Evaluation of a Double-lumen Multiorifice Catheter for Resuscitation of Swine from Lethal Venous Air Embolism

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Background: A double-lumen multiorifice catheter has been developed to potentially enhance accurate electrocardiographic central venous localization and resuscitation from a massive venous air embolism (VAE). This double-lumen multiorifice catheter was compared to a Bunegin-Albin multiorifice catheter for flow characteristics, air aspiration efficiency, and efficacy in resuscitating swine from a lethal VAE.

Methods: Flow characteristics of both catheters were determined by aspirating both agitated and unagitated citrated swine blood with a 50-ml syringe. Swine were anesthetized with halothane and positioned to approximate a modified sitting craniotomy position (45-degree elevation). By a random block method, 24 swine were assigned to either catheter (n = 12 each catheter) for the initial air aspiration. Catheters were positioned, using intravenous electrocardiography, with the distal aspiration orifice in the high right atrium. A 5-ml/kg air embolism was administered over 30 s into the sagittal sinus, and the swine were resuscitated by aspirating air through the multiorifice catheters and then positioning the swine horizontally. Surviving animals were allowed to recover for 60 min. The initial catheter was exchanged and repositioned in the high right atrium using intravenous electrocardiography. A 5-ml/kg air embolus was administered, and the swine were resuscitated as in the first challenge. Surviving swine recovered for 60 min, repositioned, and administered a third 5-ml/kg air embolism. On this final challenge, no attempt was made to resuscitate the animal by aspirating the multiorifice catheter.

Results: Flow characteristics of both catheters were similar in the unagitated blood (195.3 ± 1.9 *vs.* 196.7 ± 2.5 ml/min). The flow rate of agitated blood through the double-lumen multiorifice catheter was 14% greater than through the Bunegin-Albin catheter (136.3 ± 6.8 *vs.* 117 ± 5.9 ml/min, *P* = 0.001). Forty-three air embolism trials were conducted at 5 ml/kg. All nine trials at 5 ml/kg without air aspiration resulted in death. Five animals died during the embolism dose determination trials, and four died during the third embolism challenge. The use of a multiorifice catheter for aspiration after a VAE enhanced survival after a 5-ml/kg sagittal sinus air embolus (14/34 *vs.* 0/9, *P* = 0.02). Although the double-lumen multiorifice catheter was more efficient than the Bunegin-Albin catheter in percentage of air retrieved (37.7 ± 12.0 *vs.* 29.7 ± 10.1, *P* = 0.042). Aspiration of the VAE with the double-lumen multiorifice catheter successfully rescued 9 of the 15 trials, and aspiration using the Bunegin-Albin catheter resuscitated 5 of the 19 (*P* = 0.08).

Conclusions: Multiorifice catheters are effective in resuscitating swine from a lethal VAE. The double-lumen multiorifice catheter evaluated aspirated a larger percentage of the VAE but was not statistically more effective than the Bunegin-Albin catheter in resuscitating the animals. Based on these findings of improved flow rate and efficiency in air aspiration, further investigation of this double-lumen multiorifice catheter is warranted. (Key words: Catheterization: central venous; instrumentation. Embolism: air; therapy. Resuscitation: methods.)

THE incidence of venous air embolism (VAE), a potential life-threatening complication, which ranges from 10% to 15%, usually is associated with neurosurgical procedures performed with patients in the sitting position.[1–4] The cornerstones of the management of a VAE are a high index of suspicion, early recognition, and prevention of further air entrainment. Although early recognition and prevention of further VAE usually will limit the systemic effects, definitive therapy for a massive VAE relies on the ability to aspirate air from a properly placed central catheter.[5] Whereas single-orifice catheters can be used, the most effective design is a high-flow multiorifice catheter located in the immediate region of the junction between the superior vena cava and the right atrium (SVC-RA).[6–9] In a silastic heart model, a 16-G Bunegin-Albin multiorifice catheter positioned at the SVC-RA junction can retrieve 60–90% of the air entrained into the right heart.[6] Those results

