Effects of Cardiac Output on the Clearance of Air Emboli from the Superior Vena Cava

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The authors assessed the effect of cardiac output on the rate of clearance of air emboli from the superior vena cava (SVC) in 11 dogs placed in a supine 30° head-up inclined position. Venous air emboli were produced by infusing 4 ml of air into the dorsal sagittal sinus. Air emboli appearance and clearance from the SVC were determined from the analog record produced by a transesophageal Doppler ultrasound monitor. Cardiac output was altered by changing the level of anesthesia and the administration of intravenous fluid. Eighty-eight per cent of air infusions resulted in an analog response of consistent amplitude indicating that all or a similar fraction of the infused air arrived consistently at the ensonified region of the SVC. In this group, air emboli passed from the SVC with a clearance time (CT) that was related inversely to the cardiac index (CI), CT = 24 CI⁻¹ with a correlation coefficient = 0.57. Following 12% of the air infusions, there was evidence that a part of the air became detained in vascular sites cranial to the ensonified portion of the SVC. This evidence consisted of the following observations: analog responses were diminished in amplitude; subsequent air injections evoked responses that sometimes were exaggerated; and/or subsequent increases in cardiac output alone, produced spontaneous analog responses characteristic of air emboli. The authors postulate that air similarly may be detained in clinical settings and may explain such phenomenon as persistent precordial Doppler sounds of air emboli after pulmonary artery pressure has returned to normal following symptomatic air embolism and occurrence of air emboli after scalp closure. (Key words: Anesthesia: neurosurgical. Complications: embolism, air, clearance. Embolism: air. Equipment: Doppler, transesophageal. Heart: cardiac output.)

The clinical manifestations of venous air emboli range from very brief alterations in precordial Doppler sounds to acute cardiovascular collapse. These manifestations generally have been attributed to differences in the volume and rate of air entering the circulation. As a consequence, effects of varying the rate and volume of air injection on hemodynamics have been studied extensively. Less attention, however, has been paid to hemodynamic alterations that might themselves affect the behavior of air once it has entered the circulation.

We have studied the use of an ultrasonic sensor placed in an esophageal stethoscope to detect air emboli in dogs. During the investigation, we observed that small volumes (0.1–0.5 ml) of air emboli occasionally could be entrapped and/or retained for extended periods of time at the level of the superior vena cava (SVC) after injection into the jugular vein. The evidence for detainment was in the form of prolonged high-frequency Doppler sounds indicating the presence of air lasting from 3 to 24 min. Bunegin et al. observed in an in vitro model that air emboli of a few milliliters would tend to float in the SVC just above the atrium until broken into smaller emboli and then passed through the circulation. They described how the force applied by the moving fluid in proportion to the square of the fluid velocity competes with the buoyancy force of an air bubble in determining its movement. We hypothesized that at reduced cardiac output blood velocity would be lowered and air emboli therefore would be prolonged in their passage into the pulmonary circulation. This concept was supported by our earlier observations that Doppler air emboli sounds lasted the longest in conditions in which cardiac output and blood velocity were most likely reduced, i.e., under deep halothane anesthesia, hypovolemia, and inclined posture. In this article we report the results of studying this phenomenon in more detail by measuring the clearance time of small volumes of air emboli from the superior vena cava of dogs at different values of cardiac output.

Method

Eleven mongrel dogs weighing from 18.5 to 26.4 kg had anesthesia induced with intravenous sodium thiopental (50 mg/kg), their tracheas intubated and anesthesia maintained with halothane in 100% oxygen. Catheters were placed in the femoral artery for monitoring blood pressure and in the femoral vein for administration of fluid. A thermal dilution flow-directed catheter also was advanced to the pulmonary artery from the femoral vein for determination of cardiac output (Q) (Edwards Laboratories 9520A). Cardiac index (CI) was calculated by dividing Q by the body surface area (BSA), the latter calculated from the following formula: BSA = 0.112 (weight in kg)²/₃ (m²).

