Echocardiographic detection and treatment of intraoperative air embolism

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A real-time two-dimensional echocardiogram was used to detect the presence of an air embolism in patients undergoing neurosurgical procedures in the sitting position. The technique could with good sensitivity detect the appearance of a single air bubble intraoperatively, thus allowing early intervention to prevent development of further air emboli. Two types of air embolism could be differentiated: the single-bubble type and the "stormy-bubble" type. The single-bubble type was observed during skin and muscle incisions, craniotomy, and brain lesion excision. Further embolism development was prevented by electrocoagulation and application of bone wax. The stormy-bubble type occurred during dura and muscle incisions and was prevented by electrocoagulation, reflection of the dura, or suturing the affected muscle.

The routine use of a Swan-Ganz catheter for removal of air embolism by suction proved effective for the treatment of the stormy-bubble type of air embolism. Masking the operative field with saline-soaked cotton strips was of moderate benefit in the stabilization of the single-bubble type of air influx, but proved to be of little value in controlling the entrance of the stormy-bubble type.

KEY WORDS • air embolism • echocardiography • intraoperative monitoring

The sitting position is commonly chosen for patients undergoing neurosurgical procedures as it affords better access, a clear operative field, and improved venous and cerebrospinal fluid drainage. However, the incidence of air embolism, widely recognized as the major life-threatening complication of neurosurgery, is dramatically increased. It occurs in an average of 25% of procedures most frequently during posterior fossa and transsphenoidal pituitary operations. It may also occur at sites remote from the operative field, such as a wound caused by pin-type headholders.

A negative pressure gradient develops between the cerebral vasculature and the right atrium in patients in the sitting position. When non-collapsible venous channels such as the mastoid and occipital emissary veins, diploic veins, dural sinuses, or intrasosseous venous lakes are cut during surgery, air can enter the vasculature. If preventative measures are not taken within minutes of a slow air infusion, it becomes symptomatic and a potentially fatal physiological chain of events is initiated. Adornato, et al., have described this sequence in the dog.

The consequences of air embolism and its associated morbidity and mortality depend upon the techniques utilized to detect its initial appearance and development, and upon the subsequent treatment. Detection techniques have included precordial monitoring by Doppler ultrasound, arterial blood pressure or central venous pressure (CVP) monitoring, electrocardiogram, and esophageal stethoscope monitoring, and recording of end-tidal CO₂. The principles of treatment consist of occlusion of the open vein or other source of air access, removal of air from the circulatory system by aspiration of intracardiac or pulmonary air, and maintenance of cardiorespiratory stability. It is generally agreed that the earlier the air embolism is detected (preferably prior to physiological changes), the sooner preventative treatment can be initiated, and the greater the possibility of avoiding serious consequences.

In this paper, we report the successful use of real-time two-dimensional echocardiography in the detection and quantitation of venous air influx during neurosurgery on two patients in the sitting position and one in the lateral decubitus position. We also describe rapid and effective treatment techniques to prevent air emboli from detrimentally affecting the operation's progress.
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Clinical Material and Methods

The subjects of this study were three operative patients who gave informed consent. All were undergoing neurosurgery: one for a metastatic brain tumor (adenocarcinoma from the lung) in the posterior fossa, one for an arteriovenous malformation in the occipital lobe, and one for cervical spinal cord disease. Operations were performed in the sitting position in the former two patients and in the lateral decubitus position in the third patient. In all three patients general anesthesia consisting of nitrous oxide and oxygen supplemented with halothane was administered via endotracheal intubation. A Swan-Ganz catheter was inserted into a vein in the right elbow, and the pulse, pulmonary artery pressure, right atrium pressure, and CVP were recorded. The pulmonary blood vessel resistance and total blood vessel resistance were calculated for each patient to detect the development of pulmonary edema, which has been associated with the presence of air embolism. After these physiological parameters were recorded, the tip of the Swan-Ganz catheter was placed at the level of the right ventricle outflow for the withdrawal of air if required during the operative procedure.

Real-time two-dimensional echocardiography was performed on each patient throughout the operative procedure by means of a Toshiba SSH-11A electronic scanner with a video recorder.* The echocardiograph probe was placed directly below the xiphoid process to give a four-chamber apical view of the heart (Fig. 1), and was securely attached to the patient with adhesive tape. The positioning of the probe was determined on the day preceding surgery. The patient was placed in the same position as at surgery the following day while the probe was manipulated against the chest to obtain the clearest view of the heart. This probe position was then marked for use at surgery.

