

Evaluation of Transesophageal Doppler Detection of Air Embolism in Dogs

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The authors assessed the use of a cylindrical sensor which transmits (transmits and receives) ultrasound in a 360° arc mounted on a standard esophageal stethoscope catheter to detect air embolism in dogs. They used electronic circuitry developed specifically to provide a continuous analog recording of high frequency Doppler energy as well as an audible signal. They found that the esophageal Doppler sensor was easy to position. In 25 of 30 dogs, the system distinguished Doppler sounds of venous air emboli that were present either in the superior vena cava, right atrium, right ventricle, or pulmonary artery from normal cardiovascular sounds. In the remaining five animals, Doppler heart and air emboli sounds were initially of poor quality, but improved with aspiration of air from the esophagus. In another five dogs, arterial air emboli produced by left ventricular injections also were detected. The esophageal sensor was sensitive to both venous and arterial air emboli ranging from 0.05–0.2 ml of air, and the authors consistently detected repeated intravenous injections of air throughout a 5-h time period. Optimal position of the sensor for detection of venous air emboli was at the level of the superior vena cava above its junction with the right atrium. Optimal position to detect arterial air emboli introduced via a left ventricular catheter was at the level of the aortic arch. Tissue analysis of the esophagus revealed no morphologic damage due to the sensor or transmitted energy. (Key words: Anesthesia: neurosurgical. Complications: air embolism. Embolism: air. Equipment: Doppler, esophageal. Monitoring: Doppler, esophageal.)

EARLY DETECTION of venous air emboli has been facilitated greatly by the use of the precordial Doppler ultrasonic sensor.¹ In practice, the sensor which transmits a beam of ultrasound energy is placed in the proper position on the precordium to detect right ventricular sounds, usually at the third and fourth costal interspaces along the right sternal border. Once positioned, the sensor must be taped or strapped to the precordium. Although precordial Doppler placement is satisfactory in most patients, in some patients, because of their chest wall configuration, lung volume, or other unknown factors, the quality of Doppler sounds may be impaired,^{2,3} or the presence of air emboli missed altogether.^{2,4} In an early report, Michenfelder *et al.*³ re-

ported that in two of 69 patients undergoing craniotomy in the sitting position, the precordial Doppler failed to detect air emboli diagnosed by other monitoring methods. More recently, Bedford *et al.*⁴ reported that the precordial Doppler failed to detect air emboli in three of 100 patients undergoing neurosurgery in the sitting position in whom the magnitude of air emboli was such as to produce obvious changes in pulmonary artery pressure and end-tidal carbon dioxide.

Because of the occasional shortcomings exhibited by the precordial Doppler, it appeared worthwhile to evaluate an alternative method of Doppler detection of air emboli. The purpose of this study was to evaluate the ability of a cylindrical Doppler sensor placed in the esophagus to detect air emboli. We evaluated the esophageal sensor's ability to detect both venous air emboli and arterial air emboli in view of the latter's occurrence following cardiopulmonary bypass⁵ and in the form of paradoxical arterial air emboli.⁶ We anticipated that the efficacy of a Doppler sensor placed in the esophagus would be unaffected by chest shape or form. Because of the close proximity of the esophagus, the superior vena cava, and the heart, little attenuation of ultrasound should occur. Use of the esophagus for the Doppler sensor also avoids the likelihood of the sensor being dislodged. By using a cylindrical sensor that radiates ultrasound in a 360° arc, we also make positioning easier. In this paper we report the results of using the esophageal Doppler sensor for detection of air embolism in dogs.