The dorsal sagittal sinus was catheterized for subsequent air infusions. A mid sagittal incision was made, and the skin was reflected to reveal the nuchal crest, the anterior portion of which was removed. A hole was drilled in the calvaria to reach the sinus just inferior to the bone.
in the folds of the falx cerebri. The dura was punctured with an 18-gauge needle, and a polyethylene catheter (PE-200) was advanced into the sinus. Wax and dental acrylic were used on the bone around the catheter to ensure a tight seal. To confirm the seal and placement in a main venous channel, we verified that venous blood easily could be withdrawn from the catheter, that positive pressure of several centimeters of water was present with the animal in the lateral decubitus position, and no changes in heart rate or blood pressure occurred in response to a 5-ml saline injection into the sinus. In the latter consideration, a change indicated the puncture was too deep and the injection produced pressure on the cranial surface that undesirably affected the hemodynamics. No studies were conducted in the few animals in which this occurred.

The transesophageal sensor used to detect the air emboli consisted of a cylindrical piezoelectric ultrasonic element (6.5 mm OD) mounted on an esophageal stethoscope catheter. The sensor was passed down the esophagus and positioned at the site at which cardiovascular Doppler sounds of the highest frequency were heard. Previous studies had shown this position to be at the level of the superior vena cava near the entrance to the right atrium.

To simulate to some degree the conditions encountered during craniotomies in the sitting position, the study was done with the animals supine but inclined at 30° from the horizontal with the head up. This angle was a compromise between fully simulating the sitting position but avoiding excessive cardiac output depression caused by tilting the anesthetized animals to larger angles. Analog Doppler responses to air emboli were recorded on a chart recorder by electronically filtering and rectifying the Doppler energy in the 1–2 kHz range. A proportional relationship between this signal and the magnitude of moving air present in the ensonified field of the transducer was found with this method in vivo with bolus injections of 1 ml or less into the jugular vein and in an in vitro for continuous infusion rates of 5 to 25 ml/min (unpublished data). Venous air embolism was produced by slowly injecting 4 ml of air followed by 4 ml of saline during a 15-s total injection time (an infusion rate of 16 ml/min) into the dorsal sagittal sinus. The clearance time for air to pass through the SVC was calculated by determining the time during which the analog response was increased above baseline.

Thermal dilution cardiac output determinations (Qc) were made in duplicate before injection of air and after the analog response returned to baseline. The before and after values were averaged unless a considerable difference existed because of large changes in Qc during the clearance of the air in which case that trial was not analyzed. This rarely happened. We did not make Qc determinations during the actual clearance of air in order to avoid dislodging air emboli from the superior vena cava with the saline injections required in measuring Qc. We thereby avoided artifactually changing the clearance time. We did monitor arterial pressure throughout in order to reject any trials in which major changes occurred during the clearance since such a change might have resulted from a change in Qc. However, we rarely observed any change and certainly no consistent change. The total air injected for each trial was only 4 ml at a rate of 0.27 ml·s⁻¹. English et al. found an injection of 0.5 ml·kg⁻¹ or less at a rate of 1 ml·s⁻¹ produced no change in cardiac output. Even in the smallest animal our relative injected volume was less (0.2 ml·kg⁻¹) and a rate lower than 1 ml·s⁻¹, so we doubt that the injected air altered cardiac output during its clearance.

Qc was manipulated by varying the inspired halothane concentration and, if necessary, the administration of intravenous fluid. In each dog we attempted to vary the Qc in a stepwise manner recording the analog response to air at each level after stabilization. Qc was varied from low to high levels and from high to low levels over a wide range. In some animals measurements were made over a limited range of Qc because of a prolonged delay in recovery to baseline of the analog responses following air injection and/or resistance of Qc changes to our manipulations.