Results

Detection of Embolism

Echocardiography presented a clear picture of the heart in motion. The four chambers, the left and right ventricles and atria, could be clearly differentiated and appeared in negative contrast to the surrounding heart muscles (Figs. 1 and 2). Despite the continuous pulsating movement of the heart, the interventricular and interatrial septi and tricuspid and mitral valves could be clearly distinguished (Fig. 2 left).

Figure 2 left demonstrates a static echocardiographic picture of the heart under normal conditions. When air entered the circulatory system during surgery, it appeared as either a single-bubble type or stormy-bubble type of embolism in the right ventricle and atrium. The single-bubble type could be distinguished as one or more single-entity high-contrast areas (Fig. 2 center). The stormy-bubble type formed when a large quantity of air entered the circulation en masse and appeared as a large high-contrast blur within the right ventricle.

* Toshiba electronic scanner, Model SSH-11A, manufactured by Toshiba Medical, Bunkyo-ku, Tokyo, Japan.
and atrium (Fig. 2 right). Both embolism types could be readily identified and quantified by the size of the high-contrast area.

Causes and Treatment of Embolism

The Swan-Ganz catheter, inserted prior to surgery, was of considerable use in the withdrawal of large stormy-bubble type air infusions, but was less useful in the aspiration of small air influxes. The best method of treating air emboli depended upon their mode of entry.

Skin Incision. The single-bubble type of embolism was detected immediately following skin incision. It could be controlled and stopped by the application of pressure to the wound or by the use of skin clips.

Fascia and Muscle Incision. Both the single- and stormy-bubble types of embolism occurred after the incision of fascia and muscle. The former could be controlled either by electrocoagulation or by application of pressure with a muscle retractor. The stormy-bubble type of influx was more difficult to control. Electrocoagulation reduced air entry, but only extensive muscle ligation completely stopped it. Air entry also occurred during detachment of muscle from bone.

Bone Incision. The single-bubble type of air entry was generally observed following bone incision. The air entry point was easy to determine, and the air flow could be eliminated by the application of bone wax or electrocoagulation.

Dura Mater Incision. The largest quantity of air entered the circulation following incision of the dura mater. Frequently, air flowed in continuously, giving rise to a typical stormy-bubble type of embolism visible on the echocardiogram. The source of air inflow was generally difficult to identify; consequently, the operative site was irrigated immediately. The routine technique of packing the wound with wet cotton strips and immersing the area in physiological saline reduced the air inflow only slightly. Quick reflection of the dura mater and electrocoagulation proved considerably more effective in completely halting air flow.

Excision of Brain Lesion. During extraction of tissue from the brain parenchyma, the presence of a single-bubble type of embolism was detected by the echocardiogram. The source of air inflow within the operative field was generally easy to identify and was controlled by electrocoagulation.

Discussion

There has been considerable discussion concerning which technique most sensitively and consistently diagnoses the development of an air embolism. Monitoring devices have included the use of the precordial stethoscope, esophageal stethoscope, end-tidal CO$_2$ monitoring, CVP and electrocardiogram monitoring, and precordial monitoring by Doppler ultra-

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**Fig. 2.** Echocardiograms and diagrams showing structures visualized. IVS = interventricular septum; IAS = interatrial septum; MV = mitral valve; RV = right ventricle; RA = right atrium; LV = left ventricle; LA = left atrium. **Left:** Preoperative “control” echocardiogram of the heart. There are no air bubbles in either the right atrium or ventricle. **Center:** Echocardiogram during surgery demonstrating the “single-bubble” type air embolism. Several single air bubbles are present in the right atrium outflow. **Right:** Echocardiogram during surgery demonstrating the “stormy-bubble” type air embolism. Massive air bubbles are present in the right atrium and ventricle.
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It is generally accepted that Doppler ultrasoundography is by far the most sensitive method. It has been clearly demonstrated that the other techniques do not detect air within the circulatory system before physiological deterioration has begun. Gildenberg, et al., have described the sequence of events that occurs with increasing venous air influx in the dog. Doppler ultrasoundography could detect air infusion at a rate as low as 0.015 ml/kg/min, and proved consistently accurate in diagnosis at rates of 0.02 ml/kg/min. The first physiological response, a gasp reflex associated with alveolar stimulation, was observed at 0.36 ml/kg/min. A decrease in end-tidal CO₂ and rise in CVP occurred at 0.4 ml/kg/min, and heart rate increased at 0.42 ml/kg/min. Alterations in the electrocardiogram became apparent at 0.6 ml/kg/min, and blood pressure began to fall at 0.69 ml/kg/min. Only at infusion rates approaching 2.0 ml/kg/min, just below the lethal dose, was the characteristic "mill wheel" murmur consistently heard.