Methods

The esophageal Doppler system consists of a cylindrical piezoelectric sensor (6.5 mm OD by 6.5 mm length) mounted on a standard 40-cm length plastic esophageal stethoscopic catheter. The external surface of the sensor is coated with epoxy to provide electrical isolation greater than 50 kohms between sensor and esophagus. The sensor radiates ultrasonic energy (7.0 mw/cm²) in a 360° arc, and receives it in a plane perpendicular to the axis of the catheter. The transcepi-tional pattern is fairly uniform in all directions around the circumference (no more than ±8 dB variation). The pattern parallel to the axis of the catheter lies in the "near-field" of the sensor to a radial distance of 11 cm, which is beyond the design range for detecting air emboli. Therefore, the pattern is approximately 6.5 mm

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Received from the Department of Anesthesiology and Center for Bioengineering, University of Washington, Seattle, Washington, and the Department of Anesthesiology, University of Washington, Seattle, Washington. Accepted for publication June 10, 1982. Supported by NIH Grant GM26187. Presented at the annual meeting of the American Society of Anesthesiologists, St. Louis, Missouri, October 1980.

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in width parallel to the catheter axis (equivalent to the length of the sensor) and uniform except for the usual maximum and minimum points of the near-field of a sensor.⁷ Air passage through the esonified plane results in an increase of high-frequency Doppler energy received, particularly in the 1–2 kHz region.

The transmitter emits 16 cycles of 4-MHz energy at a repetition rate of 7.8 kHz. The system therefore operates in the "pulsed Doppler" mode, but we do not use range gating (selecting of echoes originating from a specific distance from the sensor) as is common practice with this mode. The gain of the receiver is varied with time to compensate for loss of energy with distance from the sensor due to dispersion and attenuation. The received Doppler energy is processed through two separate pathways: one for audio presentation, and the other for an air emboli analog output. An analog output of the Doppler energy is produced by passing the Doppler energy through a bandpass filter (1–2 kHz), rectifying circuit, and lowpass filter (0–1 Hz). This processing provides an output that is favorably sensitive to air emboli but not the wall motions associated with cardiac action. Consequently, air emboli manifest their presence both by characteristic sounds and recorder deflection.

The performance of the esophageal Doppler sensor was assessed in 35 anesthetized dogs. Anesthesia was induced with intravenous thiopental, an endotracheal tube was inserted, and the dogs were mechanically ven-

tilated with anesthesia maintained using halothane in oxygen. Dogs were studied while they were supine, both horizontally and with head-up tilt varying between 40 and 80 degrees.

The ability of esophageal Doppler sensor to detect venous air emboli was determined in 30 dogs by placing the sensor to elicit optimal heart sounds and determining the response to air bubbles ranging in size from 0.5–2 ml injected into catheters inserted into the external jugular and femoral veins. We then studied the sensitivity of the sensor in 19 of these dogs to varying size air bubbles ranging from 0.05–1.0 ml intravenously injected both as part of a bolus of saline or as part of a slow infusion of saline. The relationship between the amplitude of the sensor's analog response and the size of air embolus was determined in five of these dogs in which air emboli passed rapidly through the ultrasonic field.

The effect on sensitivity of varying the esophageal Doppler sensor position was determined in four of these dogs placed in the supine position by varying the position of the sensor at 1- to 2-cm intervals in relation to the pulmonary artery. Pulmonary artery position, determined by x-ray visualization of a Swan-Ganz catheter, corresponded to the fifth thoracic vertebra. An ECG electrode attached to the esophageal catheter tip permitted identification of the right atrial level from the shape of the "P" wave. Simultaneously, we investigated