### Results

The analog responses to air injected into the dorsal sagittal sinus were of several distinct patterns varying both in amplitude and duration. Eighty-eight per cent of the responses (120 out of a total of 135 injections) were found to have amplitudes that were significantly greater than the other 12% (table 1). In fact, in this set of responses, the amplitudes detected in most animals varied

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* Means are significantly different (P < 0.05).
little as indicated by proportionally small values of standard deviation as shown in the table. A typical analog response from this set of responses for a high CI value is shown in figure 1A. The rise time of that analog response was rapid, and the amplitude decreased smoothly and rapidly to the baseline as air apparently passed through the ensonified superior vena cava. In figure 1B the analog response to air injected in the presence of a low CI for the same animal was illustrated. The rise time was not as steep as before, and the time required for the signal to return to the original baseline was prolonged. Almost invariably the duration of the analog response was longer than 1 minute and ranged up to 20 minutes. The average duration (time required to recover to baseline) in 11 dogs versus CI is shown in figure 2.

In the remaining 12% of the air injections, analog responses were obtained with amplitudes that were significantly smaller (table 1). Because these responses were so much smaller, unpredictable, and very often unrepeatable, we excluded their clearance times from the plot of figure 2. After observing a response with a markedly diminished amplitude, we repeated the infusion within several minutes after the analog signal had returned to the baseline. In 16 of these repeat infusions: five responses were obtained that were similar in amplitude to the mean response for that animal shown in the left column in table 1. Eight responses again were significantly smaller than the mean, and three were of exaggerated amplitude and/or duration as shown in figure 3.

In eight instances, a third type of event was observed. In each case, one or more injections of air emboli had been made in the dorsal sagittal sinus in the presence of a reduced CI, and Doppler responses had returned to baseline, indicating that all air had cleared from the SVC site ensonified by the sensor. CI then was increased by reducing the inspired halothane concentration resulting in the spontaneous occurrence of Doppler sounds and analog responses characteristic of air emboli. An example of this phenomenon is shown in figure 4.

**Discussion**

It is well known that air emboli in the venous system will produce characteristic sounds in the precordial Doppler that are different from the normal cardiac sounds. Accordingly, the Doppler has been used widely for diagnosing air emboli in neurosurgery since first described. We have found that the presence of a significant level of Doppler energy in the 1–2 kHz range with our transesophageal monitor (and the analog output signal produced by it) is also coincident with the presence of air emboli in the ensonified field of the transducer.

In our study, in vivo evidence was found that the passage of air emboli through the SVC can be retarded. Although retarded, it is obvious that air emboli are in motion because stationary air bubbles would not produce the Doppler frequency shift. Our in vivo results confirm the in vitro observations of Bunegin et al. and support their sug-
gestions that the SVC might be the optimal site for positioning an intravascular catheter for aspiration of air emboli. Our results also indicate that the duration of passage is at least partially a function of Qe. Finally, evidence was obtained that air emboli also could be retained at sites cephalad to the SVC for an indefinite period of time, but they could be dislodged by subsequent injections of air or increases in Qe.

Insight into how air can be delayed or retained in a vessel is provided by consideration of the physics of air bubble motion in a liquid flowing through vessels. Of specific interest are the relationships between blood velocity and the size of air bubbles, blood velocity and cardiac output, bubble size versus vessel cross-section, inclination of the vessel with respect to the force of gravity, and adherence of air emboli to vessel walls.

Bunegin et al. described how the buoyancy of air would cause bubbles to float in the SVC of their model and that forces applied to it by the fluid velocity were in relation to the square of the velocity and in proportion to the surface area of the bubble. The net effect of the impeding forces would dictate the movement of the air. Quantitative information is obtainable by studying the velocity at which a bubble rises in a motionless fluid, since this is measured easily. This velocity is equivalent to the downward fluid velocity at which the air bubble would be retained in a moving fluid due to bubble buoyancy. Equally important, a bubble will be propelled downward in proportion to the difference between the fluid velocity and a given bubble rising velocity. Air bubble rising velocities are shown in figure 5 for different size bubbles in a fluid with a viscosity similar to blood. The velocity increases with the diameter of the bubble except between diameters of 0.3–0.5 cm and a velocity of approximately 20 cm/s, where a decrease occurs due to bubble wobble and/or zigzag movement. In the jugular vein, superior vena cava, and right atrium, blood velocity is pulsatile and varies from 3 to 30 cm/s. Therefore, bubbles in the range of 0–1.5 cm in diameter have rising velocities similar to blood velocities encountered in the venous system. This near identity of bubble rising velocity and blood velocity establishes that conditions are such that during part of the cardiac cycle air emboli may rise and during other parts of the cycle they may move toward the heart, producing an oscillatory movement throughout the cardiac cycle. Bunegin et al. describe a vortex motion in their model with pulsatile flow. It is feasible to expect a net zero movement of an air bubble throughout a cardiac cycle if blood velocity, air bubble size, and other conditions provide an average balance of forces.

