Massive air embolism from continuous venovenous haemofiltration causing electromechanical dissociation in a cardiac surgical patient

Lisa Ku, Laurence Weinberg, Siven Seevanayagam, Ian Baldwin, Helen Opdam and Laurie Doolan

ABSTRACT

Venous air embolism is a rare but life-threatening complication of continuous venovenous haemofiltration. We report a case of massive venous air embolism associated with haemofiltration in a 75-year-old man after complicated cardiac surgery. Haemofiltration circuitry and air detector alarms are not infallible and air embolism should be considered in patients receiving such therapy who develop cardiopulmonary instability. We discuss our early intervention, which focused on restoration of the circulation, prevention of further air entry, retrieval of air and supportive care. The use of transoesophageal echocardiography for diagnosis of air embolism and to aid the insertion of a pulmonary artery catheter for air aspiration was essential for management.

Crit Care Resusc 2012; 14: 154–158

Clinical record

A 75-year-old, 54-kg man with a history of hypertension, type 2 diabetes mellitus, hypercholesterolaemia and normal preoperative renal function (serum creatinine level, 87 μmol/L [reference interval, 30–110 μmol/L]) developed acute renal failure after coronary artery bypass graft surgery. At the start of surgery, transoesophageal echocardiography (TOE) revealed anterior hypokinesis and inferior dyskinesis, an ejection fraction of 28% and extensive thoracic aortic atheroma. Ventricular fibrillation developed during conduit harvest, necessitating urgent institution of cardiopulmonary bypass. At completion of surgery, results of TOE were unchanged and bypass was weaned with milrinone (loading dose, 25 μg/kg, followed by an infusion, 0.5 μg/kg/min), noradrenaline (5 μg/min) and insertion of an intra-aortic balloon pump via the left femoral artery. The patient returned to the intensive care unit on milrinone (0.5 μg/kg/min) and noradrenaline (1 μg/min).

The next day (postoperative day 1), the patient was extubated. On postoperative day 2, continuous venovenous haemofiltration (CVVH) was commenced for anuric acute renal failure. Access was provided by a Niagara 24 cm 13.5 Fr dual-lumen venous catheter (Bard Access Systems, Salt Lake City, Utah, USA) inserted into the right femoral vein. An HF440 dialysis machine (Infomed, Geneva, Switzerland) was prepared in pure convective clearance mode using 50% predilution. A 20 mmol bicarbonate-based solution (Accusol, Baxter, Sydney, NSW, Australia) was used to correct metabolic acidosis. Two-litre-per-hour volume exchanges were performed using no anticoagulation and a blood flow rate of 200 mL/min with the setting of a 50–100 mL/h fluid loss, with the aim of achieving a neutral patient fluid balance.

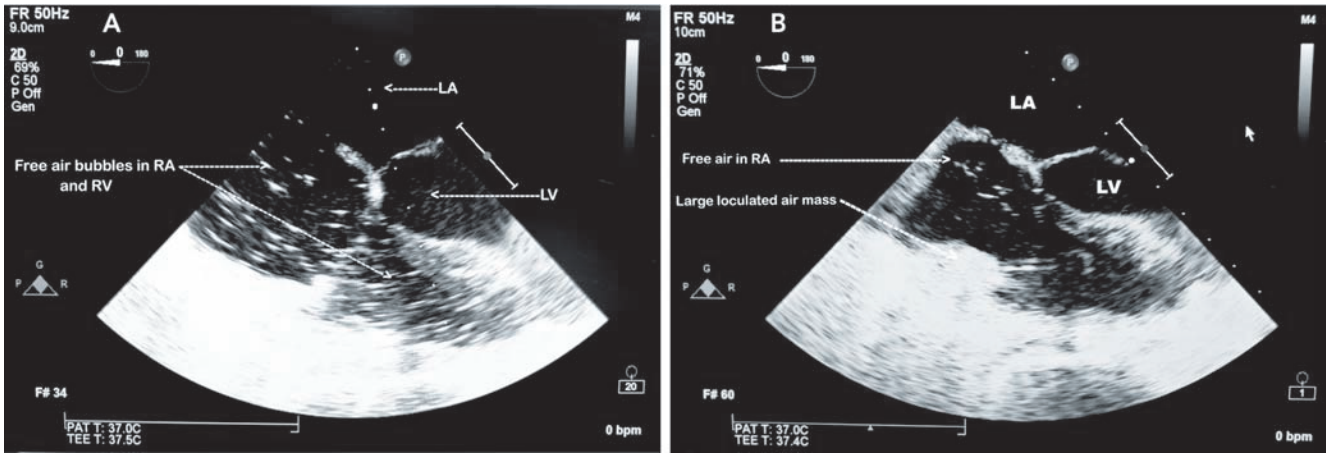
The intra-aortic balloon pump was removed on postoperative day 3, and milrinone and noradrenaline were ceased on postoperative day 4. Progressive thrombocytopenia with haemolysis developed on postoperative day 2, and required platelet and clotting factor support under haematologist guidance. On postoperative days 5 and 6, the patient became increasingly confused. Brain computed tomography (CT) was performed, but revealed no infarct or haemorrhage.