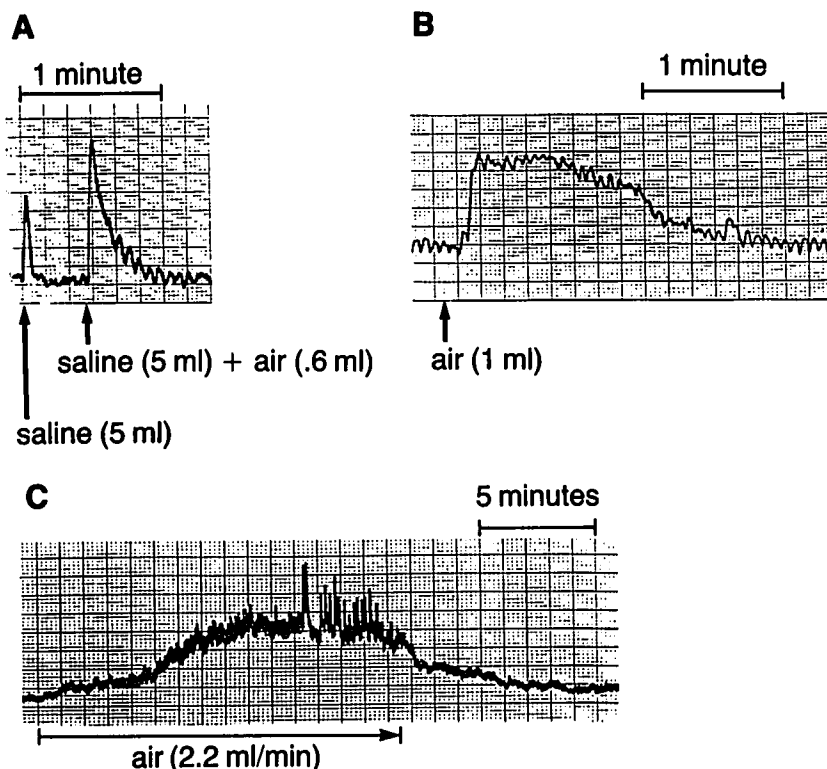


FIG. 1. Analog responses recorded to air introduced into three animals by different methods. The ordinate represents the relative Doppler energy at 1,000–2,000 Hz with different scale factors in each record. The abscissa represents time also with different scale factors. (A) The response to bolus injections. (B) The response to air introduced into saline infused into the jugular vein at a rate of 16.7 ml/min. (C) Response to a continuous jugular vein infusion of air only.

the esophageal sensor's sensitivity to air emboli present at different locations by injecting air into the pulmonary artery, the right ventricle, the right atrium, and the jugular vein and femoral vein. We varied the level of the sensor as needed with each injection site.

The effect of time on the sensor's reliability in detecting venous air emboli was assessed over a 5-h period in six dogs. Every 15 min an injection of 5 ml of saline followed by 1 ml air in 4 ml saline was given through a jugular vein catheter and recordings were made. At the end of five hours, the esophagus of each of these six dogs was evaluated for morphologic changes caused by the sensor. The location of the sensor was marked by sutures, and this area as well as adjacent areas of esophagus were removed and fixed in Hollande's fixative. Ensonified and unsonified (control) regions of the esophagus were sectioned into 50 1-mm wide slices. Five slices randomly selected from each region were stained with hematoxylin and eosin for light microscopic studies.

We also determined the ability of the esophageal sensor to detect arterial air emboli. In five dogs, a catheter was passed through the left carotid artery into the left ventricle with its position confirmed by the appearance of a characteristic left ventricular pressure wave. Air varying in volume between 0.05–1.0 ml was injected through the left ventricular catheter with the sensor inserted to the level where pulsating high-frequency sounds were heard. Initial studies were done with the chest closed, and then repeated in the open-chested animal following a midline sternotomy and rib retraction. With the chest open, the position of the sensor within the esophagus was determined by palpation.

Results

The esophageal sensor detected venous and arterial air emboli in all dogs studied. Examples of analog responses to venous air emboli are shown in figure 1. In five of the 30 animals, however, the quality of Doppler sounds was muted. Venous air embolism detection was not possible in those five dogs until air was suctioned from the esophagus, apparently improving sensor contact with the esophageal wall. During light anesthesia, occasional transient high-frequency Doppler sounds occurred which appeared to result from muscle movement or esophageal peristalsis. These sounds were easily differentiated from the high-frequency sounds produced by air emboli.

