Detection of Air Embolism by Transesophageal Echocardiography

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In this study transesophageal echocardiography was utilized for detecting air embolism in dogs in the supine position and in patients undergoing neurosurgery in the sitting position. In dogs, the threshold dose of venous air for detection was determined using either a bolus injection or continuous infusion of air via the jugular vein for up to three minutes. The ability to detect air in the aorta also was determined by a bolus injection into the left ventricle via an arterial catheter. For venous injection of air, the threshold dose by bolus was 0.02 ml/kg. When given by infusion, air could be detected in all cases by both contrast echocardiogram and Doppler sound changes at the rate of $0.05 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. When air was injected into the left ventricle, the threshold dose was 0.001 ml/kg using contrast echocardiogram. In the clinical evaluation, air was clearly demonstrated in five of six patients by transesophageal echocardiogram along with appropriate changes in Doppler sounds, pulmonary artery pressure, and end-tidal carbon dioxide concentration. Our results suggest that transesophageal echocardiography may be a more sensitive and accurate method for detecting venous air embolism than other commonly used monitors for patients undergoing neurosurgical procedures in the sitting position. This device may also be able to detect air in the aorta in patients experiencing paradoxical air embolism during surgery due to intracardiac or pulmonary shunts. (Key words: Anesthesia: neurosurgical. Complications: embolism, air. Embolism: air. Equipment: echocardiography.)

VENOUS AIR EMBOLISM is a potentially serious complication that most commonly occurs during neurosurgical procedures done with the patient in a sitting position. A variety of methods are available for detecting air embolism; these include changes in Doppler sounds, decrease in end-tidal carbon dioxide concentration, increase in pulmonary artery pressure, aspiration of air from a central venous catheter, and changes in esophageal heart sounds.[1-4]

Recently, transesophageal echocardiography has been introduced for continuous monitoring of cardiac function in patients undergoing cardiac surgery.[5,6] Air in the heart can also be readily detected by contrast echocardiography.[7] In this study, we evaluated the sensitivity and usefulness of esophageal echocardiography for the detection of air in both the right ventricular outflow tract and the aorta, using dogs maintained in the supine position.

Also, clinical application of this method was evaluated during neurosurgical procedures in patients undergoing surgery while in the sitting position.

Materials and Methods

Eight mongrel dogs weighing 9–16 kg were anesthetized with pentobarbital (5 mg/kg) intravenously, and anesthesia was maintained with 1 mg/kg of pentobarbital given intermittently. Five dogs were used for studies to detect air in the right ventricular outflow tract and three dogs were used for studies to detect air in the aorta. The trachea was intubated and the lungs were ventilated with oxygen by a pressure-limited ventilator to maintain Pa_{CO_2} at 30–40 mmHg. A 5-F triple-lumen Swan-Ganz® catheter was inserted through the right external jugular vein, and the catheter tip was positioned in the pulmonary artery. The femoral artery was cannulated with a 20-gauge Teflon® catheter. Systemic arterial pressure, right atrial pressure, and pulmonary artery pressure were measured and recorded continuously. End-tidal carbon dioxide concentration was measured (Cavitron Anarad Gas Analyzer®) and was recorded continuously, as was the electrocardiogram. A Doppler probe (Parks Electronics Model 611®) was positioned on the precordium.

Transesophageal echocardiograms were obtained and recorded using a Fukuda Echocardiogram Model SSD-110S® and a 3.5 MHz nonfocused transducer, 10 mm in diameter (Aloka Industries, Ltd.). The dogs were placed in a supine position, and the transducer was inserted into the esophagus. When possible, the tip of the transducer was positioned at a point where a clear reflection from the right ventricular outflow tract was obtained; alternatively, the right ventricle itself was identified when the right ventricular outflow tract could not be detected easily. Precise positioning of the transducer was accomplished as follows: the transducer was placed in the esophagus at a distance of 40–50 cm from the teeth. At this point the transducer was situated facing anteriorly, and the mitral valve was identified on the transesophageal echocardiogram. The transducer then was withdrawn about 1 cm to identify the aortic valve on the echocardiogram. The aortic valve is a good marker for detecting the right ventricular outflow tract. Thereafter, several milliliters of cold 5% glucose solu-

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tion were injected into the right external jugular vein, and the aortic root and the right ventricular outflow tract were identified by contrast echocardiogram.

