HYPERBARIC OXYGEN THERAPY FOR MASSIVE ARTERIAL AIR EMBOLISM DURING CARDIAC OPERATIONS

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Background: **Massive arterial air embolism is a rare but devastating complication of cardiac operations. Several treatment modalities have been proposed, but hyperbaric oxygen is the specific therapy.** ***Methods:*** **The Israel Naval Medical Institute is the only referral hyperbaric center in this country for acute care patients. We reviewed our experience in the hyperbaric oxygen treatment of massive arterial air embolism during cardiac operations.** ***Results:*** **Seventeen patients were treated between 1985 and 1998. Eight patients (47.1%) experienced a complete neurologic recovery; 6 patients (35.3%) remained unconscious at discharge, and 3 patients (17.6%) died. Mean (± SD) delay from the end of the operation to hyperbaric therapy was 9.6 ± 7.4 hours (range, 1-20 hours). This delay was 4.0 ± 3.4 hours (1-12 hours) for patients who had a full neurologic recovery, 12.8 ± 7.1 hours (5-20 hours) for patients with severe neurologic disability, and 18.0 ± 2.0 hours (16-20 hours) for patients who died (1-way analysis of variance; *P* = .002). The source of variance among the groups mainly resulted from the short delay for patients who experienced complete recovery compared with the other 2 groups (Tukey test). All 5 patients who were treated within 3 hours from the operation and 50% (2 of 4 patients) of those patients treated 3 to 5 hours from operation experienced a full neurologic recovery. With a delay of 9 to 20 hours, only 1 of 8 patients had a full neurologic recovery. The association between outcome and treatment delay was found to be statistically significant (τ = 0.65 with exact 2-sided *P* value = .0007).** ***Conclusion:*** **Hyperbaric oxygen therapy should be administered as soon as possible after massive arterial air embolism during cardiac operations. (J Thorac Cardiovasc Surg 1999;117:818-21)**

Massive arterial air embolism during cardiac operations and cardiopulmonary bypass (CPB) is a rare event that is associated with high morbidity and mortality rates.[1] The presence of air bubbles in the cerebral arteries causes an abrupt decrease of blood flow in areas supplied by these vessels. The most common causes for massive arterial air embolism during cardiac operations are low oxygenator blood level, reversal of vent flow, and air from the cardiac chambers.[2] Several treatment modalities were suggested for massive arterial air embolism during CPB,[3,4] but hyperbaric oxygen (HBO) is the main therapy for massive arterial air embolism from any cause.[5] In this report, we review our experience with HBO therapy for massive arterial air embolism after cardiac operations.

Methods

The Israel Naval Medical Institute (INMI) is the only referral hyperbaric center in Israel for acute care patients. We reviewed the records of all the patients who were admitted for HBO therapy after sustaining massive arterial air embolism during cardiac operations between 1985 and 1998. Collected data included age, gender, year of operation, surgical procedure, delay from operation to HBO therapy, and neurologic status at discharge from the hospital. The diagnosis of systemic arterial air embolism during CPB was made by the surgical team. Immediate treatment strategies and the decision whether to consult the INMI was also made by the same team.

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Table I. *Demographic data, year of the operation, and surgical procedure*

Patient	*Age (y)*	*Gender*	*Year of operation*	*Surgical procedure*
1	73	M	1998	CABG
2	4	F	1990	Closure of ASD
3	62	F	1993	CABG
4	70	F	1991	AVR
5	2.5	M	1996	Repair of TOF
6	77	M	1996	CABG
7	65	M	1996	MVR
8	52	M	1992	CABG
9	75	M	1996	CABG
10	71	F	1994	AVR
11	4	F	1993	Repair of TOF
12	79	M	1997	CABG + AVR
13	53	M	1989	CABG
14	62	F	1985	CABG + CEA
15	57	M	1988	CABG + MVR
16	77	F	1993	CABG
17	55	M	1987	CABG

CABG, Coronary artery bypass grafting; *ASD*, atrial septal defect; *AVR*, aortic valve replacement; *TOF*, tetralogy of Fallot; *MVR*, mitral valve replacement; *CEA*, carotid endarterectomy.