In four of the dogs, small amounts of air injected into the jugular vein were not detected during several minutes of observation when the sensor was located at the level of the pulmonary artery. In contrast, air injected into the femoral vein was detected within seconds, thus

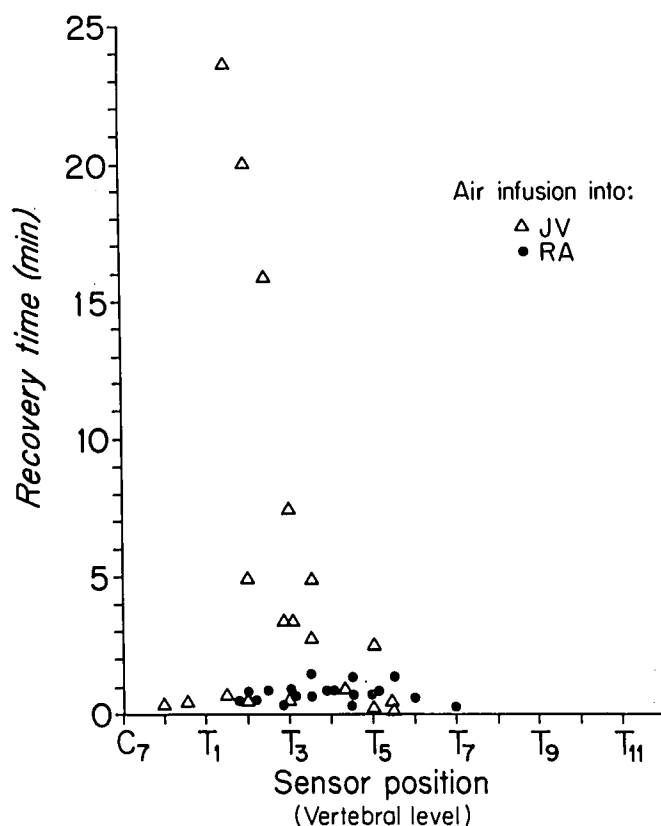


FIG. 2. Time for analog response to return to baseline following infusion of 0.5 ml air into the jugular vein (JV) or right atrium (RA). Data recorded from four dogs in the supine position.

indicating that the sensing system was working properly. We hypothesized that air injected in the jugular vein was lodged in the superior vena cava above the level of the ultrasonic field. As for the femoral vein injection, the sensor apparently was detecting air when it passed through the lower superior vena cava from the azygos vein, or through the right atrium or pulmonary artery from the inferior vena cava. The hypothesis that air could lodge in the superior vena cava was supported by finding, in other dogs, that small amounts of air injected into the jugular vein produced changes in Doppler sounds and recorder deflection that lasted for several minutes when the sensor was at the level of the superior vena cava. Right atrial injections, however, produced changes that were transient (fig. 2).

In the animals used to assess the sensitivity of the esophageal sensor, the threshold for detection of venous air embolism was found to range from 0.05–0.2 ml of air (0.0025–0.01 ml of air/kg). In the dogs used to assess the relationship between the magnitude of the analog response and the size of the air embolism, an approximate linear dependence was indicated up to an