After a 30-min stabilization period, sequential bolus injections of 0.01, 0.02, 0.05, and 0.1 ml/kg of air were given via the right external jugular vein. The transesophageal echocardiogram was monitored continuously and was recorded as necessary. At least 20 min were allowed to pass between each injection when there was no change in end-tidal carbon dioxide concentration or pulmonary artery pressure. At least 30 min was allowed to pass when there was some change in either pulmonary artery pressure or end-tidal carbon dioxide concentration. The effect of continuous venous air infusion was studied at the rates of 0.01, 0.02, 0.05, and 0.1 $ml \cdot kg^{-1} \cdot min^{-1}$ using a Harvard® infusion pump. The infusion was continued until either pulmonary artery pressure increased or end-tidal carbon dioxide concentration decreased. The maximum infusion time was three minutes if neither pulmonary artery pressure nor end-tidal carbon dioxide concentration changed. In the study for detection of air in the aorta, a 5-F pig-tail catheter was inserted into the left ventricle via the femoral artery. The transducer of the transesophageal echocardiography was positioned at the point where the aortic valve could be identified as previously described. Air was injected into the ventricle by bolus using volumes of 0.0005, 0.001, and 0.002 ml/kg. In all studies, judgment concerning change in the transesophageal echocardiogram was determined by an observer who was unaware of whether or not air was being injected or which doses were being used.

The transesophageal echocardiogram was evaluated in six patients operated in the sitting position. Anesthesia was maintained with fentanyl, diazepam, and nitrous oxide. The transducer for transesophageal echocardiography was inserted at the time of endotracheal intubation, and the right ventricular outflow tract was identified as described previously in the animal study. Radial artery pressure, pulmonary artery pressure, central venous pressure, and end-tidal carbon dioxide concentration were measured and recorded continuously. The Doppler probe was placed in the proper precordial position. Air embolism was suspected when changes occurred in these variables, and was considered to be confirmed when pulmonary artery pressure increased and end-tidal carbon dioxide concentration decreased.

Results

LABORATORY EVALUATION

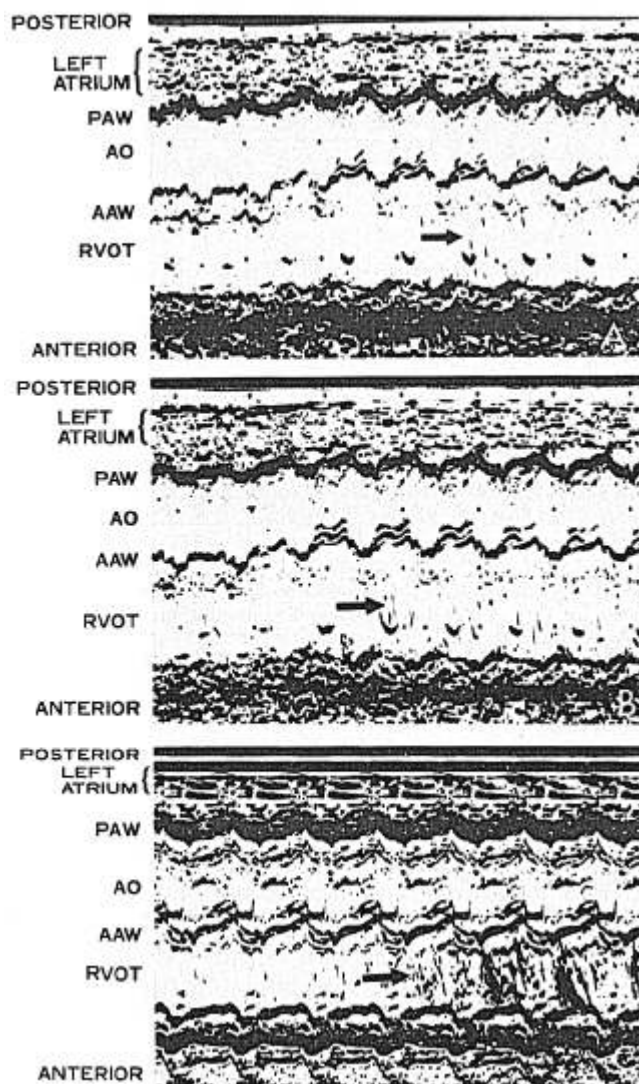When air was given by bolus injection, air embolism was suspected on contrast echocardiogram at a volume

FIG. 1. Contrast echocardiogram. Arrows indicate contrast echocardiograms of 0.02 (A, upper), 0.05 (B, middle), and 0.1 (C, lower) ml/kg bolus injection of air. As the volume of air was increased, the degree of intensity in contrast echocardiogram increased. PAW = posterior aortic wall; AO = aortic root; AAW = anterior aortic wall; and RVOT = right ventricular outflow tract.

of 0.01 mk/kg and was confirmed at a volume of 0.02 ml/kg. As the volume of injected air was increased, the degree of intensity in the contrast echocardiograms increased (fig. 1). Pulmonary artery pressure and end-tidal carbon dioxide concentration did not change with injections of air up to 0.1 ml/kg. Changes in Doppler sounds detected the injected air in all cases when 0.05 ml/kg of air or more was given by bolus injection (table 1, bolus injection data).