We found a relationship of \( CT = 24 \cdot C_i^{-1.3} \) between the clearance time (CT) of air emboli from the SVC and cardiac index (CI) with a correlation coefficient of 0.57 (fig. 2). This nonlinear power relationship provided a better fit and correlation coefficient to the data than a linear regression. The low value of correlation we believe is due in part to the random or unstable behavior of air emboli as a consequence of the many forces imposed on it and its pliable form. However, the correlation coefficient is significantly different from zero \((P < 0.001)\) and the 95% confidence interval for the correlation, ranges from \( r = 0.44 \) to \( r = 0.67 \). We hypothesize that the inverse relationship with respect to cardiac index is due in part to a direct relationship between blood velocity and cardiac output and the likelihood that air emboli would be cleared at a rate in proportion to the difference between blood velocity and the rising velocity of the air bubbles. While we did not measure blood velocity, circulation time has been found to be related reciprocally to cardiac output by Selzter et al. Therefore, we postulate that as cardiac output is decreased, blood velocity also is decreased such that it approaches the rising velocity for air emboli promoting retarded net movement.
FIG. 3. The analog response to two infusions of 4 ml air into the dorsal sagittal sinus in a dog with a low cardiac output (CI = 1.3 l·min⁻¹·m⁻²). The initial infusion occurred at the time indicated by the first arrow and resulted in a subnormal response. A second infusion was made a few minutes later (second arrow) and resulted in a larger than normal response, which briefly exceeded the range of the recorder.

The size of the bubble in relationship to the size of the SVC may be another factor in air emboli retardation at the level of the SVC. As the cross-sectional area of a bubble decreases in relationship to the cross-sectional area of the vessel, its rising velocity increases.³ This phenomenon would promote delay in large vessels such as the SVC.

The degree of tilt of the animal is also important. Our animals were inclined at an angle of 30 degrees to the horizontal. It has been shown that the inclination angle

FIG. 4. Apparent spontaneous washout of air. The analog response to prior injections of air had recovered completely to baseline, indicating all air emboli had been removed. As the cardiac index was increased, this analog response occurred, indicating the passage of air.
of the vessel affects the rising velocity of an air bubble. As the vessel is tilted from a horizontal angle, the velocity will increase up to a point of 40 degrees inclination; further tilting decreases the rising velocity. Therefore, the tilt we applied to the animals may have contributed to air detainment.

When little or no Doppler response occurred in audible or the analog record response following injection (12% of the time), we conclude that air must have been retained at a level cranial to the area of ensonified SVC or that air passed through or was lodged in the SVC in a manner that did not produce motion that would generate Doppler signals. This latter situation could be produced only if air adhered or slowly slid along the vessel wall in “slug” form in such a manner as to have no rapid motion. We do not know whether this occurs in vivo for amounts of air as low as 4 ml with the presence of pulsatile flow. Bunegin et al. described the existence of an air–blood vortex motion in their model in the superior vena cava just outside of the atrial entrance. This vortex produced a “churning” effect of emboli and contributed to their motion and breakage. Consequently, we suspect air emboli passing through the SVC would have motion that would produce Doppler signals. In light of this and our observations that in subsequent injections exaggerated analog responses occasionally occurred (3 out of 16 trials) and in eight instances spontaneous analog responses occurred following increases in CI alone, the first conclusion seems plausible (i.e., at least some of the time air was retained at levels higher than the ensonified SVC).