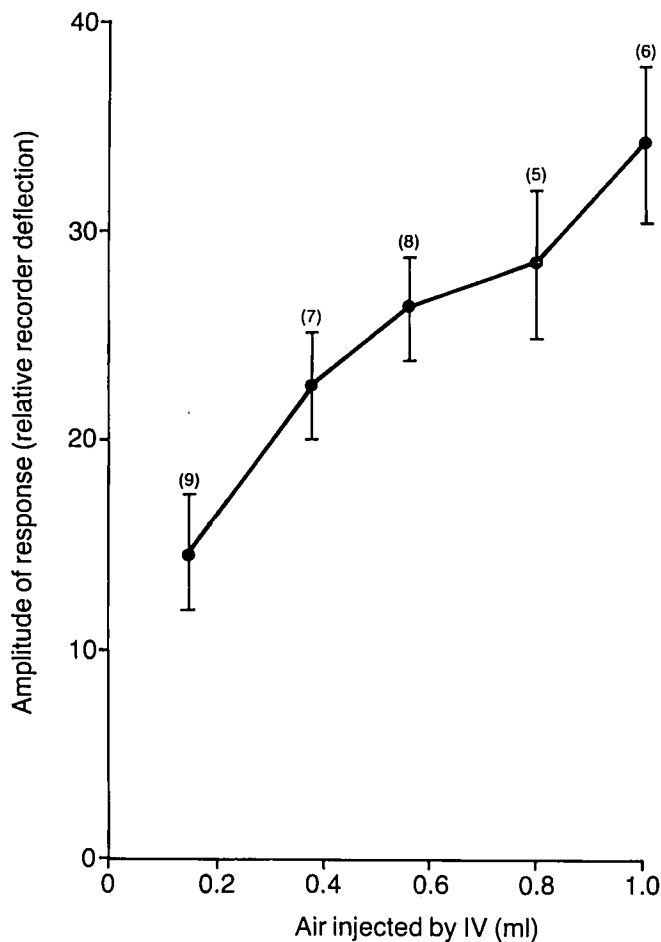


FIG. 3. Analog response amplitude vs. injected amount of air. The mean values \pm SEM and the number of trials (number in parentheses) are shown for four dogs in the supine position to either jugular vein or femoral vein injections.

air embolism size of 1 ml which was the maximum volume of air used to examine this relationship (fig. 3).

The esophageal sensor was able to detect air at each of the injection sites. However, the optimal site for sensor placement within the esophagus for air embolism detection varied, depending upon the air injection site (fig. 4). For air injected into the jugular vein, the optimal esophageal site for detection was usually between the level of the pulmonary artery (fifth thoracic vertebra) and four rib spaces above this site. The optimal level for sensor placement to detect air injection into the right atrium, right ventricle, and pulmonary artery tended to center opposite the pulmonary artery. In these latter injection sites, air often was not detected if the sensor was positioned more than two to three rib spaces above or below the injection site.

Variability in sensitivity to saline and venous air emboli occurred throughout the 5-h study period (fig. 5).

The mean ratio of the analog responses of air-saline and saline, however, tended to be consistent at approximately 1.6. No tissue damage was found by histologic analysis of the esophagus at the end of the five hour studies. At a magnification of 100 \times the original, surface epithelium appeared unbroken, and no morphologic changes appeared in either ensouffled or unsouffled (control) sections. Mucosal and submucosal tissue showed no evidence of cell lysis or edema.

Both rapid and slow injections of air in volumes as low as 0.2 ml into the left ventricular catheter produced marked, transient deflections of the analog recorder from baseline in dogs with both closed and open chests. By palpating the esophagus in the open-chested animals, the sensor was found to be at the level of the aortic arch.

Discussion

Edmunds-Seal and Maroon, in an early description of the precordial Doppler sensor as a venous air embolism detector, suggested that the esophagus might

