

Pathophysiology of Intravenous Air Embolism in Dogs

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Despite increasing awareness of the clinical incidence of venous air embolism, the pathophysiology of the resultant cardiovascular collapse is still obscure. Since venous air emboli frequently result from gradual aspiration of air into a vein opened surgically, slow infusion (0.01 to 2.00 mg/kg/min) was compared with injection of boluses (25-200 ml; 1.0 to 13.3 ml/kg) of air into the external jugular veins of 52 dogs during various forms of anesthesia. Cardiopulmonary variables measured included heart sounds, respirations, systemic blood pressure, pulmonary arterial and central venous pressures, heart rate, cardiac output, and peripheral resistance with slow infusions. On slow infusion a progressive increase in central venous pressure, an abrupt increase in pulmonary arterial pressure to a plateau, a progressive decrease in peripheral resistance, and a compensatory increase in cardiac output were demonstrated. Blood pressure decreased moderately until compensation was exceeded, at which point blood pressure decreased sharply. Electrocardiographic changes initially involved peaking of the P waves, but later depression of the S-T segment occurred. Changes in heart sounds occurred only when significant cardiovascular decompensation had already occurred.

Changes in physiologic variables on injection of a bolus of air included increase in central venous pressure, a decrease in pulmonary arterial pressure, S-T segment depression, and shock. It is concluded that bolus injection might lead to an air lock in the heart, but slow infusion initially causes a reflex decrease in peripheral resistance, possibly mediated through receptors in the lung. (Key words: Embolism: air. Complications: embolism. Heart: cardiac output; vascular pressures.)

DOCUMENTATION of the incidence of venous air embolism is increasing, especially for such neurological procedures as operations on the posterior fossa with the patient in the sitting position, where the pressure in exposed veins may be less than atmospheric and air may be sucked in if a vein is entered. The mechanism by which venous air embolism leads to cardiovascular collapse is still undetermined. When such embolism occurs clinically, air enters an open vein gen-

erally at a low rate until it suddenly becomes clinically significant.¹⁻⁴ However, most laboratory research on venous air embolism involves air injected in a single large bolus,⁵⁻⁸ so that conclusions may not necessarily be relevant to clinical situations.

It seemed appropriate to study the pathophysiology of venous air embolism induced by both slow infusion and a sudden bolus. In order to test the appropriateness of currently recommended maneuvers for the detection and treatment of clinical venous air embolism, conditions under which such air embolism occurs and how patients are monitored were simulated in dogs. Additional physiologic variables were monitored in order to elucidate observed cardiopulmonary changes.

Materials and Methods

Venous air embolism was induced in 52 mongrel dogs weighing between 10 and 21 kg. Forty-one dogs were anesthetized with halothane following endotracheal intubation, and nine were anesthetized with a combination of α -chloralose, 60 mg/kg, intravenously, and morphine, 2mg/kg, intramuscularly.

Phasic and mean aortic blood pressures were measured through a catheter placed via a femoral artery. Central venous pressure was monitored with a catheter placed through the cephalic vein into the superior vena cava immediately above the right atrium; proper position of the central venous catheter was assured by monitoring either phasic venous pressure or the electrocardiogram using the saline-filled catheter as an electrode.^{2,9,10} Right pulmonary arterial pressure was measured through a catheter inserted via a femoral artery and positioned under fluoroscopic guidance. Heart rate was monitored with a cardiometer.** Respiration was monitored through a transthoracic impedance pneumogram,** which recorded changes in pattern. These values were recorded with an eight-channel recorder.**

Aortic blood flow was monitored in nine dogs by implanting a blood flow transducer around the root of the aortic arch through a thoracotomy incision during general anesthesia. The transducer was protected with a sheet of Dacron mesh sutured around the surfaces in contact with the aortic wall. The cable of the transducer was passed through a subcutaneous tunnel to the skin overlying the posterior portion of the neck.

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A minimum of two weeks was allowed for recovery before the animals were monitored during the induction of venous air embolism. The output signal from the flowmeter was fed into an integrating circuit (summing, capacitance, feedback integrator), and stroke volume was recorded^{††} as a voltage step proportional to the area under the systolic portion of the aortic flow wave. The voltage steps were accumulated and automatically recycled every 4 sec to compute cardiac output.

Peripheral resistance was recorded on-line as the quotient of the mean aortic pressure divided by cardiac output, a function performed by an electronic multiplier/divider. All information was stored on a magnetic tape recorder^{‡‡} for later offline calculations.¹¹

A 16-gauge polyethylene catheter was inserted into the left external jugular vein. Air was infused at various controlled rates of 0.12 to 2.20 ml/kg/min by a Harvard infusion pump. Each infusion was given until changes in physiologic variables occurred, but for no longer than 3 min. When no change occurred, a period of at least 30 min was allowed before increasing the rate of air infusion in order to ensure the stability of control values. When a response occurred and control levels could not be reestablished, the infusions were stopped.

