Experimental Pulmonary Air Embolism in Dogs

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Air infused into the jugular vein of dogs at a constant rate for one hour produced transient hypotension, modest elevation of the systemic venous pressure and a considerable fall of the arterial oxygen tension. All of these measurements returned almost to normal on the termination of the infusion. A lethal rate of infusion, 0.69 ml of air per kg of body weight per minute, produced heart failure with a decided rise of systemic venous pressure and fall of blood pressure. The pre-failure oxygen pressure did not fall to a lethal level. Six and a half minutes was the longest time that the characteristic murmur could be heard after the cessation of infusion of non-fatal doses of air.

Air embolism has been reported in many clinical situations, and among the causes are abortion, douching, gunshot wound of the neck, operation on the bladder, root canal therapy, craniotomy with pressurized drill, neurosurgical procedures, operations on the head and neck, antrum lavage, air insufflation of the bladder and joints, pneumoperitoneum, vaginal insufflation with powder blowers, and blood donations. Death does not always result from air embolism, particularly when it is diagnosed immediately and vigorously treated.

Many studies have been done with animals to determine the cause of death in air embolism of the right heart. Richardson injected air into the veins of dogs and summarized his work conclusively: "The pulmonary capillary bed acts as an effective barrier to intravenous air. Death occurs from failure of the pulmonary circulation." Jacques observed: "The cause of death in massive pulmonary embolism presents no problem. It results from pure mechanical blockage of the lesser circulation. This results in an elevation of pulmonary artery pressure, a fall in systemic pressure, right heart dilatation and cardiac failure."

The present study was done with dogs to determine if a low arterial oxygen tension was the cause of heart failure in right heart air embolism. Progressively larger doses of air were introduced into the jugular veins of dogs until the lethal rate of infusion was reached.

Method

Each dog was anesthetized with thiopental, intubated and hyperventilated with oxygen-enriched air mixture at a terminal inspiration pressure of 20 mm of mercury. An esophageal stethoscope was placed to monitor the heart sounds. The right femoral artery was punctured with a 16-gauge...
plastic needle for determining arterial pressures with a mercury manometer. The pressures were expressed as the mean of each reading. The left external jugular vein was ligated and catheterized with a 6 mm plastic tube advanced as far as the superior vena cava for determining the systemic venous pressure with a water manometer. The readings were expressed as averages in millimeters of water. The position of the tip of the catheter was checked at postmortem examination for the exact zero of the venous pressure. The right external jugular vein was punctured with a 16-gauge plastic needle for the infusion of air. The vessel was left intact to allow a normal flow of blood. The left carotid artery was ligated and catheterized with a 3 mm catheter which was introduced to the arch of the aorta for collection of blood to determine oxygen tensions.

Each dog was suspended by the muzzle so that the upper half of the body was upright. Air was infused for one hour into the right jugular vein at a constant rate by drip displacement of air from 30 ml syringes. The rate of infusion was increased in successive animals from 0.13 ml of air per kg of body weight per minute to 0.69 ml per minute. The doses in eight animals were 0.13, 0.24, 0.31, 0.36, 0.37, 0.51, 0.61 and 0.69 ml per kg per minute. Arterial blood samples for oxygen determination were taken 15 minutes before infusion began, immediately before infusion and every 15 minutes thereafter including a final sample 15 minutes after the infusion was stopped. Eight young normal animals were included in this series.

In a second series of dogs a microphone was sutured under the skin over the precordial area, and tape recordings were made during the constant infusion of air into the jugular vein.

Results

The seven dogs receiving air at the rate of 0.13 to 0.61 ml per kg per minute did not die during the experimental period. The variations of the arterial oxygen tension, systemic venous pressure and systemic arterial pressure of these animals are shown graphically (Charts 1, 2 and 3).

The systemic arterial oxygen tension fell in every instance during the infusion but rose after the infusion was stopped. The lowest level of oxygen tension was 47 mm of mercury. The tension did not rise to the pre-infusion normal in any animal during the 15-minute recovery period. The 15-minute post infusion oxygen tension varied from 74 to 119 mm of mercury. The average was 100 mm.