With continuous infusion of air, the contrast echocardiogram changed about one minute after the start

TABLE 1. Incidence of Detection of Air Embolism (Per Cent)

Bolus Injection

Monitoring Methods	Volume of Bolus Injection (ml/kg)			
	0.01 (n)	0.02 (n)	0.05 (n)	0.1 (n)
TEE	0 (5)	100 (8)	100 (7)	100 (7)
Doppler sound	0 (5)	60 (5)	100 (5)	100 (5)
PAP	0 (5)	0 (8)	0 (7)	0 (5)
FET_{CO_2}	0 (5)	0 (8)	0 (7)	0 (5)

Continuous Infusion

Monitoring Methods	Volume of Continuous Infusion (ml·kg^{-1}·min^{-1})			
	0.01 (n)	0.02 (n)	0.05 (n)	0.1 (n)
TEE	25 (4)	86 (7)	100 (7)	100 (4)
Doppler sound	0 (4)	0 (4)*	100 (4)	100 (4)
PAP	0 (4)	25 (4)	43 (7)	75 (4)
FET_{CO_2}	0 (4)	25 (4)	43 (7)	75 (4)

TEE = transesophageal ecocardiography; PAP = pulmonary artery pressure; FET_{CO_2} = end-tidal carbon dioxide concentration; n = number of examinations.

* The change in Doppler sounds could not be confirmed definitely, although a slight change was suspected.

of the infusion rate of 0.05 ml·kg^{-1}·min^{-1} (fig. 2A and 2B). Change in the Doppler sounds was noticed simultaneously or shortly after the change on the transesophageal echocardiogram. Change in the Doppler sounds could not be confirmed at a rate of 0.02 ml·kg^{-1}·min^{-1}, although we suspected a slight change. By contrast transesophageal echocardiography detected air in 86% of the examinations at this infusion rate (table 1, continuous infusion data). Pulmonary artery pressure and end-tidal carbon dioxide concentration changed in 75% of the dogs at an infusion rate of 0.1 ml·kg^{-1}·min^{-1} (fig. 2C and table 1, continuous infusion).

When air was injected into the left ventricle, a bolus injection of 0.0005 ml/kg caused suspected changes in the contrast echocardiogram and this was confirmed with a bolus injection of 0.001 ml/kg of air (fig. 3).

CLINICAL EVALUATION

Air embolism occurred in five of six patients evaluated. The comparative results of air embolism monitoring methods are shown in table 2. For illustrative purposes, the first case will be described. The patient was a 41-year-old woman who was operated for the removal of a fourth ventricle tumor. Figure 4A shows the remarkable contrast echocardiogram in this case. This change was seen first and was followed by an increase in pulmonary artery pressure and decrease in end-tidal carbon dioxide concentration (fig. 4B). In this case, air