In several groups of dogs, various other manipulations were performed. For example, three animals received sodium pentobarbital, 3.5 mg/kg, prior to instillation of the air embolism. Two animals had procaine blockade of the vagus nerves, and three animals had surgical vagotomy. Three other animals had parasympathetic blockade with atropine, 1 mg/kg. In another three animals, afferent blockade of the tracheobronchial and possibly alveolar receptors in the lung was produced by nebulizing cocaine, 3 ml, 10 per cent, through the endotracheal tube prior to induction of air embolism. In nine animals, the air was instilled into the pulmonary artery rather than the jugular vein to distinguish whether the observed effects were due to the effect of air passing through the lungs or the heart. In nine animals, air embolism was produced during controlled ventilation with a pressure respirator.^{§§}

In 14 dogs the position was varied. Air embolism was induced in the prone, right and left lateral decubitus positions, with the head elevated, and with the head lowered. In six animals, a Gardner G-suit was used to evaluate potential protection against the physiologic effects of air embolism. Those animals in which

values returned to control levels following the final slow controlled injection were studied on injection of large boluses of air into the jugular vein. Boluses ranged from 25 to 200 ml (1.0 to 13.3 ml/kg); during injection, the previously indicated variables were monitored.

The standard deviation and standard error of the mean threshold dose for each of the modalities studied, as well as the control and response values at each infusion rate, and standard deviation and standard error of the percentage increase or decrease between control and response values, were calculated using a computer.^{¶¶} The data for each variable were used to plot a dose-response linear-regression function. The threshold dose, the lowest dose at which a change in the control value occurred, was plotted for each variable.

Necropsies were performed with the animals under water to determine whether air was present primarily in the heart or in the pulmonary circulation.

Results

SLOW INFUSION OF AIR

The first change seen at the lowest rate of air infusion was a characteristic alteration in the pattern of respiration (fig. 1). At a threshold dose of 0.36 ml/kg/min, a characteristic "gasp" occurred (fig. 2). Generally it began 30 sec to 4 min after the start of infusion, with the shorter latency occurring at higher rates of infusion. The gasp consisted of a small cough, followed immediately by a brief expiration and then a long forced inspiration that was held for several sec. A period of apnea lasting from 10 to 30 sec followed. On occasion, it occurred in chains of several gasps. When an infusion was repeated shortly after a gasp was evoked, the latency was less and the gasps were more likely to be multiple.

During the forced inspiration of the gasp, central venous pressure became abruptly negative by an average of 1.2-1.5 torr, and then became positive during apnea. Heart rate and blood pressure correspondingly increased transiently during the forced inspiration and then decreased during the prolonged apnea.

The clinical significance of the gasp was demonstrated in three animals by cannulating the contralateral external jugular vein and leaving the cannula open to the air. Ordinarily, no air was sucked into this cannula when the dog was supine. However, when the gasp was induced, air could be seen entering the jugular-vein cannula during the forced inspiration, corresponding to the sudden decrease in central venous pressure. Although the amount of air enter-

^{††}Clevite Brush Mark 200.

^{‡‡}Honeywell Model 7600 FM.

^{§§}Bird Model VIII.

^{¶¶}General Electric Mark I Computer.

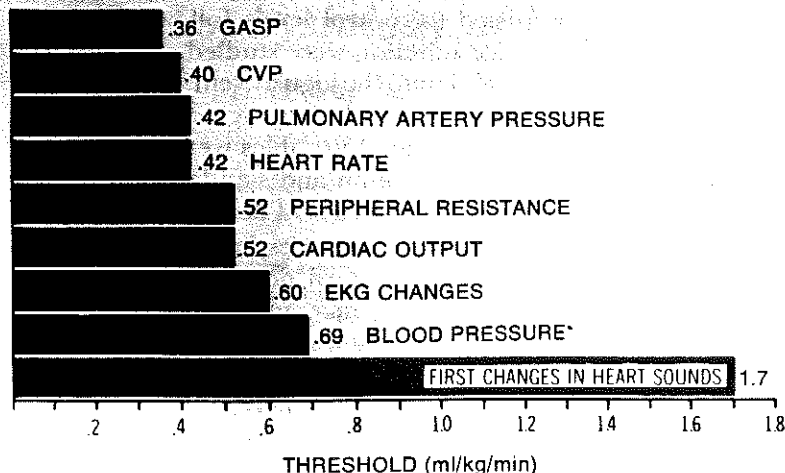


FIG. 1. Thresholds for the earliest changes in the modalities monitored. The first changes in heart sound do not occur until other physiologic changes are well under way.

ing the contralateral jugular vein was not measured, it proved to be a fatal bolus, even when initially air had been infused only at a threshold rate to cause a gasp. This closely simulated the clinical situation that may occur when a small vein is opened intraoperatively with spontaneous respiration. A minimal air embolism may precipitate the gasp reflex, which, in turn, causes a large bolus of air to be sucked into the yet open vein, leading to death. Consequently, the nature of the gasp is significant, and an attempt was made to demonstrate the afferent mechanism involved.