In all animals, the systemic arterial pressure fell immediately after the infusion was started. The
lowest level to which the arterial pressure fell was 32 mm of mercury. When 30 minutes of infusion had elapsed, the blood pressure had begun to rise in all animals and had reached a near normal level by the end of the infusion. The systemic venous pressure rose rapidly after the start of the infusion. The highest level was 84 mm of water. Within 30 minutes after the start of infusion, the venous pressure in all seven animals had begun to fall but remained somewhat elevated until the cessation of infusion. After the air infusion stopped the venous pressure quickly fell to the pre-infusion normal.

The recordings of the animal that received air at a rate of 0.69 ml per kg per minute and died are shown graphically in Chart 4. The systemic arterial pressure fell initially to 25 mm of mercury, which was a lower level than was recorded for the other animals. Then the arterial pressure rose to 50 mm of mercury before it fell to a terminal level. The venous pressure rose steadily to 262 mm of water within 18 minutes and fell to 152 mm at the time the arterial pressure had fallen to a terminal level. The systemic arterial oxygen tension fell to 47 mm of mercury as the arterial pressure and venous pressure went to terminal levels. The animal died within 20 minutes from the start of the air infusion.

In the series of dogs where recordings of the heart sounds were made, the lowest rate of infusion which altered the normal heart sounds was 0.2 ml per kg per minute. The sound was a "tinkle" similar to that of water being poured into a half empty jug. As the volume of air increased, the sound of air in the heart became a "squish," and finally when the larger volumes were injected the sound became "chuck" with each heart beat. The sound became discernible in 17 minutes with the 0.36 ml per kg per minute rate of injection, in nine minutes with the 0.5 ml rate and in two minutes with the 0.61 ml rate. When the infusion of air was stopped, the air murmur began to disappear and became fainter and fainter until it could no longer be heard. Six and a half minutes was the longest that an air murmur persisted after the cessation of infusion of a non-lethal dose of air.

Discussion

Systemic Arterial Oxygen Tension

As all the animals had artificial respiration, there was no indication of respiratory changes. Studies with other dogs27 have shown that an end respiratory pressure of 20 mm of mercury and minute rate of 14 to 16 produced a systemic arterial partial pressure of carbon dioxide of near 25 mm of mercury. In this study, lethal or near-lethal rates of infusion occasionally caused the animals to attempt to breathe despite the hyperventilation. This suggests that the level of carbon dioxide had built up to or above normal.
Mandelbaum\textsuperscript{14} showed that an immediate rise of pulmonary arterial pressure follows embolization of the lung. However, he also showed that the embolic gas is not excreted in the lung but passes through to form bubbles in the pulmonary veins. The rise of pulmonary artery pressure may be due to mechanical blockage in the capillaries, but Hampton\textsuperscript{11} showed that the rise of pulmonary artery pressure after embolization can be prevented by sectioning the vasi. Perhaps the normal pulmonary arterial pressure which is maintained by sectioning the vasi is the result of an opening of arteriovenous channels. Niden\textsuperscript{19} demonstrated such shunts by injecting glass beads into the pulmonary circulation of dogs. He stated: “The perfused lung shows arteriovenous communications that are at least 420 micra in diameter.” Richardson\textsuperscript{22} found that in air embolism “there was a concentration of red cells in the capillaries and an absence of cells in the veins,” phenomena which he attributed to pulmonary edema, although they could be due to constriction of the pulmonary capillaries.

The fall of systemic arterial oxygen tension observed in this study can be explained by the presence of pulmonary edema and by the opening of arteriovenous shunts. Even before the sound of air could be heard in the heart, crepitant rales were audible through the esophageal stethoscope. During preliminary studies, it was found that animals receiving lethal or near-lethal doses of air developed so much pulmonary edema that thin fluid bubbled out of the endotracheal tube. Other investigators have shown that air embolism produced pulmonary edema\textsuperscript{14,22} and proliferation of the arterial intima.\textsuperscript{1}

The return of the arterial oxygen toward normal after the cessation of air infusion can be explained as due to a reversal of the processes that produced the lowering of the oxygen tension. There probably remained a residual edema and that is why the oxygen tension did not return completely to normal.