have been corroborated in a second silastic heart model[10] and in canine evaluations.[7–9,11] However, to achieve such success, precise localization of the multiorifice catheter is needed. Localization of the distal orifice near the SVC-RA junction usually is accomplished using intravenous electrocardiography monitoring.[12,13] Although multiorifice catheters have been shown to be effectively placed for air aspiration in animal models, the ability to accurately localize the distal orifice without a guidewire to within 1 cm of the SVC-RA junction in humans has been questioned.[14,15] Current multiorifice catheters do not allow for the precision necessary because of the variable summation of electrical activity from all orifices.[14] A new double-lumen multiorifice catheter has been designed for VAE aspiration. The theoretical advantage of this double-lumen multiorifice catheter design is the inclusion of a small-caliber single-orifice lumen that can be used to monitor the intravenous electrocardiogram without a guidewire and thus attain precise localization, and the multiorifice lumen can be used for air aspiration.

Since 1986, various central venous catheters and sheaths for the treatment of VAE have been evaluated. The methodology used to assess the aspirating capabilities of these multiorifice catheters has involved injecting a quantity of air through an internal jugular vein, a femoral vein, or the same catheter studied, then aspirating the VAE when the end-tidal carbon dioxide decreased.[7–11,16] However, the introduction of air into the distal jugular vein, femoral vein, or proximal superior vena cava may not adequately model the problem of VAE originating from dural sinuses during seated neurosurgical procedures. This investigation was designed to compare the efficiency and efficacy of the double-lumen multiorifice catheter against the 14-G Bunegin-Albin catheter in the resuscitation of swine from a lethal venous air-embolism administered through a dural sinus.

Methods

The protocol was approved by the Brooke Army Medical Center Animal Care and Use Committee. The catheters to be studied in this investigation were both manufactured by Cook Critical Care (Bloomington, IN). The Bunegin-Albin catheter has been described in detail elsewhere.[6] In brief, it is a 66-cm, 14-G catheter with a distal orifice and six spiraled sideports (1 mm diameter) that span the distal 5 cm of the catheter. The

double-lumen catheter was a 66-cm catheter of multiorifice design. A 21-G lumen exits at the distal tip. This lumen can be used for intravenous electrocardiographic localization of the catheter. A larger 14-G lumen terminates 1 cm from the tip of the catheter. This lumen has 36 orifices (1.2 mm) that are staggered in two rows over a distance of 9 cm (fig. 1).

Phase 1: Multiorifice Catheter Flow Characteristics

The flow characteristics of the multiorifice catheters were determined for both agitated and unagitated citrated fresh whole swine blood. The agitated blood was used to simulate the air fluid interface of an air embolism. Two catheters of each type were evaluated five times each for aspiration of the agitated and unagitated blood. This was accomplished by inserting the orifices of the catheters into either vigorously agitated or unagitated fresh citrated swine blood. A 50-ml syringe was connected to the aspiration lumen of each catheter. The syringe was clamped to a pole with the plunger toward the ground, and a 10-pound weight was suspended from the plunger. After releasing the weight, the time to aspirate 50 ml of the agitated or unagitated blood was recorded. One minute after aspiration of the agitated blood, the percentage of air in the aspirated sample was recorded.

Phase 2: Experimental Procedure

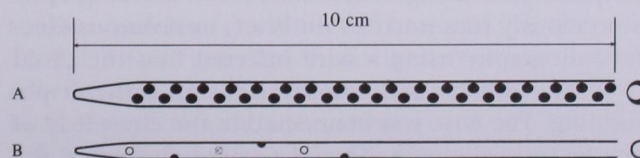Thirty-two swine (*Sus scrofa*, 18–22 kg) were studied. All animals were anesthetized with halothane