The threshold for the gasp was not changed by unilateral vagotomy. After bilateral vagotomy, a pat-

tern of respiration consisting of forced hyperventilation developed, which made it impossible to determine whether any change in respiration occurred with infusion of air. Atropine, 1 mg/kg, caused an increase in the vigor of the gasp. To determine whether the gasp was mediated through a cardiac or pulmonary afferent mechanism, the air was infused through a catheter in the pulmonary artery. The thresholds for the gasp and the other measured physiologic variables were identical on infusion into the pulmonary artery and on infusion into the external jugular vein, demonstrating that the initial reflex influence is in the pulmonary vascular bed.

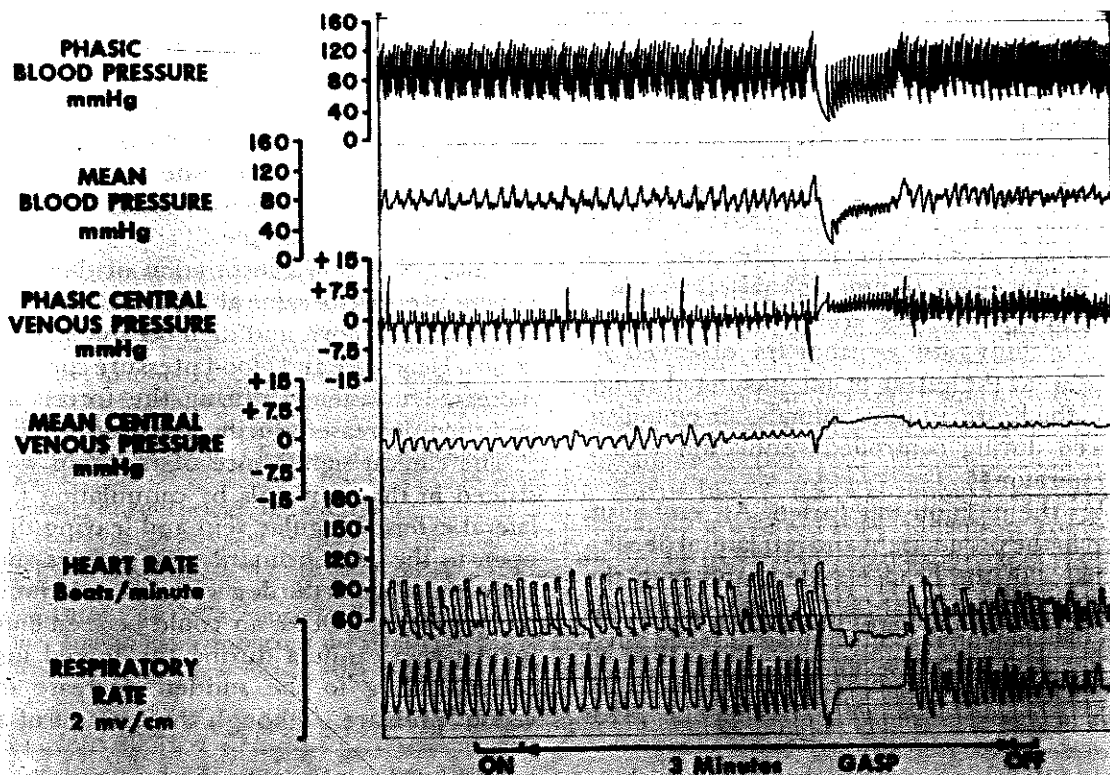


FIG. 2. When a reflex gasp occurs, there is a sudden negative central venous pressure, followed by a period when respiration and heart rate change. Infusion rate 0.36 ml/kg/min.