In humans\textsuperscript{17,50,21} as well as in animals\textsuperscript{6,10} life has been maintained for many hours with an arterial oxygen tension of 25 mm of mercury. The arterial oxygen level of the dogs in the present study fell no lower than 47 mm of mercury; it was down to 22 mm of mercury only at death in the dog that had heart failure. In right heart air embolism produced in this study there was a continued partial oxygenation of the blood that passed through the lungs. The level of arterial oxygen was sufficient to maintain life. Therefore a reason other than low arterial oxygen tension must be found to explain the heart failure.

Durant\textsuperscript{2} injected air into thoracotomized dogs and found an area of ischemia “just to the right of the lower reaches of the anterior descending branch of the left coronary artery” when right ventricular dilatation occurred. Durant also presented electrocardiograms showing ischemic changes of the T wave and the ST segment. Electrocardiograms of dogs in our preliminary studies also had deep inversions of the T waves, which returned to normal after the cessation of air infusion. Therefore we can assume that cardiac dilatation produces right heart ischemia. Another factor contributing to the ischemia of the right ventricle was failure of the heart to increase the cardiac output and coronary perfusion by increasing the heart rate. In fact, in every animal bradycardia developed shortly after the infusion of air began. The rates almost halved in each instance during the infusion and increased after the infusion was stopped. In the animals that died from large doses of air, the pulse gradually slowed until effective beats ceased. In none of the animals did ventricular fibrillation develop until the heart was manipulated during the resuscitation efforts, and ventricular fibrillation then was not uniformly produced.

Systemic Arterial Pressure

Preliminary studies of air embolism showed that the fall in systemic arterial pressure reversed itself within 30 minutes so an arbitrary experimental period of one hour was chosen. The return of blood pressure toward normal during the end of the hour of infusion can be explained as due to the reflex opening of arteriovenous shunts\textsuperscript{11} and greater return of blood to the left side of the heart. However, there is also the probability that systemic vascular reflexes caused a drop of pressure early and then raised the pressure later. In addition, the return of the arterial pressure during the last half of the infusion may have been due to a reflex release of catecholamines by hypoxia.

Systemic Venous Pressure

The rise in venous pressure and sustained moderate elevation during the infusion was consistent with the idea of mechanical obstruction in the lung. It is surprising that the level of venous pressure did not rise higher in the near-lethal doses
of air. The drop of venous pressure to the pre-injection level further substantiates the claim that air rapidly leaves the heart even in the upright position at these rates of infusion.

Failure of Normal

The systemic venous pressure rose above a normal level in the animal receiving 0.69 ml of air per kg of body weight per minute. The abnormal elevation occurred after the systemic arterial pressure had fallen below 40 mm of mercury and even though the arterial pressure rose to 50 mm, the venous pressure continued to rise. Two abnormal animals were infused with air and their courses were quite similar to that of the normal animal that had heart failure. The abnormal animals were old dogs, as evidenced by the front lower incisors being worn down almost to the gum. They were infused with 0.4 and 0.44 ml of air per kg per minute. The systemic arterial blood pressure in both fell to below 40 mm of mercury within 18 minutes after the start of infusion, at which time the systemic venous pressures were 70 and 120 mm of water but the venous pressures continued to rise to 282 and 245 mm of water. Shortly after these elevated levels were reached, the arterial pressures fell to zero and the venous pressures fell to 150 and 130 mm of water. At no time did the arterial oxygen pressure fall below 64 mm of mercury in the old dogs.

Additional Observations

All the studies in this series were acute experiments. Therefore there was no opportunity to observe the late effects of capillary obstruction described by Mendelbaum and Richardson. These late complications were pulmonary congestion, atelectasis, pulmonary edema and broncho-pneumonia.