embolism was suspected simultaneously by changes in Doppler sounds and the contrast echocardiogram, and was considered to be confirmed by changes in pulmonary artery pressure and end-tidal carbon dioxide concentration. As soon as these signs appeared, nitrous oxide was discontinued and pulmonary artery aspiration of air was attempted. Small volumes of air were aspirated. There was no postoperative complication in this patient.
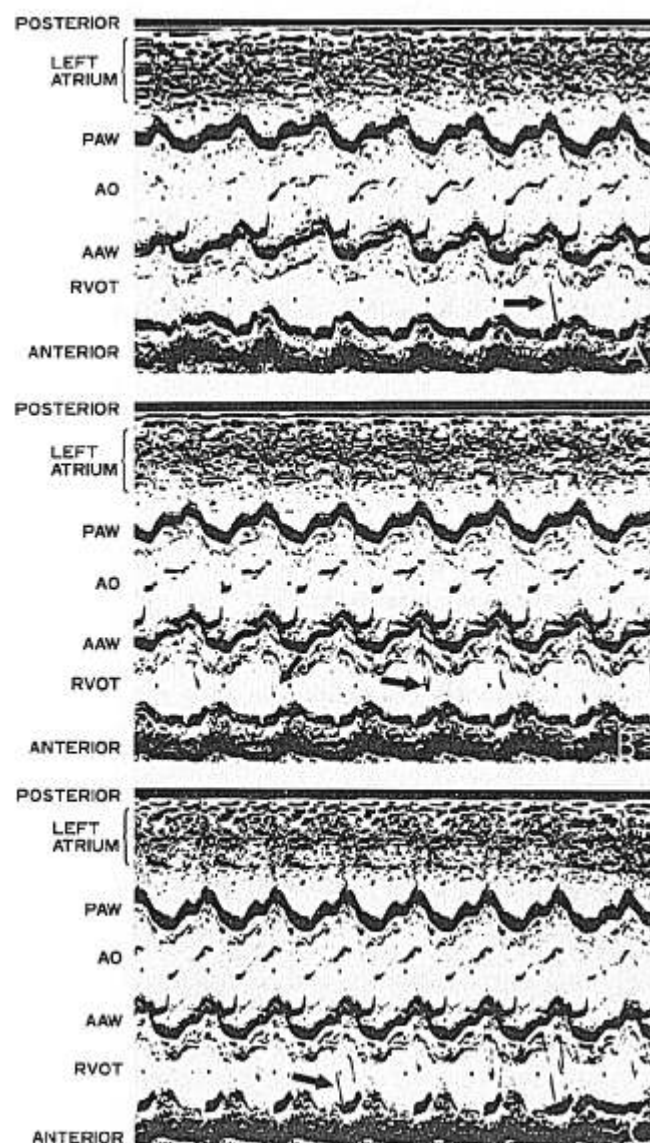

FIG. 2. Contrast echocardiograms. In 2A (*upper*), the arrow shows the first sign of air infusion, and 2B (*middle*) shows the contrast echocardiogram at 2.5 min after the start of a continuous infusion of 0.05 ml·kg^{-1}·min^{-1} of air. 2C (*lower*) shows the contrast echocardiogram two minutes after the start of continuous infusion of 0.1 ml·kg^{-1}·min^{-1} of air. Abbreviations are the same as in figure 1.

POSTERIOR

LEFT
ATRIUM

PAW

AO

AAW

RVOT

ANTERIOR

FIG. 3. Contrast echocardiogram in the aortic root with a bolus injection of 0.001 ml/kg of air. Abbreviations are the same as in figure 1.
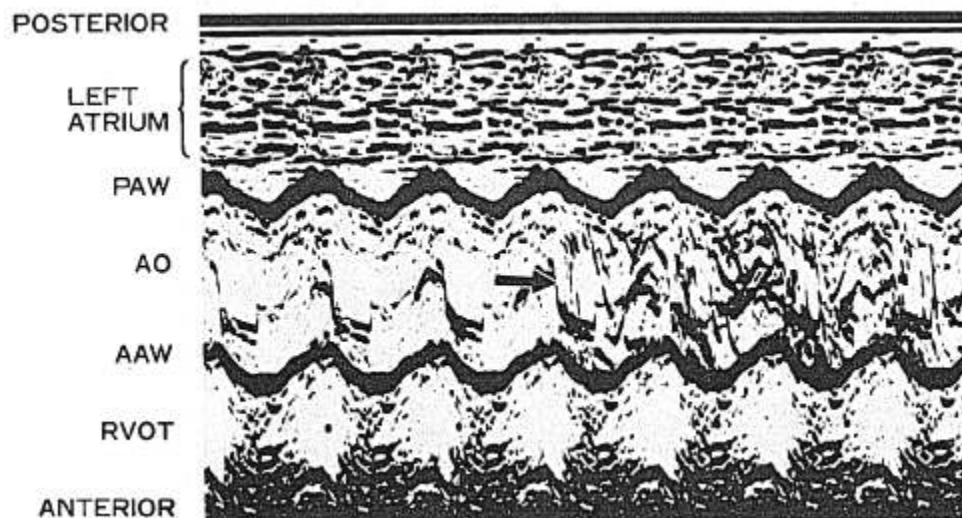
Discussion

Venous air embolism during neurosurgical procedures in the sitting position can lead to lethal complications if recognition is delayed. Therefore, it is important to detect and treat air embolism as soon as possible. The combination of monitoring Doppler sounds, pulmonary artery pressure, and end-tidal carbon dioxide concentration is thought by some to be the best method.[8,9] Among these methods, monitoring Doppler sounds is the most simple and sensitive means of detecting air embolism. However, in cases where the volume of air is small or when diathermy is used, it may be difficult to detect air embolism. The latter problem may be solved by use of a filtering system that allows for monitoring the Doppler signal even during diathermy.