Table II. *Delay from the end of the operation to the beginning of HBO therapy and neurologic outcome*

Patient	*Delay from operation to HBO (h)*	*Neurologic outcome*
1	1	Recovery
2	2	Recovery
3	2.5	Recovery
4	3	Recovery
5	3	Recovery
6	3.3	Recovery
7	5	Recovery
8	5	Disability
9	5	Disability
10	9.5	Disability
11	12	Recovery
12	16	Death
13	17	Disability
14	18	Death
15	20	Disability
16	20	Disability
17	20	Death

In all cases in which the INMI was consulted, we recommended an immediate transfer for HBO therapy, regardless of the time delay. Patients were transferred by an intensive care ground ambulance and were admitted at the surgical intensive cardiac care unit of the nearby hospital. They were transferred for HBO therapy as soon as possible thereafter. Monitoring during the HBO session included a 3-lead electrocardiogram, body temperature, pulse oximetry, end-tidal carbon dioxide, invasive blood pressure, and central venous or left atrial pressure. Arterial blood gas analysis was done at least once for every HBO session. Inotropic medications, vasodilators, crystalloids, colloids, red blood cells, and blood products were administered as needed. Neurologic status was evaluated by the patients' surgical service. A neurologist was consulted as needed. The end point was the neurologic status at discharge from the hospital.

Statistical analysis. Results are reported as mean ± SD. One-way analysis of variance and Tukey tests compared the mean differences in the time delay from the operation to HBO among the groups. The nonparametric correlation coefficient Kendall's tau (τ) with exact 2-sided P value was used to examine the association between outcome and treatment delay (STATISTICA for Windows, Release 4.3 B; StatSoft, Inc, Tulsa, Okla).

Results

Seventeen patient records were available for review. Patients were transferred from 5 cardiac surgical centers. Age, gender, year of operation, and the surgical procedure are listed in Table I. Fourteen patients (82%) were adults with ischemic and/or valvular heart disease, and 3 patients (18%) were children with congenital heart disease. All patients were neurologically intact before the operation. Neurologic status before HBO treatment could not be assessed because of the effect of anesthetics, sedatives, opioids, and, in some cases, muscle relaxants. Mean age was 55 ± 26 years (range, 2.5-79 years). All patients underwent a cardiac operation with CPB. In all cases, systemic arterial air embolism was either suspected or clearly diagnosed while the CPB circuit was running. Immediate management included stopping pump flow, head-down position, evacuation of air, hypothermia, high pump flow after resumption of circulation, and, in few cases, glucocorticoid administration. Retrograde perfusion was not performed. In several occasions, the surgical team elected not to consult the INMI immediately but to treat the patient in the intensive care unit first. The delay from the end of the operation to the beginning of HBO therapy was 9.6 ± 7.4 hours (range, 1-20 hours; Table II). All patients were intubated and mechanically ventilated on arrival to the hyperbaric center. Sixteen patients (94.1%) were treated according to the US Navy Table 6A.[6] One patient (5.9%) received hyperbaric therapy at 2.8 atmospheric absolute for 90 minutes. Three patients received additional hyperbaric sessions. Eight patients (47.1%) had a complete neurologic recovery; 6 patients (35.3%) remained unconscious at discharge, and 3 patients (17.6%) died during the same hospitalization; 1 of the deaths

occurred while the patient was being treated in the hyperbaric chamber. The delay from the operation to HBO was 4.0 ± 3.4 hours (range, 1-12 hours) for patients who had a full neurologic recovery, 12.8 ± 7.1 hours (range, 5-20 hours) for patients with severe neurologic disability, and 18.0 ± 2.0 hours (range, 16-20 hours) for patients who died (1-way analysis of variance; $P = .002$). The source of variance among the groups mainly resulted from the shorter delay for patients who experienced complete recovery compared with the other 2 groups (Tukey test). All 5 patients who were treated within 3 hours from the operation and 50% (2 of 4) of those patients who were treated 3 to 5 hours from the operation had a full neurologic recovery. With a delay of 9 to 20 hours, only 1 of 8 patients had a full neurologic recovery. The association between outcome and treatment delay was found to be statistically significant ($\tau = 0.65$, with exact 2-sided $P = .0007$).

