Anesthesiology
68:107–110, 1988

Treatment of Air Embolism With a Special Pulmonary Artery Catheter Introducer Sheath in Sitting Dogs

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The treatment of venous air embolism by aspiration from central venous catheters is well established. However, some anesthesiologists prefer to use a pulmonary artery catheter to monitor patients undergoing a neurosurgical procedure in the sitting position. While offering certain advantages, pulmonary artery catheters may be of limited use in the treatment of venous air embolism because the small diameter of the proximal port is poorly suited for efficient air aspiration. The authors have designed a special pulmonary artery catheter introducer sheath which can be positioned by intravascular electrocardiography to provide an efficient and effective means of air aspiration, while permitting the simultaneous use of a pulmonary artery catheter for pressure monitoring. The flow characteristics of this sheath, with and without side holes, were tested *in vitro* by measuring the time required to aspirate 50 ml of blood. The introducer sheath was compared to a Sorenson CVP catheter, a Bunegin-Albin Air Aspiration CVP Catheter, and the proximal port of a pulmonary artery catheter. The rank order of flow rate was: Bunegin-Albin CVP > introducer sheath without side holes = introducer sheath with side holes > Sorenson CVP > pulmonary artery catheter ($P = 0.0001$). The introducer sheath was then compared to a pulmonary artery catheter for the treatment of a 4 ml/kg venous air embolism in sitting, anesthetized dogs. The mean proportion of air retrieved by the sheath with or without side holes, 57% and 80%, respectively, was significantly greater than that retrieved by simultaneous aspiration of atrial and distal ports of the pulmonary artery catheter, 16% ($P = 0.01$). The efficiency of air aspiration was related to survival, with 68% of the injected air being recovered in surviving dogs, whereas only 33% of the injected air could be removed from the non-survivors ($P = 0.007$). Based upon these findings, a special introducer sheath is being developed for use in patients. (Key words: complications: air embolism. Equipment: catheters; pulmonary artery; venous. Position: sitting. Surgery, neurosurgical.)

AMUSSAT AND SENN demonstrated more than 100 yr ago that air in the right side of the heart could be removed by aspiration of a catheter whose tip lay in the atrium.[1,2] More recently, Michenfelder *et al.* proposed that the central venous pressure (CVP) catheter should be aspirated routinely for the treatment of air embolism in patients in the sitting position.[3,4] Since then, a variety of technological improvements have been made with respect to the type of catheter and the optimal position in the central circulation.[5-8] Currently, special multi-orificed catheters designed for air aspiration may be precisely placed relative to the sino-atrial (SA) node, using electrocardiographic guidance. Aspiration of such catheters, positioned at the atrial-caval junction, has been shown to improve survival in dogs given large air emboli.[8]

However, pulmonary artery catheters are preferred over CVP catheters by some anesthesiologists for procedures performed on patients in the sitting position.[9] Pulmonary artery pressure is a sensitive parameter for the detection of air embolism,[9] and the capability to measure cardiac output and pulmonary capillary wedge pressure may be helpful in managing fluid balance.[10] Neurosurgical patients are commonly hypovolemic from the use of diuretics, and blood pressure and urine output may not reflect the volume status as well as cardiac output.[11] Moreover, a pulmonary artery catheter may be indicated in neurosurgical patients because of co-existing cardiac disease. Unfortunately, the pulmonary artery catheter is not well suited for aspiration of air from the right atrium, because of the small size of the atrial lumen.[8]

To solve this problem, we have devised a special pulmonary artery catheter introducer sheath, with multiple orifices, which can be positioned at the atrial-caval junction, electrocardiographically. We now report the *in vitro* flow characteristics of the sheath, and the use of the sheath to treat experimental venous air embolism in sitting dogs.

Materials and Methods

Special pulmonary artery catheter introducer sheaths were fabricated by Cook Inc. (Bloomington, IN). They are 25 cm in length, 9 French size, with a "side arm" for aspiration or infusion. The open (distal) tip of the sheath has a diameter of 2.5 mm. The distal 5 cm of the sheath is perforated with six 1.0 mm diameter holes (fig. 1). Identical introducer sheaths without the side holes were also fabricated. Both introducer sheaths were examined *in vitro* and *in vivo*.