In the evening of postoperative day 6, the patient was noted to have bilateral lower limb ischaemia, left worse than right. In the early hours of postoperative day 7, he underwent a lower-limb contrast CT angiogram. After return to ICU and about 30 minutes after restarting CVVH, he became agitated, tachypnoeic and dyspnoeic. The inspired oxygen was increased to 15 L/min and an arterial blood gas revealed hypoxia (PO_2, 47 mmHg; PCO_2, 46 mmHg).

It was then observed that a large amount of air was present in the CVVH venous air trap chamber forming bubbles in the venous return line of the circuit. The likely diagnosis of air embolism became apparent. Haemofiltration was immediately stopped and the venous limb of the CVVH circuit clamped with the aim of preventing further entrainment of air. The patient became rapidly and progressively hypotensive, and developed electromechanical dissociation cardiac arrest.

Cardiopulmonary resuscitation was commenced, the patient was intubated, and positive-pressure ventilation was initiated with 100% inspired oxygen. Adrenaline was administered intravenously (total dose, 2 mg), with restoration of adequate circulation occurring 7 minutes after the onset of the arrest. After the cardiac arrest, the haemodynamic state stabilised, with reducing doses of adrenaline (5 μg/min) and noradrenaline (1 μg/min)

Figure 1. Four-chamber transoesophageal echocardiography



A. *Free air (echo-opaque) in the right atrium (RA) and right ventricle (RV). No air was visualised in the left atrium (LA) or left ventricle (LV).*
B. *A large loculated echo-opaque air mass attached to the lateral wall of the RA. Free air is visualised in the RA.*

required. Transthoracic echocardiography did not reveal any intracardiac air or pericardial collection.

About 4 hours after the event, the patient's blood pressure fell, and escalating doses of adrenaline (40 μg/min) and noradrenaline (40 μg/min) were required. Consideration was given to proceeding to the operating theatre for resternotomy and exploratory cardiac surgery. Before proceeding, TOE was performed, which revealed right-sided intracardiac air. A mid-oesophageal four-chamber echocardiograph demonstrated free bubbles of air in the right atrium and right ventricle (Figure 1A). A large loculated mass of free air was also found attached to the lateral wall of the right atrium (Figure 1B). The TOE also revealed right ventricular hypokinesis, left ventricular hypovolaemia and inferoseptal hypokinesis. The patient did not have a patent foramen ovale, and no free air was visualised in the left atrium or left ventricle.

Under TOE guidance, a VIP+ Swan–Ganz pulmonary artery catheter (Edwards Lifesciences, Irvine, Calif, USA) was floated through a 9 Fr sheath to 44 cm depth to aid the aspiration of about 20 mL of air. Aggressive fluid resuscitation was provided. Stabilisation of haemodynamics was achieved, and inotropic support subsequently decreased to 18 μg/min of noradrenaline. Initial cardiac index was 2.2 L/min/m^2, and milrinone 0.25 μg/kg/min was added. The large column of air bubbles noted in the haemofiltration circuit suggested that air had been entrained through a loose connection. Extensive technical testing of the haemofiltration system circuit and HF440 machine air detector did not reveal any faults. Subsequent examination of the 24 cm vascular access catheter did not reveal any fracture lines or other faults.

Over the next 10 days, although there was haemodynamic stabilisation, severe thrombocytopenia persisted. It was treated as possible heparin-induced thrombosis and thrombocytopenia (with non-heparin anticoagulant danaparoid), then possible thrombotic thrombocytopenic purpura (with plasma exchange). The patient underwent a left popliteal embolectomy; however, both feet remained ischaemic and appeared non-viable. There was persisting anuric renal failure requiring CVVH and an infarcted left kidney on CT angiogram, which was undertaken to diagnose a large retroperitoneal haemorrhage that was not amenable to treatment with embolisation.