Using the echocardiogram, the threshold dose for bolus air injection was 0.02 ml/kg in our anesthetized dogs, while the threshold dose for the Doppler was 0.05 ml/kg. This difference may be of little significance be-cause both are sensitive enough for clinical purposes. By comparison, English et al.[8] reported that Doppler sound changes occurred in only 90% of his animals with 0.1 ml/kg of air, at which point the pulmonary artery pressure was increased in 20%.

With continuous infusion, air was detected in all cases by change in the contrast echocardiogram and the Doppler sounds at a rate of $0.05 \ ml \cdot kg^{-1} \cdot min^{-1}$. Pulmonary artery pressure and end-tidal carbon dioxide concentration were changed in 75% of the dogs at an infusion rate of $0.1 \ ml \cdot kg^{-1} \cdot min^{-1}$. Since the threshold dose for contrast transesophageal echocardiography may depend on the total volume of air infused into the subject rather than volume per kilogram body weight, air might be detected at an infusion rate less than $0.05 \ ml \cdot kg^{-1} \cdot min^{-1}$ in subjects larger than the dog. In the experiments evaluating air detection in the aorta, transesophageal echocardiography detected air in the aorta more sensitively than in the right ventricular outflow tract. The threshold dose for confirmation was 0.001 ml/kg in the aorta. This difference in sensitivity may

TABLE 2. Clinical Evaluation of Air Embolism Monitoring Methods during Neurosurgery in the Sitting Position

Number of Patients	Age (yr)	Sex	Diagnosis	Doppler Sound	TEE	Increase PAP	Decrease $F_{ET_{CO_2}}$	Aspiration of Air from Central Venous Line
1	41	F	Fourth ventricle tumor	+	+	+	+	+
2	50	M	Acoustic neurinoma	+	+	+	+	−
3	21	F	Arteriovenous malformation	+	+	+	+	+
4	15	M	Pinealoma	−	−	−	−	−
5	40	M	Cerebellar tumor	+	+	+	+	+
6	22	F	Arteriovenous malformation	+	+	+	+	−

TEE = transesophageal echocardiography; PAP = pulmonary artery pressure; $F_{ET_{CO_2}}$ = end-tidal carbon dioxide concentration; M = male; and F = female.
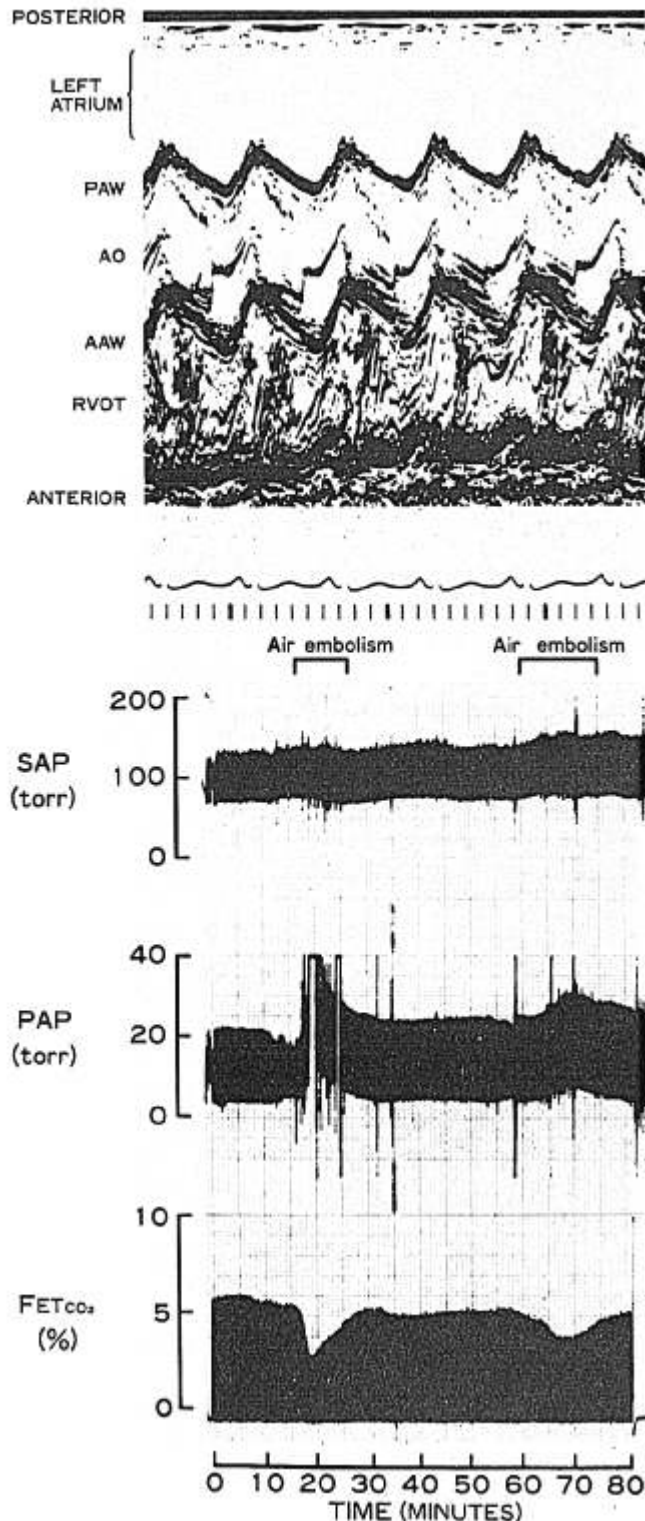+: positive sign; −: negative sign.