The *in vitro* studies examined the flow characteristics of both introducer sheaths after a 7.5-French Edwards

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Received from the Department of Anesthesiology, University of Washington, Seattle, Washington. Accepted for publication August 5, 1987.

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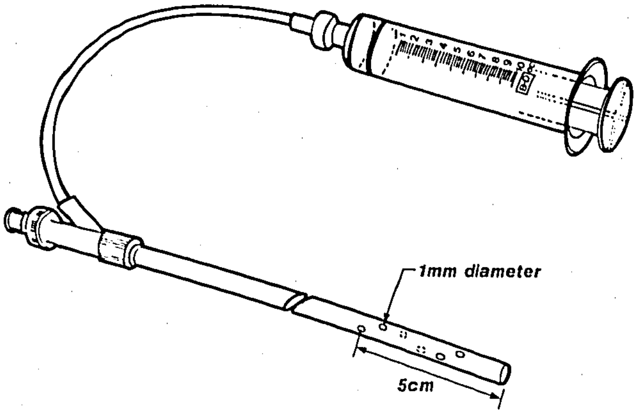

FIG. 1. A schematic diagram of the special pulmonary artery catheter introducer sheath, with side holes, shows the six 1.0-mm side holes, located in the distal 5 cm of the 25 cm long catheter. The "side arm" with aspirating syringe attached is also shown. All experiments were performed with a 7.5-French pulmonary artery catheter through the lumen of the sheath.

pulmonary artery catheter was placed through the lumen. Also examined were the flow characteristics of the Sorenson CVP catheter (Sorenson Research, Salt Lake City, UT; 15 gauge by 23.5 cm), the Bunegin-Albin Air Aspiration CVP catheter (Cook Inc., Bloomington, IN; 14 gauge by 24 cm), and the Edwards 7.5-French, VIP pulmonary artery catheter (American Edwards Laboratories, Anasco, Puerto Rico) without an introducer sheath. A 60-ml syringe was clamped to a bench, with a 10-pound weight suspended from the plunger. Each catheter was filled with canine blood and connected to the syringe. The tip of the catheter was placed in a container filled with blood and the weight was released, exerting a constant force on the plunger. The time required to fill the syringe with 50 ml of blood was determined. Each trial was performed five times. The special introducer sheath, with and without side holes (with a pulmonary artery catheter through the lumen), was compared to the Sorenson CVP catheter, the Bunegin-Albin Air Aspiration CVP catheter, and the proximal port of the pulmonary artery catheter.

The *in vivo* studies examined resuscitation of dogs from venous air embolism. Dogs were anesthetized with isoflurane (>1.8%, inspired) and nitrous oxide (66%) in oxygen, and their tracheas were intubated. Muscle relaxants were not used. Ventilation was controlled, and end-tidal CO_2 and temperature (nasopharyngeal) were measured continuously. A femoral artery was cannulated for blood pressure measurement and to permit blood sampling for blood gas analysis. Mean arterial pressure (MAP) was determined by electronic integration. An incision was made in the left internal jugular vein and a catheter was advanced 2–3 cm beyond the incision to permit injection of air. The tip of this air-injection catheter was not in the vicinity of the right atrium. Twenty-four mongrel dogs (six dogs per group) were assigned randomly to receive a pulmonary artery catheter inserted through a special introducer sheath with side holes (group 1), a pulmonary artery catheter inserted through a special introducer sheath without side holes (group 2), a pulmonary artery catheter without the introducer (group 3), or no catheter (controls, group 4). The introducer sheaths (groups 1 and 2) or pulmonary artery catheters (group 3) were placed in the right internal jugular vein, and positioned using the catheter or sheath as an exploring ECG lead, as described by Martin.[5] Sodium bicarbonate (1 mEq/ml) was the electrolyte solution. When the pulmonary artery catheter was positioned for air aspiration, the proximal (CVP) port was the source of the ECG. The distal orifice of the introducer sheath without side holes (group 2) and the proximal (CVP) port of the pulmonary artery catheter (group 3) were located 1–3 cm proximal to the SA node, and the distal tip of the introducer sheath with side holes (group 1) was located 0.5–2.5 cm distal to the SA node. These positions previously were reported to allow the most efficient retrieval of air emboli for single or multiple-orifice devices.[6,8] The location of the sheaths or catheters with respect to the right atrium was verified by postmortem examination. MAP, CVP, end-tidal CO_2, and the electrocardiogram (ECG) were recorded with a multichannel strip chart recorder.