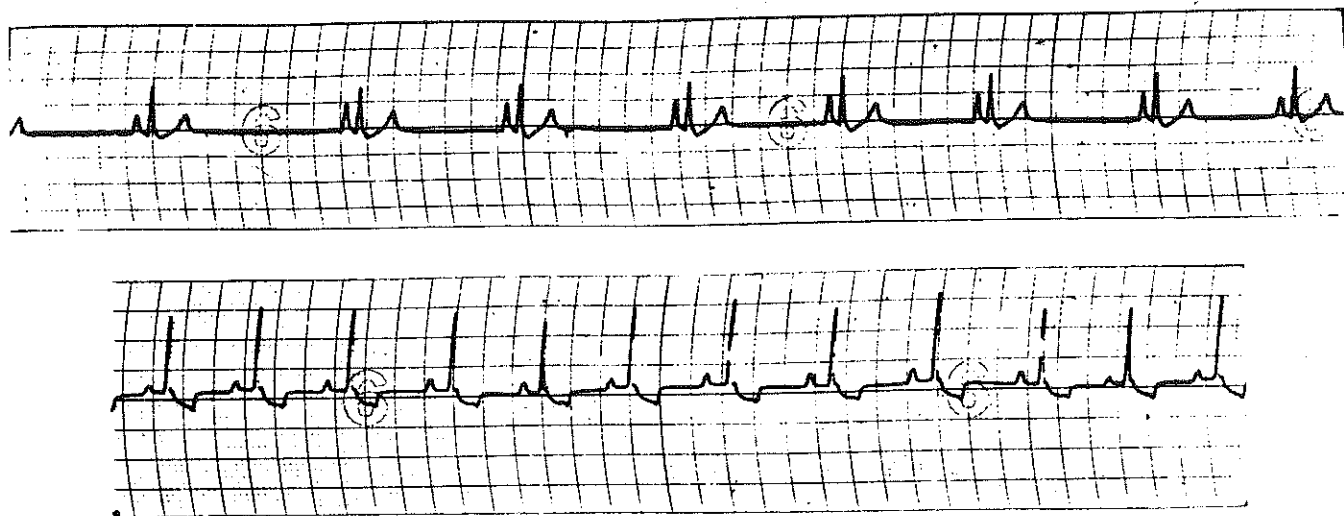


FIG. 3. A, the first change in the electrocardiogram is peaking of the P wave at 0.6 ml/kg/min. B, S-T segment depression does not occur until a rate of 1.2 ml/kg/min has been reached.

To localize the afferent mechanisms further, cocaine, 3 ml, 10 per cent, was nebulized through the respirator to anesthetize the exposed tracheobronchial tree and possibly the air-containing portions of the lungs. This completely blocked the gasp reflex, further indicating that the gasp is mediated via receptors in the lung. The same amount of cocaine injected intravenously did not alter the threshold or the characteristics of the gasp. As further evidence of the reflex nature of the gasp, it was demonstrated that the threshold dose of air infusion was markedly increased with relatively modest doses of sodium pentobarbital. A dose of 3.5 mg/kg increased the threshold to 1.2 ml/kg/min from a control of 0.36 ml/kg/min.

The presence of an endotracheal tube did not alter the threshold at which the gasp occurred, nor did it affect the change in the central venous pressure during the gasp. It was possible to prevent the gasp reflex by substituting halothane anesthesia for α -chloralose and morphine. Of course, when respirations were controlled in an animal paralyzed by succinylcholine, no gasp could be seen, which prevented additional air from being sucked into an open vein. Other physiologic changes were unaltered when the gasp was blocked by any of these methods.

Electrocardiographic changes first appeared in all dogs at a mean threshold infusion of 0.6 ml/kg/min. The first change was peaking of the P wave (fig. 3A). With higher rates of infusion there was no further change in the electrocardiogram until a mean dose of 1.22 ml/kg/min caused depression of the S-T segment (fig. 3B). No further change in the EKG was seen with higher rates of infusion until other cardiovascular effects became profound.

Central venous pressure increased 20 per cent at a mean threshold of 0.4 ml/kg/min (fig. 4). With in-

creasingly large doses of air, central venous pressure increased progressively. A plateau representing a threefold increase occurred between 0.9 and 1.2 ml/kg/min. Above that rate, another progressive increase in central venous pressure was demonstrated, reaching a maximum of 18 times control values at an infusion of 2 ml/kg/min. Right pulmonary arterial pressure increased 25 per cent at 0.42 ml/kg/min (fig. 4). The pressure increased abruptly to reach a maximum of three times control levels at 0.46 ml/kg/min, but did not increase significantly beyond that, even with rates of infusion as high as 2 ml/kg/min.

Heart rate increased 18 per cent at a threshold dose of 0.42 ml/kg/min. With successively higher rates of infusion, heart rate increased twofold. However, at infusion rates greater than 1.52 ml/kg/min, heart rate decreased steadily to less than control levels as cardiovascular decompensation occurred. Although blood pressure decreased gradually with increasing doses of air, significant decreases did not occur with infusion rates greater than 1.7 ml/kg/min (fig. 4). At a rate of 2 ml/kg/min, blood pressure decreased to 25 per cent of control values.

Peripheral resistance decreased 15 per cent between infusion rates of 0.52 and 1.2 ml/kg/min (fig. 5). Above that rate it decreased abruptly by 75 to 85 per cent. It decreased further at doses above 1.6 ml/kg/min.

Aortic blood flow increased 18 per cent at an infusion of 0.76 ml/kg/min (fig. 5). Successively higher rates caused gradually increasing aortic flow until it doubled at a rate of 1.5 ml/kg/min. At higher infusion rates, there was no further increase. The threshold for significant changes in stroke volume was 0.4 ml/kg/min, at which a 4 per cent mean increase occurred. The increase in stroke volume was linearly related to the increase in infusion rates to a dose of 1.5 ml/kg/