The patient never regained consciousness and at best withdrew limbs and grimaced to painful stimuli, with a repeat brain CT on postoperative day 13 unchanged from the previous scan. On postoperative day 17, a worsening shocked state developed associated with ischaemic hepatitis and after medical consensus that death was inevitable, treatment was withdrawn with family agreement.

Discussion

We describe an unexpected case of massive air embolism in a cardiac surgery patient associated with continuous renal replacement therapy. We think the use of TOE was useful to confirm and guide subsequent management. Massive air embolism is a known rare but life-threatening event associated with many clinical settings.[1-4] Development of air embolism requires a direct communication of air with the vasculature and a pressure gradient favouring the passage of air into the circulation. Richardson and colleagues suggested the volume of air required to cause a clinically

Table 1. Methods to prevent air entrainment during continuous venovenous haemofiltration (CVVH)

Source of air/gas bubbles	Suggested prevention method
Priming the circuit	Use crystalloid solutions at room temperature. Use additional solution to prime the circuit at the end of the machine sequence to remove any residual air (a total of 2 L is usual). Use a slow blood pump speed during priming to prevent "champagne" effect — large bubbles breaking into many small bubbles with pressure and resistance. Perform gentle tapping of the CVVH membrane while held in the vertical position at the last stages of priming to allow air to rise to the top. This air should then be released.
Venous bubble trap chamber	Ensure this is fitted to the machine correctly and the air sensor tubing interface is correct. The air sensor test is a component of the machine set-up and self-test — observe this being done. Keep this chamber level high — near full during clinical use to allow for larger volumes of air/gas to be trapped before empty state occurs. Check — look at this chamber frequently during use as clot formation inside the chamber, around the outer walls, can mask the true blood level within.
Circuit tubing	Do not connect any additional lines or taps to the circuit after the air detector (ie, on the venous return blood line) at the vascular access catheter connection. Check — tighten all connections throughout the circuit, particularly those in the outflow ("arterial") pathway before the blood pump as this is a negative pressure zone and entrainment is likely with loose connection.
Fluids — substitution fluids	Do not use glass or rigid bottles requiring a needle airway that fills with air as they empty. Use collapsible plastic bags that do not require an airway to reduce the likelihood of the machine drawing in air/gas from the bags when empty. Set the alarms (scales alarms) above the true empty level; a small residual volume should always remain to prevent any air entry from the bags at empty.
Nurse — operator training	Provide ongoing and regular training and reviews for the use of CVVH (eg, "quality checks during CVVH"), in particular the use of the air detect alarm. Make a simple one-page checklist for shift change and nursing checks to include above checks.

significant air embolus in dogs is about 1 mL/kg/min;[5] however, as little as 0.67 mL/kg/min was shown to be fatal when this experiment was repeated by Wycoff and Cann.[6] It is clear that the speed and site of introduction of air into the circulation, and the quantity of air are important factors in determining the systemic effects of the embolus.

Air embolism has been described with central venous access catheters, including those used for renal replacement therapy.[7] Most (60%–90%) venous-catheter-related air embolisms appear to be associated with fracture of the catheter or detachment of catheter connections. Other risk factors include events surrounding insertion or removal when the open needle hub or catheter entrains air, especially with insertion in spontaneously breathing patients during deep inspiration, faults in self-sealing valves in introducer sheaths, a persistent catheter tract in the patient, hypovolaemia, and upright positioning of the patient.[2,4,8,9]

The morbidity and mortality associated with air embolism is difficult to quantify, and there may be subclinical events that are never reported. Based on their recent case series, Bessereau and colleagues reported a prevalence of iatrogenic air embolism of 2.65 cases per 100 000, with a crude mortality rate of 21% at 1 year.[10]

Although it is a known complication of renal replacement therapy, minimal reference is made to this cause of air embolism in the literature. In 1971, Ward and colleagues reported seven cases of air embolism associated with haemodialysis (1 : 2000 haemodialysis treatments).[11] Since that time, there have been improvements in renal replacement therapy circuitry and incorporation of sensitive air detectors. Air may still enter into the circuit through the arterial needle (during dialysis via a fistula), pre-pump arterial tubing segment, open venous catheter, empty fluids bags and infusion sets.[12] A less obvious but insidious problem is that of dissolved gas in water. If heated, this comes out of solution to form small bubbles that can be entrained into the dialyser.[13] We noted the absence of activation of the air detector alarm in our case, despite the presence of air in the venous return limb. Using in-vitro testing with an ultrasound monitor, Stegmayr and colleagues and Jonsson and colleagues showed that it is possible for air or gas bubbles to pass the safety sensor associated with the air trap without triggering the alarm.[14,15] This highlights the requirement for clinicians to maintain vigilance and suspicion of massive air embolism in acutely decompensated patients receiving renal replacement therapy.