Occasionally air could be heard as a bubbling sound when it passed down the jugular vein. The bubbling occurred only during the expiratory phase of the respirator. The valve used was a non-rebreathing valve which allowed the positive pressure of the respirator to inflate the lungs; but expiration was directed to the atmospheric pressure. There was no creation of a negative intrathoracic pressure by the respirator. As the infusion of air was by water displacement of air, a positive infusion pressure forced the air to overcome any rise of venous pressure. When a small column of water was placed in the plastic infusion tubing, it moved along with the infused air and only moved during the expiratory phase of the respirator. The positive phase of the respirator prevented any infusion of air during respiratory inflation.

Richardson observed that the level of the systemic arterial blood pressure before infusion determined the resistance of the dog to the infusion of air. We had the same impression and noted that the dog receiving 0.61 ml of air per kg per minute had an initial blood pressure of 142 mm of mercury and the air murmur cleared in two minutes, whereas the dog receiving 0.51 ml per kg per minute had an initial arterial pressure of 92 mm of mercury and the air murmur did not clear until six and a half minutes had elapsed.

In other experiments, we found that 0.3 ml of air per kg per minute caused the death of a dog whose chest had been opened. Durant quickly injected large volumes of air and found that smaller volumes produced fatalities in dogs with open chests but larger volumes did not produce fatalities in dogs with closed chests. The stress and failure of the heart following air embolism of the right heart are influenced by many factors. Richardson, Mandelbaum and Boerema showed that the volume of air and the speed of injection are important factors in the production of heart failure. The larger the volume of air and the more rapidly it is injected, the more likely failure. Also the partially collapsed lungs following thoracotomy increase the likelihood of fatality from air embolism.

There are no reports in the literature of incompetent valves increasing the risk in air embolism but it seems reasonable to assume that such would be the case. Any factors which increase the movement of air through the heart and lungs are likely to reduce the possibility of fatality. These factors are: Adequate blood volume, normal myocardial contractile force, normal or elevated blood pressure, competent valves, low pulmonary vascular resistance, mild vagal reflex and patent pulmonary arteriovenous shunts. The factors favoring heart failure from a given amount of air embolism are: Diminished circulating blood volume, hypotension, poor myocardial reserve, incompetent valves, high pulmonary vascular resistance, active vagal reflex and small pulmonary arteriovenous shunts.

Another factor that can contribute to fatality with a small volume of air entering the right heart is a patent foramen ovale. Such a patent opening
would allow air to go directly from the right atrium into the left atrium and thereby produce systemic arterial embolism. Smaller volumes of air in the coronary and cerebral arteries are required to produce fatality than the amounts necessary to cause death in the pulmonary circulation. On the basis of studies in cats, Moore calculated that over 37.5 ml of air passing through the left side of the heart would be required to produce fatality in a 150-pound man.18

A review of some of the physiologic features associated with air embolism of the right heart will clarify the steps taken in treating the clinical situation. When air ceases to go into the heart, the murmur stops in a very short time, provided the blood pressure is not at a shock level and the heart has not dilated to a point of failure with a high venous pressure. The cessation of the murmur is assumed to be due to the passage of air from the heart into and through the pulmonary circulation. The movement of air through the heart occurs only if the heart does not fail. Pronounced venous distension is a manifestation of heart failure. Hypotension is also a sign of the heart failure.

Turning the patient onto the left side increases the amount of air that can be tolerated in the right heart. Experimental data have demonstrated that, on turning, the large bubble of air in the pulmonary conus rises into the right ventricle, allowing blood to flow through the heart.2 Clinical experience has shown that the patient turned to the horizontal position with the left side down responds quickly from the hypotension of air embolism.5,16

Very large volumes of air, slowly or rapidly introduced, produce acute right heart failure. This situation has been effectively treated by opening the heart to allow the air to escape from the atrium15 and by needling the heart to remove the air.98

Diagnosis of air embolism is best made by listening for the sound of the characteristic murmur. This can be done by having an esophageal stethoscope in place when patients are operated on in the sitting or semisitting position. Also, when hypotension develops in situations in which air embolism can occur, the precordium should be auscultated. When the characteristic murmur is heard, the following steps should be taken in sequence to establish a normal blood pressure:

1. Stop air entry into the vein.
2. Turn the patient into the horizontal position with the left side down.
3. Aspirate the air from the heart.
4. Perform external cardiac massage.

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REFERENCES