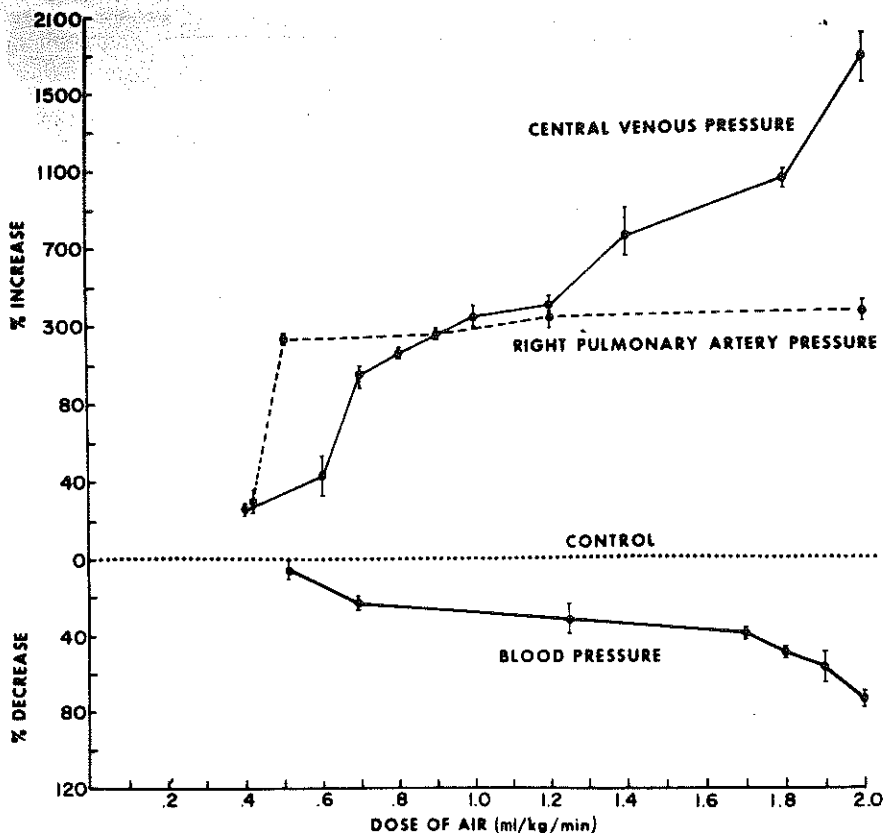


FIG. 4. Right pulmonary arterial pressure increases markedly with relatively small venous air embolism but reaches a plateau above which it does not increase.

min, where an 80 per cent mean increase in stroke volume was recorded.

In ten animals aspiration of air from an additional catheter inserted into the right atrium was attempted with an infusion of air, 120 ml, at a rate of 2 ml/kg/min. A mean value of 60 ml air was recovered, which returned the circulatory changes to control levels, and all animals survived.

Heart sounds monitored by an attentive experienced anesthesiologist through an esophageal stethoscope demonstrated no change until a mean threshold rate of infusion of 1.7 ml/kg/min was reached. This produced a tinkling "drum-like" sound. The classic "mill-wheel" murmur did not occur until a mean infusion rate of 1.96 ml/kg/min was reached.

BOLUS INFUSION OF AIR

The gasp that was so characteristic at slow rates of infusion was not seen when boluses of air of 25 to 200 ml were injected. With rapid injection of 25 ml, hyperpnea was seen. When a 75-ml bolus was injected, a brief period of hyperpnea was followed by a period of apnea corresponding to a significant decrease in blood pressure; after 30 sec, a second period of hyperpnea occurred, followed sometimes by profound respiratory depression. The final period of respiratory depression was seen consistently when the bolus of air

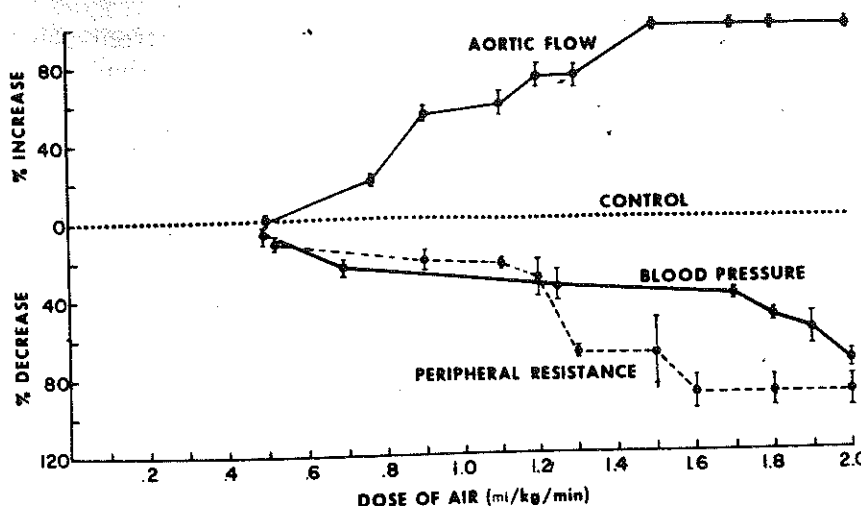
was 125 ml or greater, and usually signaled a fatal outcome.

An increase in central venous pressure was observed with a bolus of air as small as 25 ml. With increasingly larger boluses there was a linear increase in central venous pressure, so that a 150-ml bolus of air resulted in a mean central venous pressure of 54 torr. With boluses larger than that, the increase in central venous pressure was less.

No change in heart rate was seen until injection of a 75-ml of bolus air, which caused a mean increase of 32 per cent. As progressively larger boluses were injected, heart rate increased in a linear fashion; heart rate doubled transiently following rapid injection of 200 ml air. With a 25-ml bolus of air, mean control blood pressure decreased 31 per cent. When progressively larger boluses were injected, there were progressively greater decreases in blood pressure. The peaking of the P waves observed during slow infusion was not seen when boluses were injected. However, even when a 25-ml bolus of air was injected, S-T segment depression occurred. A bolus of 100 ml air produced supraventricular tachycardia. With the rapid injection of 200 ml air, fatal ventricular tachycardia was consistently seen.

