Air Embolism;May 1977, Toronto, Canada
- Helps SC, *et al*: **Air Embolism of the Brain in Rabbits Pretreated With Mechlorethamine.** Stroke, 1991; 22:351-354.
- Helps SC, *et al*: **The effect of gas emboli on rabbit cerebral blood flow.** Stroke, 1990;21:(1):94-99.
- Hills BA: **Pulmonary Barotrauma: A Possible Role For Surfactant in Opposing the Entry of Air Into the Circulation.** SPUMS Journal 1993;23(2);59-64.
- Howsare C, *et al*: **Comparison of USNTT6 vs. TT6A for the treatment of AGE in the US Navy. A retroscpective study. (Abstract)** Undersea and Hyperbaric Medicine 1997; 24(Supplement):147
- Kearns PJ, *et al*: **Homonymous hemianopia due to cerebral air embolism from central venous catheters.** The Western Journal of Medicine 1984;140:615-617
- Lau K, *et al*: **Systemic air embolism: a complication of ventilator therapy in hyaline membrane disease.** Clinical Radiology 1991;43:16-18
- Leitch D, *et al*: **Cerebral arterial air embolism: 1. Is there benefit in beginning HBO treatment at 6 bar?** Undersea Biomed. Research 1984;11(3):221-235.
- Mader JT, *et al*: **Delayed hyperbaric treatment of cerebral air embolism.** Archives of Neurology 1979;36:504-505
- Mark DB, *et al*: **Protecting the brain in coronary artery bypass graft surgery (Editorial).** JAMA 2002;287(11):1448-1450.
- Masey EW, *et al*: **Hyperbaric Oxygen Therapy of Iatrogenic Air Embolism.** J. Hyperbaric Medicine 1990;5(1):15-21.
- Mitchell SJ: **Lidocaine in the treatment of decompression illness: a review of the literature.** Undersea Hyper Med 2001;28(3):165-174.

- Mitchell SJ, *et al*: **Cerebral protection by lidocaine during cardiac operations.** Ann Thorac Surg 1999;67:1117-1124.
- Moon RE: **Adjunctive therapy in decompression illness: Present and future.** SPUMS 2002;30(2):99-112.
- Moon RE, *et al*: **Guidelines for treatment of decompression illness.** Aviat., Space & Environ Med 1997;68(3):234-243.
- Moorthy SS, *et al*: **Patency of the Foramen Ovale in the Critically Ill Patient.** Anesthesiology 1974;41(4):405-407.
- Newman MF, *et al*: **Longitudinal assessment of neurocognitive function after coronary-artery bypass surgery.** New England J Med 2001;344:395-402.
- Oyama Y, *et al*: **Cardiopulmonary effects of intravenous gas embolism; with special reference to fate of intravascular gas bubbles.** Japanese Circ J 1971;35(12):1541-1549.
- Pearson RR, *et al*: **Delayed cerebral edema complicating cerebral arterial gas embolism: case histories.** Undersea Biomed Research 1982;9(4):283-296.
- Polak B, *et al*: **Traumatic air embolism in submarine escape training.** US Naval Medical Bulletin 1932;30:165-177
- Stoney WS, *et al*: **Air embolism and other accidents using pump oxygenators.** Annals Thoracic Surgery. 1980;29(4):336-340.
- Stonier JC: **A study in prechamber treatment of cerebral air embolism patients by a first provider at Santa Catalina island.** Undersea Biomedical Research 1985;12:ABST. 58
- Stygall J, *et al*: **Cerebral microembolism detected by transcranial doppler during cardiac procedures.** Stroke 2000;31:2508-2510.
- Thompson T, *et al*: **Paradoxical Embolism.** Quarterly Journal of Medicine,1930;23:135-152.
- Tovar EA, *et al.*: **Postoperative management of cerebral air embolism: gas physiology for surgeons.** Annals of Thoracic Surgery 1995;60:1138-1142
- **US Navy Diving Manual, 1999, Revision 4.** Published by Direction of Commander, Naval Sea Systems Command, Washington, DC 20362.
- Van Diik D, *et al*: **Cognitive outcome after off-pump and on-pump coronary artery bypass graft surgery.** JAMA 2002;287(11):1405-1412.
- Verstappen FTJ, *et al*: **Effects of Pulmonary Gas Embolism on Circulation and Respiration in the Dog.** European Journal of Physiology 1977;370:67-70.
- Warren LP, *et al*: **Neuroimaging of scuba diving injuries to the CNS.** AJR 1988;151:933-938:1003-1008
- Wherrett CG, *et al*: **Cerebral arterial gas embolism following diagnostic bronchoscopy: delayed treatment with hyperbaric oxygen.** Can J Anesth 2002;49(1):96-99.


Additional Reading


- Edmonds C, Lowry C, Pennefather J, Walker R: **Diving and Subaquatic Medicine, Fourth Edition**, 2002. Oxford University Press.
- Bove AA: **Diving Medicine, Third Edition**, 1997. W. B. Saunders Company.