Air embolism is considered a diagnosis of exclusion in an appropriate clinical setting. Its diagnosis is difficult, as air may reabsorb into the circulation before a diagnostic test can be

performed. Of interest in our case, substantial air persisted in the right side of the heart some 4 to 5 hours after the initial event. TOE remains the most sensitive and specific monitor for air embolism and can detect as little as 0.02 mL/kg.[16] It has the added ability to detect the presence of paradoxical air emboli with intracardiac shunts and direct placement of central venous catheters for air aspiration. Other monitors used to guide diagnosis include precordial Doppler, end-tidal nitrogen, end-tidal carbon dioxide, transcranial Doppler, pulmonary artery catheter and precordial stethoscope. Clinical signs are late and often indicate a massive air embolus. Of note in our case, transthoracic echocardiography performed before the TOE failed to identify any air in the right heart, although at the time of the study it was noted that the windows and views were suboptimal.

Massive air embolism is an emergency situation that requires a specific management strategy focused on prevention of further air entrainment, cardiopulmonary support, and reduction of the mechanical obstruction. Several methods have been used to reduce further air entry into the circulation. Identification of the source is paramount, and methods used must be tailored to the given clinical situation. Flooding the operative site with saline or soaked dressings is useful in the surgical setting. Increased distal venous pressure by jugular venous compression has been shown to be a useful manoeuvre to decrease air entry originating from the face and head.[17-19]

The operating table may be tilted to lower the entry source to remove the negative air pressure gradient. The Durant manoeuvre (left lateral decubitus position) and the Trendelenburg position are purported to relieve air lock in the right heart and thus improve haemodynamics.[20] Both these strategies have come under recent scrutiny in the literature. Data in canine studies show that repositioning provides no improvement to haemodynamics, despite demonstrating transfer of air into less dependent areas of the heart.[21] Cardiopulmonary bypass has also been described as a method of overcoming air lock and may be life saving.[22]

Chest compressions should be commenced immediately as part of cardiopulmonary resuscitation for compromised patients. It also has the added benefit of aiding forward blood flow by relocating the air embolus from the pulmonary outflow tract to the smaller vasculature and has been shown to be clinically effective.[23] Right ventricular failure may ensue, as clinical air embolus will increase right ventricular afterload, which will also impact on left ventricular outflow. Physiological aims include providing right ventricular support and improving myocardial perfusion. We chose milrinone for inotropic support to increase the cardiac index and stroke volume and decrease pulmonary vascular resistance. Dobutamine and ephedrine have also been described as management options.[24,25]

High fraction of inspired oxygen aids the resorption of air bubbles by creating a positive-pressure gradient for the diffusion of nitrogen from the embolus into the blood.[26] Hyperbaric oxygen expedites this process further, and a case report by Trytko and colleagues detail its use in arterial cerebral air emboli.[27] There is sparse literature to support its use in venous air embolism, and although it appears intuitive that it could benefit patients with severe cardiopulmonary or neurological decompensation, the logistic impediments are substantial and it may not be a realistic option in most cases.[28,29]

Reduction of the size of the embolus may be achieved by aspirating air from the right atrium with a central venous catheter. We used a VIP+ Swan–Ganz pulmonary artery catheter under TOE guidance to allow targeted aspiration of air emboli along the right heart chambers, a method that has been depicted in a case by Sink and colleagues.[30] The Bunegin–Albin multiorifice air aspiration set (Cook Medical, Bloomington, Ind, USA) is reported to be the most effective at air embolus retrieval in the sitting position.[31-33] Bunegin and colleagues describe ideal catheter placement in the right atrium 2 cm below the superior vena caval junction with the right atrium at an 80-degree incline to maximise air aspiration.[34] In contrast, some clinicians view this procedure to be of minimal benefit, as an air pocket is required for meaningful retrieval with only small volumes of air (< 20 mL) usually recovered.[35,36]