In contrast to the significant increase in right pulmonary arterial pressure even at low rates of gradual infusion, the earliest change in mean pressure, a 20

FIG. 5. Aortic flow and peripheral resistance change reciprocally to maintain the blood pressure slightly less than control values. Above 1.6 to 1.8 ml/kg/min, compensation fails and blood pressure decreases.



per cent decrease, did not occur with a bolus of less than 100 ml. Although pulmonary arterial systolic pressure decreased significantly at that dose, there was an increase in diastolic pressure. At the same dose, a significant decrease in systemic blood pressure and a striking increase in central venous pressure also occurred. Although the "drum-like" murmur was heard when a 25-ml bolus of air was injected rapidly, the classic "mill-wheel" murmur did not occur until a fatal 200-ml bolus was injected. Increasing amounts of air caused the murmur to become louder, but the character of the murmur did not change further.

EFFECTS OF OTHER MANEUVERS

In order to evaluate reports that changing the patient's position might afford protection from the effects of air embolism,¹²⁻¹⁴ changes in physiologic modalities were measured with the animals in various positions. Slow controlled infusions of air were given to dogs in the prone, erect, left lateral decubitus, and right lateral decubitus positions, in addition to the supine position reported above. There was no significant difference in either the threshold or the linear-regression curves in any of these positions. However, differences were observed with the animals in the head-down position. Heart rate increased linearly to a maximum value 60 per cent above control at an infusion rate of 1.5 ml/kg/min, but the increase was less at higher infusion rates. Other variables changed even less. Central venous pressure first increased with an infusion rate of 0.36 ml/kg/min and reached a maximum increase of 37 per cent with an infusion rate of 2.2 ml/kg/min. This is in marked contrast to the dramatic increases in central venous pressure seen with the animals in the supine, prone, lateral decubitus, or erect positions. The changes in both the electrocardiogram and heart sounds were the same for the head-down position as for other positions, and the gasp was seen at the same threshold. The first sig-

nificant change in blood pressure with the animals in the head-down position was not seen until an infusion rate of 0.7 ml/kg/min, and only a slight decrease in blood pressure occurred as successively larger infusion rates were employed. At a rate of 2 ml/kg/min, blood pressure decreased only 39 per cent, and it recovered promptly when air infusion was discontinued.

Upon initial inflation of the G-suit, an increase of 0.75 torr in central venous pressure was seen, but this was not statistically significant or sustained for more than a few minutes. There was no significant difference in any of the variables monitored during either slow infusion or bolus injection of air with and without the G-suit.

Values of pH , P_{aCO_2} and P_{aO_2} were determined in 180 arterial blood samples taken from 14 dogs at the time of the gasp and 3 minutes thereafter. During the gasp, pH increased from a control of 7.32 to a mean of 7.37. P_{aCO_2} decreased correspondingly from a control of 40.1 torr to a mean of 30.8 torr. P_{aO_2} did not change significantly from a control of 90 torr to 89 torr at the time of the gasp. Three minutes after the gasp, however, P_{aO_2} had decreased significantly to 80 torr and P_{aCO_2} had increased markedly to 46.8 torr, with a resultant decrease in pH to 7.29, reflecting the period of apnea.

Necropsies showed that animals dying after slow infusion had air dispersed generally throughout the cardiopulmonary circulation. However, animals dying after rapid injection of boluses had air primarily in the right side of the heart.

Discussion

Although the peculiar gasp that accompanies clinical venous air embolism is not uncommon^{15,16} and has been witnessed by one of the authors (PLG) several times, it is hardly mentioned in the literature. It resembles the "chokes" of decompression sickness in

character and physiologic significance.¹ Demonstration that the gasp reflex may induce a sudden negative intravenous pressure in animals with spontaneous respiration has considerable clinical significance. A sudden sucking of a large bolus of air into the vein may convert a treatable slow-infusion type of air embolism into a fatal bolus. The demonstration that the gasp is reflex in origin suggests that it can be avoided during surgical procedures by controlling respiration in patients undergoing operations with significant risk of venous air embolism.^{9,17-19} Allowing the patient to breathe spontaneously "to see whether respiration is affected" during brain-stem manipulation exposes the patient to significant risk, for the most part unnecessary, since other methods such as electrocardiography can be used to detect excessive brain-stem manipulation.²⁰⁻²³

Of those modalities examined in the study, the earliest physiologic change demonstrating venous air embolism in the dog was in the electrocardiogram. Although this may be peculiar to the species, attention should be drawn to the peaking of the P waves, which is the first electrographic change with slow infusion, and to the depression of the S-T segment, which occurs later. It is not until very late that a change in rhythm occurs, so the waveform on the cardiac monitor is of paramount importance.²⁴