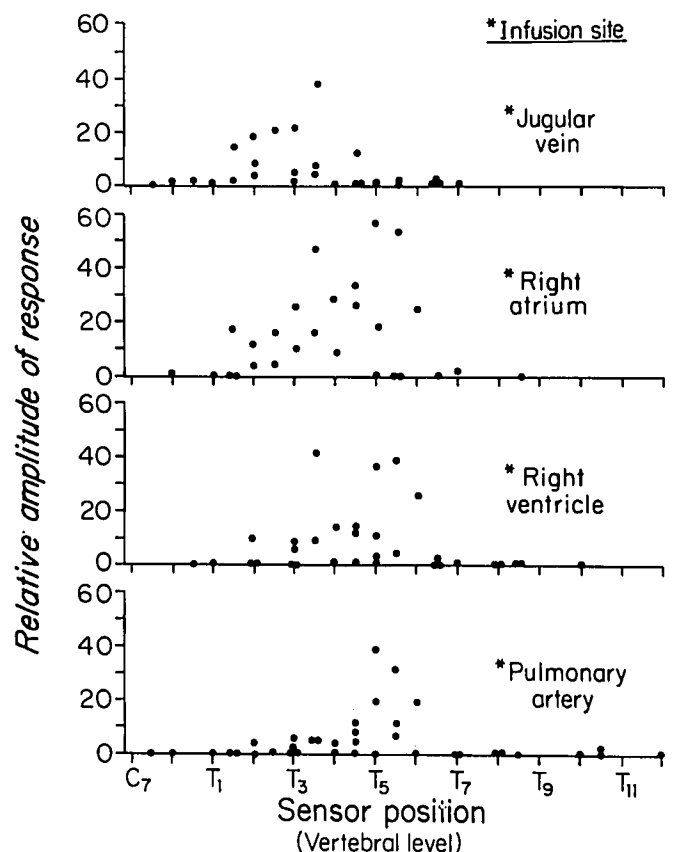


FIG. 4. Analog response to 0.5 ml air infused at different sites and with different sensor positions. Sensor position related to cervical (C) or thoracic (T) vertebral level.

provide an alternative site for Doppler sensor placement.¹ Michel recently reported introducing a standard highly directional precordial Doppler sensor into the esophagus through a stomach tube for detection of air embolism during hip surgery.⁸ Michel reported that air emboli were detected using this method, but that sensitivity depended on the directional orientation of the Doppler sensor.

The esophagus would appear to be a logical place for an ultrasonic sensor to detect air whether the air was located in the aorta, superior vena cava, or right atrium. In dogs and humans, the aortic arch lies at the upper level of T4 directly adjacent and to the left of the esophagus. But at this level, the air within the trachea may block the direct transmission of ultrasound energy to the superior vena cava. Some ultrasound energy, however, may be transmitted to and reflected from the superior vena cava indirectly by reflection from lung tissue as the cylindrical sensor used in our study emits ultrasound across a 360° arc. Below the level of the fifth thoracic vertebra, the trachea is divided and, therefore, there is no air column between the esophagus and surrounding vascular structures.⁹ The superior vena cava and right pulmonary artery lie directly anterior to the esophagus at T5, the superior vena cava and left atrium lie anterior to the esophagus at T6, and the right and left atrium lie anterior to the esophagus at T8. Below the seventh thoracic vertebra an accessory lobe of the right lung in dogs lies between the esophagus and the heart,¹⁰ interfering with ultrasound transmission. This lobe is not present in humans.

We found that the esophageal Doppler sensor was most sensitive to venous air emboli when placed opposite or one to three vertebral levels above the pulmonary artery catheter as observed on fluoroscopy. This region corresponds to the vertebral bodies of T2 to T5 and includes the lower superior vena cava above its entrance to the right atrium. The amplitude of the analog response was greatest when the sensor was between T3 and T6 for air injected into the right atrium, right ventricle, and pulmonary artery. For jugular vein injections, the greatest responses occurred between T2 and T4. There was a diminished response with the sensor in the T5 to T6 region with jugular vein injections which we believe resulted from air lodging above the level of the sensor.

Other researchers also have provided evidence that air can lodge within the superior vena cava. Bunegin *et al.*¹¹ placed a catheter tip at various positions in a model of the right atrium and vena cava of humans. These authors found that optimal aspiration of air was achieved when the catheter tip was positioned in the superior vena cava 3.0 cm above its junction with the right