Experimental animal studies of perfluorocarbon emulsions show promise for its use in the management of venous air embolism and its complications. Nitrogen has a higher solubility (10–50 times) in perfluorocarbon emulsions than in blood plasma, which aids in the resorption of air emboli. Spiess and colleagues showed enhanced survivability in animals with venous air embolism resuscitated with perfluorocarbon emulsions and demonstrated a protective effect from cerebral air emboli with enhanced recovery from transient neurological deficits.[37] Contemporary research is now taking advantage of these physiological discoveries and applying perfluorocarbons as "oxygen therapeutics", in the treatment of arterial and venous embolism.[38]

In summary, air embolus is not commonly reported in the CVVH literature. We report a case of massive venous air embolism associated with venovenous haemofiltration in a post-operative cardiac surgical patient. Although machine air detectors appear to be highly sensitive and function well in vitro and in clinical use, haemofiltration circuitry and air detector alarms are not infallible, and air embolism should be considered in any patient receiving renal replacement therapy with sudden cardiopulmonary instability. In this case, despite extensive investigation of the equipment after the event, we remain unsure of how such a large volume of air entered the heart, but postulate that the CVVH circuit was the source.

However, it is important to highlight the usual and routine methods used to prevent air entrainment during CVVH and the possibility that bubbles may pass a sensor undetected. These are indicated in Table 1. Early intervention should be focused on prevention of further air entry, restoration of the circulation, retrieval of air if possible and supportive treatment. We believe that TOE was useful in the diagnosis and treatment of air embolism in this case, including in facilitating TOE-guided pulmonary catheter air aspiration.

Competing interests

None declared.

Author details

Lisa Ku, Fellow, Department of Anaesthesia[1]
Laurence Weinberg, Anaesthetist,[1] and Senior Fellow[2]
Siven Seevanayagam, Cardiac Surgeon[1]
Ian Baldwin, Professor of Intensive Care[1,2,3]
Helen Opdam, Intensivist[1]
Laurie Doolan, Anaesthetist and Intensivist[1]
1 Austin Hospital, Melbourne, VIC, Australia.
2 Department of Surgery, University of Melbourne, Melbourne, VIC, Australia.
3 RMIT University, Melbourne, VIC, Australia.
Correspondence: LaurenceWeinberg@austin.org.au