Central venous pressure increases significantly during both slow and rapid infusion of air,^{5,25} but it is of limited value in making a specific diagnosis. The time-honored technique of listening to the heart sounds with a precordial or esophageal stethoscope for the classic "mill-wheel" murmur^{12,13,26,27} has been demonstrated to be totally inadequate. It is only after cardiovascular deterioration has been established that there is any change in heart sounds. Even then a "drum-like" murmur occurs much earlier than the typical "mill-wheel" murmur. Although monitoring the heart sounds is desirable for other reasons, it is inadequate to detect venous air embolism early enough to abort a fatal outcome consistently, and one should employ a precordial Doppler monitor.^{7,10,14,15,25,28,29}

A review of the changes in various physiologic modalities indicates that at low rates of infusion blood pressure decreases moderately and heart rate increases. Central venous pressure shows a progressive increase, whereas pulmonary arterial pressure increases quite early to a plateau. The decrease in peripheral resistance is initially compensated for by an increase in aortic blood flow to maintain blood pressure at an only slightly lowered level despite the progressive decrease in peripheral resistance. However, at successively higher infusion rates, cardiac output reaches a maximum, after which blood pressure decreases significantly.

Thus, we see three different phases of physiologic

effects of venous air embolism. The initial changes take place at thresholds between 0.4 and 0.6 ml/kg/min. An increase in cardiac output compensates for the decrease in peripheral resistance, so blood pressure is only moderately decreased. Between approximately 1.2 and 1.8 ml/kg/min, compensation begins to fail, blood pressure decreases further, and S-T segment changes are first seen on the electrocardiogram. When the infusion was discontinued after 3 min, the dogs generally survived in our study. However, at infusion rates greater than 1.8 ml/kg/min blood pressures decreased abruptly, the animals frequently went into profound shock before the end of the 3-min infusion, and most did not recover.

The initial abrupt increase in pulmonary arterial pressure appeared to result from constriction of the intrapulmonary vasculature, since it occurred with amounts of air too small to cause widespread mechanical occlusion. The later plateau may represent the opening of shunts within the lung, a concept consistent with the changes in arterial blood-gas values.³⁰

These observations lead to the conclusion that the physiologic response to slow infusion of air resulting in venous air embolism may be initiated via a reflex in the lung. Slow infusion directly into the pulmonary artery demonstrates that cardiovascular collapse can occur even with no air in the heart on the first pass, suggesting that the receptors for such cardiovascular reflexes reside in the lung. Peripheral resistance decreases and intrapulmonary vascular resistance increases, at first compensated for by increased cardiac output but leading to shock when compensation is exceeded.

This differs from the physiologic mechanisms observed with a bolus of air, wherein cardiovascular collapse is due primarily to an air lock in the right side of the heart.^{6,12,18,31} The gasp reflex is not seen on injection of a bolus, nor is peaking of the P wave. More significantly, the increase in pulmonary arterial pressure that characterizes a slow infusion does not occur. The decrease in pulmonary arterial pressure suggests that a bolus injection causes an air lock proximal to the pulmonary artery, whereas with slow infusion the impairment to blood flow is distal to the pulmonary artery. This concept is further documented by the finding on necropsy that the air from a bolus was in the right side of the heart, but the air from a slow infusion was found more consistently in the lungs. This would explain the failure of the left lateral decubitus position to protect the animal from the effects of slow infusion.^{6,12} The animal was protected from shock only in the head-down position. In all likelihood, many clinical episodes of venous air embolism result from combinations of slow infusion and rapid introduction of a bolus. Thus, in the operating room, turning the patient on his side when air embolism

occurs may offer only a minor advantage, offset partially by the hazard from excessive manipulation of a patient with an open incision. Other forms of treatment might more conveniently be initiated.^{2,3,5,6,8-10,14,29,31}

The use of the G-suit did not alter the effects of venous air embolism, nor did it increase central venous pressure for a prolonged period. It cannot be recommended for treatment or prevention of venous air embolism.³² However, it may help in the treatment of shock in general.

The dramatic reversal of shock with aspiration of air from the atrium is further laboratory evidence of the effectiveness of this clinical treatment.^{2,9,10,33,34}

Thus, it has been demonstrated that the pathophysiology of slow infusion of air into an open vein differs from that of sudden introduction of bolus of air. With slow infusion, cardiovascular changes are a reflection of a sympatholytic reflex initiated by receptors in the pulmonary vasculature, leading to shock from a decrease in peripheral resistance. A bolus of air, on the other hand, causes an air lock in the heart and results in failure of cardiac output. A reflex gasp, which occurs upon slow infusion, can cause a fatal bolus of air to be sucked into an open vein. Such maneuvers as aspiration of air from the atrium and lowering the head can be effective treatment of venous air embolism.