Discussion

Systemic arterial air embolism is a rare but devastating complication of cardiac operation with CPB. Air bubbles obstructing the cerebral arteries can cause severe neurologic disability and death.[2] There is no unanimous approach for the best medical management of the patient who experiences a sudden onset of systemic arterial air embolism during CPB. Although many management options have been suggested in the literature,[7,8] HBO remains the main treatment for air embolism from any cause.[5,9] Air bubbles in the systemic circulation cause an immediate mechanical obstruction to blood flow, followed by a local inflammatory response, which may aggravate the damage.[10] Although micro air embolism during CPB is common, macroembolism is rare and largely underdiagnosed, undertreated, and underreported.[3] The incidence is estimated to be 0.1%[1] but may have been decreased since that report, because of improved surgical and pump techniques. The favorable effects of HBO in the treatment of systemic air embolism were reported in detail.[9] In brief, according to Boyle's law, a 6-fold increase in the atmospheric pressure will decrease the gas-bubble volume and diameter to 16.6% and 55% of its original size, respectively. Mechanical ventilation (inspired oxygen fraction = 1.0) minimizes the partial pressure of nitrogen and provides a large pressure gradient for N_2 absorption from the bubble. Decreased PaN_2 has been shown to accelerate bubble absorption.[11] When oxygen is administered at a partial pressure of 3 atmospheres absolute, 6 mL of oxygen is dissolved in 100 mL of blood, an amount that is enough for the tissue metabolism at rest, without oxygen carried by hemoglobin. Oxygen diffusion distance and tissue oxygen tension are also increased.[12] HBO induces cerebral vasoconstriction and decreases intracranial pressure.[13] It may also inhibit the persistent adherence of leukocytes to cerebral endothelium.[14] In this report, we found that a shorter delay from the operation to HBO therapy, in patients with massive arterial air embolism, was associated with a better neurologic outcome. Similar results were reported by Murphy and colleagues,[15] but their study lacks statistical analysis. It must be stressed, however, that our retrospective study does not provide enough data to support any specific time frame for HBO therapy in these patients. "The sooner the better" seems to be the rational approach. All patients were treated before any neurologic assessment was possible, so evaluation of improvement could not be performed. Inspection is not recommended if the patient spontaneously regains consciousness when massive arterial air embolism is suspected or clearly diagnosed during the operation. The approach may cause unnecessary delay and decrease the likelihood of neurologic recovery. We believe that a patient experiencing intraoperative air embolism should be treated by HBO as soon as possible. The nearby hyperbaric facility, adequately staffed and equipped for the care of critically ill patients, should be consulted as soon as the diagnosis is established, and transport arrangements should be made during the last part of the surgical procedure. When massive arterial air embolism is diagnosed during the operation, radiologic studies of the brain provide very little information and may cause an unnecessary delay of treatment.[16] In the different situation, at which a neurologic deficit is diagnosed the first time in the intensive care unit, but the cause is uncertain, radiologic study will probably be the next step. Macroemboli were found in the brain several hours[17] and even days after an embolic event.[18] Delayed treatment with HBO for systemic air embolism was reported,[19] including cases of cardiac operations,[20,21] and recovery might be achieved. Therefore HBO therapy should be given even after a long delay. The exact limit of this delay is unknown.

In summary, HBO is the specific treatment for massive arterial air embolism during cardiac operations. It should be administered as soon as possible after the end of the operation.

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