The exaggerated analog responses we believe were due to the injected air plus air recruited during its passage that had been retained previously somewhere between the dorsal sagittal sinus and the SVC. Spontaneous washout of air emboli with increasing CI also suggests air bubbles that may have been retained by some mechanism (i.e., by retardation as discussed above or by lodgement due to adherence of air to vessel walls) may be dislodged with the increasing force of the blood motion as CI increases. This is consistent with the observations of Chang et al. They found, when microscopically examining the behavior of pulmonary air emboli, that when an air bubble stops within a vessel, it resumes motion again only under increased gradient pressure.

We believe the results of our studies may help explain certain clinical observations. Although a precordial Doppler unit was not used, Ordway described a case in which he believed air emboli had “pooled” in the venous system of a patient for over a day. The patient first suffered a severe symptomatic air embolism due to a disconnected hub on a central venous catheter and then the following day suffered a second symptomatic air embolism when his position was changed from left lateral decubitus to supine. Perhaps the air emboli had been detained by one of the mechanisms described above and the positional change triggered the release of it by unbalancing the detaining forces. One of the authors as well as others commonly have observed prolonged Doppler responses during surgery. In such cases one can not distinguish whether the prolongment is due to air detainment or due to air emboli continuously entering the venous system. Our results are indicative that both can occur.

Wilkins and Albin reported three cases in which air embolism was detected after closure of the scalp incision during craniectomy in the sitting position. The authors suspected air may have entered at the site of attachment to the head of the head-holding fixture. The results of our study indicate the possibility of alternative mechanism. Two of the three patients received 10 cm positive end expiratory pressure (PEEP) during the surgery. PEEP is known to promote a Q increase by depression of air embolism to promote an increase in Q. Also, decreasing the anesthetic agent in preparation for terminating the surgery may promote Q increase. The occurrence of either or both of these two events at the end of surgery may have increased Q, during this time period, resulting in
the spontaneous washout of previously retained air emboli, as we have observed in our dogs with increasing \( Q \). Air emboli washout with increasing \( Q \) also may be a contributing factor in another report describing the occurrence of air embolism at the end of surgeries and observations of air emboli when patients are lowered to the supine position following craniecotomies in the sitting position.\(^\S\) In the latter case the positional change may promote the increase in \( Q \) and washout of previously retained air emboli. In addition, Marshall and Bedford have described that Doppler air sounds often persist after other symptoms have disappeared following a symptomatic air embolism.\(^{15}\) Perhaps this observation also can be explained by prolonged detention, as we have observed can occur in animals.

In further consideration of the clinical relevance of our findings, our results indicate that if the SVC is ensonified by a Doppler monitor, cessation of Doppler air embolism sounds may not necessarily mean air continuously is entering the venous system, as such sounds may arise from retained air. In this regard, probe placement to ensonify only the right ventricle or pulmonary artery may provide a more positive detection site to identify that air is moving through the venous system. Perhaps, the phenomenon of air detention in the SVC with cardiac output reduction offers some natural safety to the patient. For example, if an air embolism is of sufficient magnitude to produce a reduction in cardiac output, this reduction, in turn, would tend to impede further flow of air to the heart by promoting detainment of air at more cranial sites. Within some limits, such action actually may prevent further cardiac output depression or at least reduce the likelihood of complete right ventricular air block.

Our study did not address the question of whether manipulation of cardiac output for the purpose of managing air embolism would have any value. Possibly the avoidance of rapid increases in \( Q \) may be desirable if a patient has had an air embolism. The purpose would be to avoid rapidly washing out retained air into the right ventricle or pulmonary circulation where it may result in obstruction to blood flow. However, we do not know if dangerous volumes of air can be retained in the venous system. On the other hand, ultimate removal of air emboli from the circulation is believed to be primarily by its excretion from the pulmonary circulation through the lung. Therefore, increases in \( Q \) may be indicated to facilitate transportation of all air to the pulmonary circulation for removal. Hopefully, the advantages and disadvantages of manipulation of \( Q \) will be learned in future research.

References


\(^\S\) Bedford RF: Personal communication.