At the completion of surgical preparation, the concentration of isoflurane was reduced (nitrous oxide unchanged) to 0.5% (inspired), and dogs were placed in the sitting position. Central venous pressure and pulmonary capillary wedge pressure (PCWP) were measured, and normal saline was administered until the CVP was at least 2 mmHg. Once systemic variables had stabilized (at least 25 min later), a 4-ml/kg bolus of air was injected evenly over 25 s into the left internal jugular vein. At the first recognizable fall in end-tidal CO_2, the introducer sheath (groups 1 and 2) or pulmonary artery catheter (group 3) was aspirated as quickly as possible with 60-ml syringes until no more air could be recovered. No attempt was made to retrieve air emboli in the control dogs (group 4). In group 3 (no introducer), the distal port and the proximal port of the pulmonary artery catheter were aspirated simultaneously. In groups 1 and 2, the side port of the special introducer sheaths was aspirated, but the distal and proximal ports of the pulmonary artery catheters were not.

Statistical analysis was performed using ANOVA with *post hoc* tests (Fisher PLSD and Student's *t* test) for continuous data, and the Fisher exact test for comparison of survival rates after air embolism, with the aid of StatView 512+™, a program for microcomputers (BrainPower Inc., Calabasas, CA).

Results

The mean time required to aspirate 50 ml of blood with each type of catheter was as follows: Bunegin-Albin CVP, 13.46 ± 0.21 s; special introducer sheath with side holes, 23.49 ± 0.88 s; special introducer sheath without side holes, 23.86 ± 0.29 s; Sorenson CVP, 34.02 ± 0.72 s; and CVP port of pulmonary artery catheter, 59.67 ± 0.73 s. The differences between the catheters were statistically significant by ANOVA ($P = 0.0001$) with *post hoc* comparison by Fisher PLSD ($P < 0.05$), except that the introducer sheaths with and without side holes were not different from each other ($P > 0.05$).

The results of experimental air embolism in dogs are summarized in table 1. There were no significant differences between groups for the dose of air, Pa_{O_2}, Pa_{CO_2}, *p*H, hemoglobin, MAP, CVP, PCWP, heart rate, or temperature. The mean proportion of injected air recovered by the pulmonary artery catheter, 16%, was far less than the mean proportion retrieved by the introducer sheaths with and without side holes, 57% and 80%, respectively (ANOVA $P = 0.003$). The difference in air retrieval between the pulmonary artery catheter and either introducer sheath was significant ($P = 0.01$ side holes, $P = 0.002$ no side holes). The difference in air retrieval between the two introducer sheaths was not significant ($P = 0.23$). Of the air aspirated from the pulmonary artery catheter, 16% was retrieved from the distal port and 84% was retrieved from the proximal port. No control dogs (group 4) survived air embolism. By comparison, three of six dogs survived in group 1 (sheath with side holes), two of six dogs survived in group 2 (sheath without side holes), and one of six dogs survived in group 3 (pulmonary artery catheter without sheath). The differences between groups in the proportion of dogs surviving was not statistically significant (Fisher exact test, $P > 0.05$). However, the volume of air aspirated from the dogs which survived (68% of injected air) was about twice as great as from dogs which died (33% of injected air) (fig. 2), and this difference was statistically significant ($P = 0.007$). Postmortem thoracotomy showed that the introducer sheath with side holes was located with the atrial-caval junction at the mid-point of the segment of catheter containing the side holes. The single end hole of the introducer sheath without side holes and the proximal port of the pulmonary artery catheter were located 1–3 cm proximal to the atrial-caval junction.