FIG. 4. (*A, top*) Contrast echocardiogram and (*B, bottom*) record of SAP (systemic arterial pressure, mmHg), PAP (pulmonary artery pressure, mmHg), and FET_{CO_2} (end-tidal carbon dioxide fraction, per cent) in case 1. When air embolism occurred, the contrast echocardiogram changed followed by an increase in pulmonary artery pressure and decrease in end-tidal carbon dioxide concentration. Abbreviations are the same as in figure 1.

depend on the injection route. Air was injected in the right external jugular vein in the study of venous air embolism, while it was directly injected into the left ventricle. Conceivably, in the venous studies, air could have been entrapped in the superior vena cava, right atrium, or right ventricle following peripheral injection.

In dogs, demonstration of the aortic valve was more difficult than in humans. Also in dogs, there was more frequent interference of the transesophageal echocardiogram by lung movement. For clinical monitoring, manipulation of the transesophageal echocardiographic transducer was easy, and the right ventricular outflow tract was identified without difficulty. Although precordial echocardiography is also available, the transducer for transesophageal echocardiography is easier to secure at the selected position and for longer periods than is that for precordial echocardiography. The transesophageal echocardiographic transducer and the Doppler device do interfere with each other. Thus, it was necessary to interrupt either the transesophageal echocardiogram or the Doppler sounds during the animal experiments, because the dog is smaller than humans and the devices are closer together. However, it is possible to use both the transesophageal echocardiogram and the Doppler simultaneously in humans, since the transesophageal echocardiographic transducer is directed at the right ventricular outflow tract while the Doppler device is over the right atrium. We therefore had little trouble in using them simultaneously in our patients. Moreover, we could not hear the Doppler sounds during use of diathermy while the contrast echocardiogram was not affected.

Another potential problem is that bolus injection of any solution causes contrast echocardiogram changes. Doppler sounds also change after bolus injections. As far as our clinical experiences were concerned, this did not produce any confusion. We also recognize that it is impossible for the anesthetist to continuously watch the echocardiogram. We believe it should be sufficient to watch the echocardiogram during the high-risk periods, such as craniotomy, manipulation of large vessels, exploration of the posterior fossa, the time of closing the skull. It should also be noted that this device is rather expensive as compared with the Doppler device. However, transesophageal echocardiography can be used for many purposes other than air detection.

A potential advantage of transesophageal echocardiography is the detection of air in the aorta. None of the other currently used devices offer this potential. Although not common, the most feared complication that may result from venous air embolism is that of paradoxical air embolism.[10] This is most likely to occur via a patent foramen ovale or possibly via pulmonary shunts. The ability to detect such paradoxical emboli-

zation at the time that a venous air embolism has occurred should permit immediate preventive actions and avoidance of significant cerebral or coronary embolization.

In conclusion, transesophageal echocardiography is a very sensitive and convenient method for detecting air embolism in its early stages, being at least as sensitive as the Doppler device. Moreover, this device can be used for detecting air in the aorta in patients experiencing paradoxical air embolism due to intracardiac or pulmonary shunts.

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