Fig. 1. The double-lumen multiorifice (*A*) and Bunegin-Albin (*B*) catheters. The double-lumen multiorifice catheter was a 66-cm double-lumen catheter of multiorifice design. A 21-G lumen exits at the distal tip. This lumen can be used for intravenous electrocardiographic localization of the catheter. A larger 14-G lumen terminates 1 cm from the tip of the catheter. This lumen has 36 orifices (1.2 mm), which are staggered in two rows over a distance of 9 cm. The orifices of the double-lumen multiorifice catheter are located on only one side of the catheter. The Bunegin-Albin catheter is a 66-cm 14-G catheter with a distal orifice and six sideports (1 mm diameter), which are spiraled around the catheter every 0.8 cm at a 90° rotation and span the distal 5 cm of the catheter.

P. D. MONGAN AND J. A. HINMAN

(1.0%, inspired) in 100% O_2 and their lungs ventilated through an endotracheal tube to maintain the arterial carbon dioxide tension at 35–40 mmHg. Expired carbon dioxide and pulse oximetry were continuously monitored using an Ohmeda RGM 5250 unit (Madison, WI). A femoral artery was cannulated for blood gas analysis and for continuous monitoring of arterial pressure. The arterial waveform was displayed and the mean arterial pressure (MAP) measured using a Marquette 7000 series monitor (Milwaukee, WI). Temperature was monitored by a rectal thermistor probe and maintained at $38.0 \pm 1°C$ with the aid of heated humidified gases and a fluid-filled warming blanket. The right internal jugular vein was cannulated with an 8.5-French introducer sheath. Intravascular volume was maintained by continuous saline infusion at $4 \text{ ml} \cdot \text{kg}^{-1} \cdot \text{h}^{-1}$. A five-lead electrocardiograph system was used to monitor cardiac rhythm and rate.

After performance of the initial monitoring procedures, each animal was placed in ventral recumbency, and a 6-cm midline scalp incision was made. The scalp tissue and galea were reflected. A craniectomy was performed to expose the distal sagittal sinus. The sagittal sinus was cannulated with a 2-inch 20-G Teflon catheter. After a three-way stopcock with extension tubing was connected and blood flow through the sagittal sinus catheter confirmed, the catheter was sutured in place, the scalp tissue opposed, and the swine placed in the dorsal recumbent position. By a random block method, an equal number of swine were assigned to either the Bunegin-Albin or double-lumen multiorifice catheter for aspiration of the initial air embolus. The assigned catheter was inserted through the introducer sheath and positioned using intravenous electrocardiography as previously reported.[13,14] In brief, intravenous electrocardiography using a wire inserted into the distal tip of the catheter was employed for all catheter positioning. The wire was connected to the chest lead of the electrocardiogram. The 21-G single lumen of the double-lumen multiorifice catheter was used for intravenous electrocardiogram. Using this method of intravenous electrocardiography, the apparent origin of the electrocardiogram complex is the distal tip of the catheter.[14] Once the maximum negative P-wave deflection was observed, the double-lumen multiorifice catheter was advanced 1.5 cm, and the Bunegin-Albin catheter was advanced 0.5 cm. This adjustment in position was made to locate the distal aspiration orifice in the high right atrium.

At the conclusion of the surgical preparation, the swine were placed in 45 degrees of reverse Trendelenburg with the head flexed to approximate the modified sitting craniotomy position. Positioning was accomplished over 30 min to allow stabilization of systemic variables that included central venous pressure (CVP), MAP, heart rate, arterial blood gas tensions, arterial hemoglobin levels, and core temperature. Normal saline was administered in 10–20-ml/kg increments as needed to optimize intravascular volume status (CVP 3–6 mmHg). The gradient for air entrainment was determined by the difference in pressure for a transducer located level with the sagittal sinus and a transducer at the level of the right atrium. Both transducers were zeroed at the level of the right atrium, and the gradient was consistently $10–12 \text{ cmH}_2\text{O}$. Heparinized normal saline was infused (3 ml/h) through the multiorifice catheter to minimize the possibility of clot formation and obstruction of the orifices.