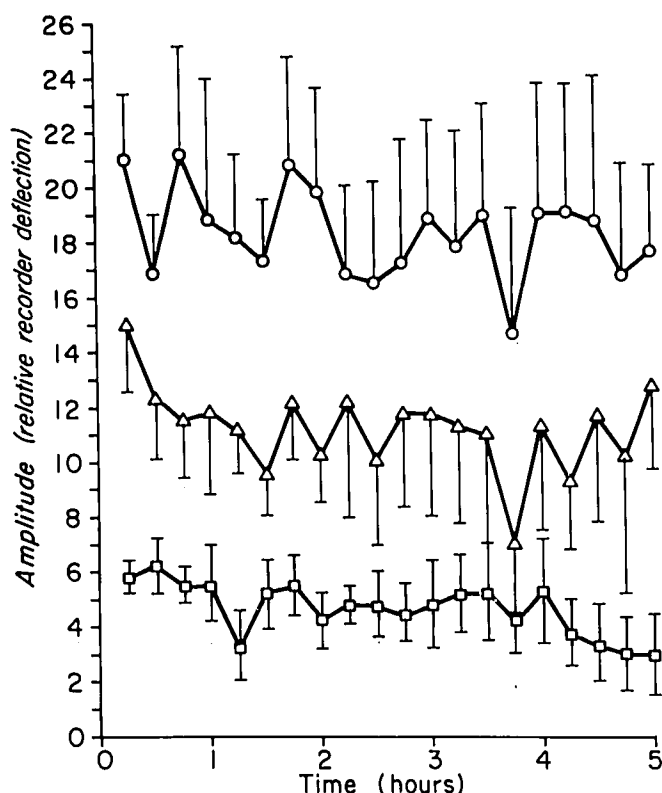


FIG. 5. Baseline heart sounds (\square), response to 5 ml saline bolus injection (Δ), and response to 1 ml air + 4 ml saline non-mixed bolus injection (\circ) in six dogs throughout a 5-h period. Values are the mean \pm SE. Three dogs were supine and three were tilted head-up; all injections were into the jugular vein.

atrium. Similarly, Motomatsu *et al.*¹² were able to aspirate 41% of injected air with a catheter tip in the superior vena cava, and only 15% with a catheter tip in the right atrium in dogs placed in an upright position, indicating that air collected in the superior vena cava. The optimal level for esophageal Doppler sensor position and that for catheter tip placement for air aspiration would thus appear to coincide. Bunegin *et al.*¹¹ found in their model that a vortex of air and blood developed. It was confined within the superior vena cava but outside the atrial entrance. The fact that the vortex, esophagus, and superior vena cava are in close proximity may explain why this level is optimal for both esophageal sensor detection of air and air aspiration. The vortex motion of air emboli would increase the Doppler energy and slow the passage of air.

The prolonged Doppler responses that we observed also provide evidence that air emboli collect within the superior vena cava (fig. 3). These observations were unexpected, but can be explained by considering the forces involved that determine air bubble movement in

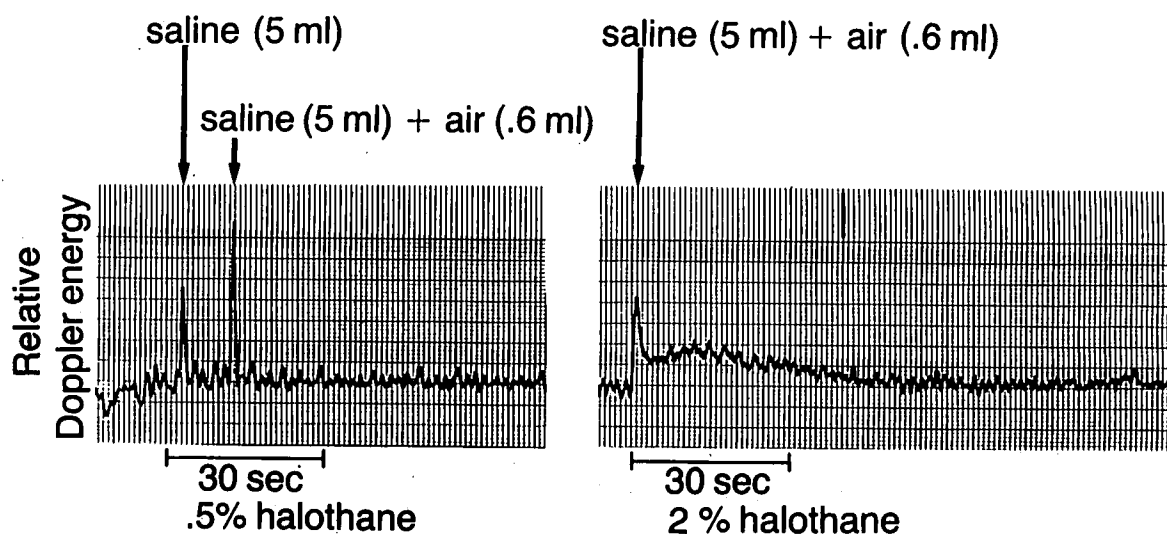


FIG. 6. Analog response to air embolism in a dog in a 30° head-up tilt during ventilation with 0.5% halothane (*left*) and 2% halothane (*right*). A prolonged delay in air passage resulted with the higher halothane concentration.