References

1 Dudney TM, Elliott CG. Pulmonary embolism from amniotic fluid, fat, and air. *Prog Cardiovasc Dis* 1994; 36: 447-74.
2 King MB, Harmon KR. Unusual forms of pulmonary embolism. *Clin Chest Med* 1994; 15: 561-80.
3 Schmitt HJ, Hemmerling TM. Venous air emboli occur during release of positive end-expiratory pressure and repositioning after sitting position surgery. *Anesth Analg* 2002; 94: 400-3.
4 Heckmann JG, Lang CJ, Kindler K, et al. Neurologic manifestations of cerebral air embolism as a complication of central venous catheterization. *Crit Care Med* 2000; 28: 1621-5.
5 Richardson HF, Coles BC, Hall GE. Experimental gas embolism: I. Intravenous air embolism. *Can Med Assoc J* 1937; 36: 584-8.
6 Wycoff CC, Cann JE. Experimental pulmonary air embolism in dogs. *Calif Med* 1966; 105: 361-7.
7 Yu AS, Levy E. Paradoxical cerebral air embolism from a hemodialysis catheter. *Am J Kidney Dis* 1997; 29: 453-5.
8 Orebaugh SL. Venous air embolism: clinical and experimental considerations. *Crit Care Med* 1992; 20: 1169-77.
9 Kashuk JL, Penn I. Air embolism after central venous catheterization. *Surg Gynecol Obstet* 1984; 159: 249-52.
10 Bessereau J, Genotelle N, Chabbaut C, et al. Long-term outcome of iatrogenic gas embolism. *Intensive Care Med* 2010; 36: 1180-7.
11 Ward MK, Shadforth M, Hill AV, Kerr DN. Air embolism during haemodialysis. *Br Med J* 1971; 3: 74-8.
12 Misra M. The basics of hemodialysis equipment. *Hemodial Int* 2005; 9: 30-6.
13 Sutherland AC. The engineering design of haemodialysis equipment. *Ann R Coll Surg Engl* 1970; 46: 350-6.
14 Stegmayr CJ, Jonsson P, Forsberg U, Stegmayr BG. Development of air micro bubbles in the venous outlet line: an in vitro analysis of various air traps used for hemodialysis. *Artif Organs* 2007; 31: 483-8.
15 Jonsson P, Karlsson L, Forsberg U, et al. Air bubbles pass the security system of the dialysis device without alarming. *Artif Organs* 2007; 31: 132-9.
16 Furuya H, Suzuki T, Okumura F, et al. Detection of air embolism by transesophageal echocardiography. *Anesthesiology* 1983; 58: 124-9.
17 Grady MS, Bedford RF, Park TS. Changes in superior sagittal sinus pressure in children with head elevation, jugular venous compression, and PEEP. *J Neurosurg* 1986; 65: 199-202.
18 Losasso TJ, Muzzi DA, Cucchiara RF. Jugular venous compression helps to identify the source of venous air embolism during craniectomy in patients in the sitting position. *Anesthesiology* 1992; 76: 156-7.
19 Takahashi T, Yano K, Kimura T, et al. Prevention of venous air embolism by jugular venous compression under superior sagittal sinus pressure monitoring in a brachycephalic patient during craniofacial reconstruction. *Paediatr Anaesth* 1997; 7: 259-60.
20 Durant TM, Long J, Oppenheimer MJ. Pulmonary (venous) air embolism. *Am Heart J* 1947; 33: 269-81.
21 Geissler HJ, Allen SJ, Mehlhorn U, et al. Effect of body repositioning after venous air embolism. An echocardiographic study. *Anesthesiology* 1997; 86: 710-7.
22 Rawlins R, Momin A, Platts D, El-Gamel A. Traumatic cardiogenic shock due to massive air embolism. A possible role for cardiopulmonary bypass. *Eur J Cardiothorac Surg* 2002; 22: 845-6.
23 Yeh PA, Chen HP, Tsai YC, et al. Successful management of air embolism-induced ventricular fibrillation in orthotopic liver transplantation. *Acta Anaesthesiol Taiwan* 2005; 43: 243-6.
24 Jardin F, Genevray B, Brun-Ney D, Margairaz A. Dobutamine: a hemodynamic evaluation in pulmonary embolism shock. *Crit Care Med* 1985; 13: 1009-12.
25 Archer DP, Pash MP, MacRae ME. Successful management of venous air embolism with inotropic support. *Can J Anaesth* 2001; 48: 204-8.
26 Dexter F, Hindman BJ. Computer simulation of microscopic cerebral air emboli absorption during cardiac surgery. *Undersea Hyperb Med* 1998; 25: 43-50.
27 Trytko BE, Bennett MH. Arterial gas embolism: a review of cases at Prince of Wales Hospital, Sydney, 1996 to 2006. *Anaesth Intensive Care* 2008; 36: 60-4.
28 Blanc P, Boussuges A, Henriette K, et al. Iatrogenic cerebral air embolism: importance of an early hyperbaric oxygenation. *Intensive Care Med* 2002; 28: 559-63.
29 Mader JT, Hulet WH. Delayed hyperbaric treatment of cerebral air embolism: report of a case. *Arch Neurol* 1979; 36: 504-5.
30 Sink JD, Comer PB, James PM, Loveland SR. Evaluation of catheter placement in the treatment of venous air embolism. *Ann Surg* 1976; 183: 58-61.
31 Albin MS, Carroll RG, Maroon JC. Clinical considerations concerning detection of venous air embolism. *Neurosurgery* 1978; 3: 380-4.
32 Bowdle TA, Artru AA. Treatment of air embolism with a special pulmonary artery catheter introducer sheath in sitting dogs. *Anesthesiology* 1988; 68: 107-10.
33 Colley PS, Artru AA. Bunegin–Albin catheter improves air retrieval and resuscitation from lethal venous air embolism in upright dogs. *Anesth Analg* 1989; 68: 298-301.
34 Bunegin L, Albin MS, Helsel PE, et al. Positioning the right atrial catheter: a model for reappraisal. *Anesthesiology* 1981; 55: 343-8.
35 Gould DS, Gould DB. Venous air embolism retrieval catheters cannot capture bubbles; an air lock is required. *Acta Anaesthesiol Scand* 1996; 40: 272-4.
36 Bedford RF, Marshall WK, Butler A, Welsh JE. Cardiac catheters for diagnosis and treatment of venous air embolism: a prospective study in man. *J Neurosurg* 1981; 55: 610-4.
37 Spiess BD, McCarthy R, Piotrowski D, Ivankovich AD. Protection from venous air embolism with fluorocarbon emulsion FC-43. *J Surg Res* 1986; 41: 439-44.
38 Spiess BD. Perfluorocarbon emulsions as a promising technology: a review of tissue and vascular gas dynamics. *J Appl Physiol* 2009; 106: 1444-52. ❑