It has been argued that precordial Doppler monitoring is too sensitive and cannot differentiate between clinically important and unimportant infusions of air. The technique is not foolproof: it is non-quantitative and gives rise to both false-positive and false-negative alerts. Standefer, et al., reported two patients who developed physiological signs of air embolism, later confirmed by air aspiration from an indwelling atrial catheter; these occurrences were undetected by Doppler ultrasound. Such cases are rare, and we believe that the operating team should be alerted to even small influxes of air which can be quickly controlled before they develop into large bolus infusions.

Most of the presently available monitoring techniques detect the presence of venous air influx by a secondary alteration in either the cardiac or the pulmonary system. Real-time two-dimensional echocardiography visualizes the air bubbles themselves and portrays them at the exact time they enter the right atrium and ventricle, giving a "living picture." It therefore circumvents many of the limitations of the classical techniques. The number and size of the bubbles can be seen and related directly to the operative procedure, and an objective decision can be made as to their clinical importance. The technique is at least as sensitive as Doppler ultrasound monitoring. It can detect the entry of a single air bubble into the heart. Finally, it is of value in the immediate assessment as to whether electrocoagulation has controlled air influx. Electrocoagulation causes interference when used with Doppler ultrasound and electrocardiographic monitoring. We consider that real-time two-dimensional echocardiography has the best potential in the early detection and quantitation of venous air influx. It was most sensitive in detecting air embolisms in our operations. Nevertheless, we strongly recommend the concurrent use of other supportive monitoring techniques during all procedures.

It proved possible to differentiate two types of venous air influx using echocardiography: the single- and the stormy-bubble type. The former was transient and generally occurred following incision of skin, muscle, surface of bone, and brain. On occasions where only a few small bubbles entered, no preventative measures were required to resolve the situation; however, when continuous bubbles were seen, either electrocoagulation, application of bone wax, or muscle ligation was necessary. The stormy-bubble type of air influx was generally noted following dura mater or muscle incision. The veins of the dura mater do not appear to collapse when they are cut, and immediate reflection of the dura mater followed by electrocoagulation of its tip proved the most effective technique to control air influx. For muscle, retraction or electrocoagulation was usually sufficient to cease stormy-bubble entry. However, some instances required muscle ligation.

The principle behind treatment of air embolism consists of closure of the point of air access, removal of the air from the circulatory system, and maintenance of cardiorespiratory stability. The entry point of air cannot be immediately identified and obliterated, the general procedure is to irrigate the operative field with physiological saline or to apply wet cotton strips to stabilize the situation. This proved to be of value in the stabilization of the single-bubble type of air influx but was ineffective for the stormy-bubble type. It is therefore recommended that, following the detection of a stormy-bubble type of air embolism, the search for the offending vessel should continue diligently.

The Swan-Ganz catheter proved to be moderately useful in the aspiration of air from the right ventricle and atrium after the detection of a stormy-bubble type of air influx, but was of less value in treating the single-bubble type of air ingress. The role of the Swan-Ganz catheter in the management of air embolism is presently open to question. Its use in confirming the diagnosis of pulmonary air embolism is probably no longer important since the development of more sophisticated and sensitive detection techniques. In our experience, despite the confirmed presence of a significant amount of air, it is often difficult to aspirate a useful quantity by this means, and this observation has been confirmed by others. In an experiment in dogs, no air could be aspirated from the right atrium following an injection of 4 ml of air into the inferior vena cava. Nevertheless, the use of a Swan-Ganz catheter can be life-saving in emergency situations, and for this reason alone we consider it essential.

It is of equal importance that, in procedures such as ours involving nitrous oxide as the anesthetic agent, the use of nitrous oxide should be discontinued following the influx of large quantities of air, and ventilation with 100% oxygen should be commenced immediately. Body nitrogen can diffuse into the air bubble, cause it to expand, and increase the lethal dose of a given air volume by a factor of 3.4. The early detection of venous air ingress by real-time two-dimensional echo-
cardiography affords treatment time sufficient to ensure that such conditions would only rarely occur.

The problem of venous air embolism is by no means restricted to operative procedures in the sitting position. It may occur in patients undergoing surgery in virtually any position, including an operation in the lateral decubitus position. The only factors required for its development are an uncollapsed vein and a negative venous pressure gradient between the operative site and the heart.3,23 For every 15 in. of vertical height between these, there is a 30-mm Hg decrease in local blood pressure.7 The best treatment is early prevention; that is, closure of the influx site before a significant air ingress occurs. Real-time two-dimensional echocardiography offers sensitive early detection and quantitation of air influx for an immediate objective assessment of its clinical importance.

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References

19. Nunn JF: Controlled respiration in neurosurgical anaesthesia. Anaesthesia 14:413-414, 1959 (Letter)

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