a flowing liquid. The rate at which a bubble rises through a stationary fluid with a viscosity similar to blood provides a measure of the necessary vertical downward fluid velocity required to exert a force equaling the upward buoyancy force of an air bubble. Equality of these forces would result in air emboli being detained in one vertical location. Tadaki and Maeda[‡] have shown that a 1-cm diameter bubble has a rising velocity of 22 cm/s. In the jugular vein, superior vena cava, and right atrium, blood velocity is pulsatile varying between -3 to +30 cm/s.¹³ Thus, it would appear that an air bubble 1 cm in diameter will move downward in some parts of the cycle and upward in others. Since less velocity is required to counter the upward buoyancy force of a smaller bubble, smaller bubbles will migrate downward over most of the cardiac cycle, while larger bubbles may undergo a vertical oscillation about some point, later being removed by breaking into smaller bubbles. On this basis, deeper levels of anesthesia, which reduce cardiac output, would be expected to prolong the time air would stay in one location (fig. 6). In the horizontal position, surface tension forces between air bubble and vessel wall, instead of buoyancy forces, would tend to retard air bubble movement explaining the prolonged Doppler response to air emboli found in supine dogs (fig. 2).

The esophageal Doppler sensor was able to detect air bubbles as small as 0.05–0.2 ml. This sensitivity is equal to or greater than that reported for the precordial

Doppler.¹ We found that the amplitude of the esophageal Doppler response correlated well with the amount of air only if the injected air passed through the Doppler field rapidly. The amplitude of the response and the baseline Doppler heart sounds also appeared to be a function of the flow rate of blood. This flow-dependence was apparent when the heart, with air emboli present, was stopped by an injection of potassium chloride solution. The amplitude of the Doppler energy due to the presence of air fell to zero. Therefore, it is unlikely that the quantity of air present can be determined using a Doppler sensor unless a method of accounting for flow rate and of calibrating individual subject sensitivity can be found.

Mills and Ochsner⁵ have reported that the incidence of arterial air emboli during cardiopulmonary bypass may be as high as 11%, and that arterial air emboli in these situations may result in severe brain damage. Similarly, paradoxical arterial air embolism is a frightening complication occurring in patients subject to venous air embolism.⁶ Immediate treatment is not possible because paradoxical arterial air embolism is undiagnosable until the postoperative period. The capability of the esophageal Doppler sensor to detect air emboli flowing through the aortic arch in animals indicates that there is a possibility that arterial air emboli may be detected intraoperatively in these patients. The precordial Doppler and the cylindrical esophageal sensor do not permit differentiation between simultaneously occurring arterial and venous air emboli. It may be possible, however, that an esophageal sensor with a more focused ultrasonic field could be placed at the level of the aortic arch

‡ Tadaki T, Maeda S: On the shape and velocity of single air bubbles rising in various liquids. *Kagaku Kogaku* 25:254–264, 1961.

and positioned so that air passing through the left atrium from a patent foramen ovale would be detected. At the present time we are investigating this possibility.

We found that air emboli can be easily detected from the esophagus in dogs. A decrease in sensor sensitivity occasionally was encountered apparently due to poor contact between the sensor and the esophageal wall. Sensitivity improved, however, with aspiration of air from the esophagus. We found that the omni-directionality of the sensor in a plane is advantageous in eliminating the need for careful orientation of the sensor and that the proximity of the esophagus to vascular structures is favorable for the detection of air emboli. We also found that the analog record of air embolism was useful in recording the presence and time history of air embolism.

The authors acknowledge the technical assistance of Mr. Bruce L. Pierson in carrying out this project.

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