References

1. Bove AA, Hallenbeck JM, Elliot DH: Circulatory responses to venous air embolism and decompression sickness in dogs. *Undersea Biomed Res* 1:207-220, 1974
2. Munson ES, Paul WL, Perry JC, et al: Early detection of venous air embolism using a Swan-Ganz catheter. *ANESTHESIOLOGY* 42:223-226, 1975
3. Perry JC, Munson ES, Malagodi MH, et al: Venous air embolism prophylaxis with a surface-active agent. *Anesth Analg (Cleve)* 54:792-799, 1973
4. Richardson HF, Coles BC, Hall GE: Experimental gas embolism: I. Intravenous air embolism. *Can Med Assoc J* 36:584-588, 1937
5. Brechner VI, Bethune RWM: Recent advances in monitoring pulmonary air embolism. *Anesth Analg (Cleve)* 50:255-261, 1971
6. Durant TM, Long J, Oppenheimer MJ: Pulmonary (venous) air embolism. *Am Heart J* 33:269-281, 1947
7. Edmonds-Seal J, Prys-Roberts C, Adams AP: Air embolism. A comparison of various methods of detection. *Anaesthesia* 26:202-208, 1971
8. Munson ES: Effect of nitrous oxide on the pulmonary circulation during venous air embolism. *Anesth Analg (Cleve)* 50:785-793, 1971
9. Michenfelder JD, Martin JT, Altenburg BM, et al: Air embolism during neurosurgery. An evaluation of right-atrial catheters for diagnosis and treatment. *JAMA* 208:1353-1358, 1969
10. Tinker JH, Gronert GA, Messick JM Jr, et al: Detection of air embolism, a test for positioning of right atrial

- catheter and Doppler probe. *ANESTHESIOLOGY* 43:104-106, 1975
11. Ferrario CM, McCubbin JW, Page IH: Hemodynamic characteristics of chronic experimental neurogenic hypertension in unanesthetized dogs. *Circ Res* 24:911-912, 1961
12. Marshall BM: Air embolus in neurosurgical anaesthesia: Its diagnosis and treatment. *Can Anaesth Soc J* 12:255-261, 1965
13. Michenfelder JD, Terry HR, Daw EF, et al: Air embolism during neurosurgery. *Anesth Analg (Cleve)* 45:390-395, 1966
14. Albin MS, Babinski M, Maroon JC, et al: Anesthetic management of posterior fossa surgery in the sitting position. *Acta Anaesthesiol Scand* 20:117-128, 1976
15. Maroon JC, Goodman JM, Horner TG, et al: Detection of minute venous air emboli with ultrasound. *Surg Gynecol Obstet* 127:1236-1238, 1968
16. Pattison WJ: End-tidal carbon dioxide levels in the early detection of air embolism. *Anaesth Intensive Care* 3:58-59, 1975
17. Michenfelder JD, Gronert GA, Rehder K: Neuroanesthesia. *ANESTHESIOLOGY* 30:65-100, 1969
18. Mortimer PLF: Controlled respiration in neurosurgical anaesthesia. *Anaesthesia* 14:205-207, 1959
19. Mortimer PLF: Anaesthesia for neurosurgery. *Lancet* 2:768-769, 1960
20. Galloon S: Controlled respiration in neurosurgical anaesthesia. *Anaesthesia* 14:223-230, 1959
21. Lewis JM, Rees GAD: Electrocardiography during posterior fossa operations. *Br J Anaesth* 36:63-64, 1964
22. Millar RA: Neurosurgical anaesthesia in the sitting position. *Br J Anaesth* 44:495-505, 1972
23. Whitby JD: Electrocardiography during posterior fossa operations. *J Anaesth* 35:624-630, 1963
24. Michenfelder JD: Multiple episodes of air emboli: Report of a case. *Anesth Analg (Cleve)* 47:355-356, 1968
25. Buckland RW, Manners JM: Venous air embolism during neurosurgery. A comparison of various methods of detection in man. *Anaesthesia* 31:633-643, 1976
26. Martin JT: Neuroanesthetic adjuncts for surgery in the sitting position: I. Introduction and basic equipment. *Anesth Analg (Cleve)* 49:577-587, 1970
27. Shivpuri DN, Viswanathan R, Sharma ML, et al: Pre-symptomatic diagnostic sign of venous air embolism. *J Indian Med Assoc* 33:86, 1959
28. Maroon JC, Albin MS: Air embolism diagnosed by Doppler ultrasound. *Anesth Analg (Cleve)* 53:399-402, 1974
29. Michenfelder JD, Miller RH, Gronert GA: Evaluation of an ultrasonic device (Doppler) for the diagnosis of venous air embolism. *ANESTHESIOLOGY* 36:164-167, 1972
30. Oyma Y, Spencer MP: Cardiopulmonary effects of intravenous gas embolism; With special reference to fate of intravascular gas bubbles. *Jpn Circ J* 35:1541-1549, 1971
31. Ericsson JA, Gottlieb JD, Sweet RB: Closed chest cardiac massage in the treatment of air embolism. *N Engl J Med* 270:1353-1354, 1964
32. Martin JT: Neuroanesthetic adjunct for surgery in the sitting position. II. The antigravity suit. *Anesth Analg (Cleve)* 49:588-593, 1970
33. Stallworth JM, Martin JB, Postelthwait RW: Aspiration of the heart in air embolism. *JAMA* 143:1250-1251, 1950
34. Senn N: An experimental and clinical study of air embolism. *Ann Surg* 2:22-50, 1885