TABLE 1. Air Retrieval, Mean (±SD)

	Dose Venous Air Embolism, ml	Air Aspirated, ml	Survival Rate
Group 1: sheath with side holes, n = 6	78.0 (4.0)	44.2* (19.5)	3/6
Group 2: sheath, no side holes, n = 6	75.7 (9.9)	61.0† (25.3)	2/6
Group 3: pulmonary artery catheter, n = 6	80.5 (6.7)	13.0‡ (14.4)	1/6
Group 4: control, n = 6	80.8 (5.7)	—	0/6

* Group 1 *vs.* group 3, $P = 0.01$.
† Group 2 *vs.* group 3, $P = 0.002$; group 2 *vs.* group 1, $P = 0.23$.
‡ Sixteen percent of air from distal port, 84% from proximal port.

Discussion

In vitro flow tests showed that the special introducer sheaths and the Bunegin-Albin Air Aspiration CVP catheter had the highest capacity for aspiration of blood. It should be emphasized that the introducer sheaths were tested with a pulmonary artery catheter in the lumen. The pulmonary artery catheter proximal port was very inefficient, which is not surprising considering its very small lumen. The rank order of the flow rates in this *in vitro* comparison: Bunegin-Albin Air Aspiration CVP catheter > the Sorenson CVP > pulmonary artery catheter, is the same as the rank order of air aspiration in a previous *in vivo* study of venous air embolism in dogs.[8]

The *in vivo* studies demonstrated the efficacy of the special introducer sheaths for treatment of experimen-

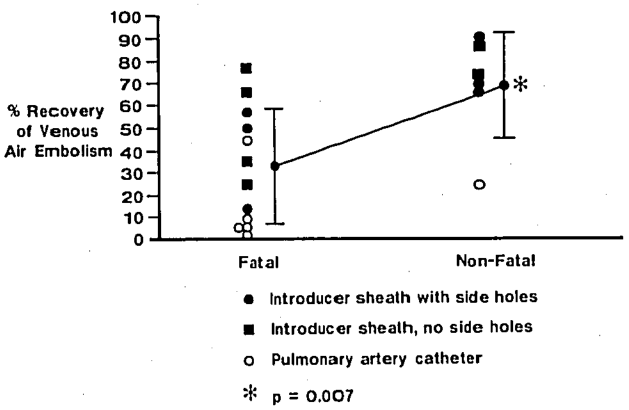

FIG. 2. The per cent of air recovered is shown for each dog. Dogs which survived are grouped on the right, and those which died are grouped on the left. The means and standard deviations for the two groups are also shown. The per cent of air recovered was significantly greater for dogs which survived (*$P = 0.007$).

tal air embolism in dogs in the sitting position. Aspiration of the introducer sheaths resulted in recovery of three to four times as much air as aspiration of proximal and distal ports of the pulmonary artery catheter ($P < 0.01$). The percentage of air recovered from the special sheaths (57–80%) was similar to that obtained with the Bunegin-Albin Air Aspiration catheter (60%), under similar conditions, in a previous study.[8] The volume of air recovered from surviving animals was about twice that recovered from non-surviving animals ($P = 0.007$), implying that the use of more efficient catheters results in a higher survival rate.

Postmortem examination of the sheath with side holes showed that the ECG complex appears to arise from the mid-point of the segment of the sheath containing the side holes. When positioned to produce the largest negative p-wave, the mid-point of the segment of the sheath containing the side holes is located at the atrial-caval junction. The same result was found in a previous study of the Bunegin-Albin catheter, which also has side holes.[8] This appears to be an effective means of positioning catheters or sheaths with side holes because the holes thereby straddle the point where air enters the right atrium.

This study shows that either version of the special introducer sheath, positioned appropriately relative to the atrial-caval junction, is an efficient and effective catheter for aspiration of venous air emboli. A pulmonary artery catheter may be used simultaneously for pressure and cardiac output monitoring without the need to rely on the narrow proximal port for air aspiration. Special introducer sheaths are now being developed for use in neurosurgical patients.

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