After completion of the surgical preparation and positioning, eight swine were used to determine the VAE dose to be administered in the remainder of the experiment. The goal was to obtain a 100% lethality in five consecutive swine. In this segment, air was injected into the sagittal sinus catheter, and a mock aspiration of 50 ml of agitated swine blood was performed when the expired carbon dioxide decreased more than 5 mmHg or when MAP decreased more than 10 mmHg. After mock aspiration (aspiration of 50 ml of agitated swine blood through a Bunegin-Albin catheter), the swine was placed in the horizontal position. No other attempts were made to resuscitate the animals. The initial dose of 4 ml/kg resulted in the death of two of three swine. A dose of 5 ml/kg resulted in the death of five of five animals.

The remaining 24 swine were used in a crossover design to compare the efficacy of the multiorifice catheters for resuscitation from a 5-ml/kg VAE. After collecting physiologic data, each animal received a VAE of 5 ml/kg over 30 s *via* the sagittal sinus catheter. Resuscitation was started when the expired carbon dioxide decreased more than 5 mmHg or when MAP decreased more than 10 mmHg. Resuscitation included manual aspiration of 50 ml (from a 60-ml syringe filled with 5 ml of heparinized saline) of blood and air through the multiorifice catheter. Aspiration force was not quantified but was the maximum that could be generated. The animal then was placed in the supine position. Aspiration was stopped after approximately

10–15 ml of blood was aspirated that appeared lacking further air. No further resuscitative measures were performed. No attempt was made to reinfuse the aspirated blood. Physiologic parameters were recorded 0.5 min before VAE, 0.5 min after the VAE, and 1, 2.5, 5, 10, and 20 after the completion of the VAE. The volume of air and blood was recorded from each aspirate and animal. Any animals that survived the initial VAE were allowed 60 min to recover. The animal was again positioned in 45 degrees of reverse Trendelenburg and allowed to equilibrate hemodynamically for another 30 min. The initial catheter was replaced with the other multiorifice catheter. A second 5-ml/kg VAE challenge was administered in the same manner as previously and the animal resuscitated in a similar manner. If the animal survived the second VAE, another 60-min recovery period was allowed. The animal was repositioned and allowed to stabilize for 30 min. A third 5-ml/kg VAE then was administered. On this administration, mock aspiration of a catheter positioned in agitated swine blood was followed by positioning the animal horizontally. *Post mortem* examination of each swine was performed to assess catheter position.

Statistical Analysis

Data are presented as the mean with standard deviation unless specified. Parametric data were analyzed using an unpaired t-test or a one-way analysis of variance. A Tukey's multiple-range test was used as necessary to correct for multiple comparisons. A chi-squared or Fisher's exact test was used to compare outcomes between treatments. A P value < 0.05 was considered significant.

Results

The flow rates for aspiration of agitated and unagitated swine blood for the two catheter types are reported in table 1. There was no difference in flow rates between catheters ($P = 0.18$) when aspirating unagitated citrated swine blood. However, though there was a decrement in aspiration for both catheters with agitated blood, the double-lumen multiorifice catheter exhibited significantly faster flow rates (136.4 ± 6.8 *vs.* 117.0 ± 5.9 ml/min, $P = 0.001$).

Before air embolism, physiologic parameters were similar for each group of animals (table 2). A graph representation of the air embolism trials is shown in

figure 2. After determining the volume of air for a lethal VAE (n = 5), 12 swine were assigned by a random block method to have the initial aspiration performed with the double-lumen multiorifice catheter, and 12 were assigned to the Bunegin-Albin catheter. The seven animals that survived the initial embolism using the double-lumen multiorifice catheter had that catheter replaced with the Bunegin-Albin multiorifice catheter. Of those seven animals only two survived the second air embolism challenge using the Bunegin-Albin multiorifice catheter for aspiration. Those two survivors expired on the third challenge with no aspiration attempts. Of the 12 animals randomized to the Bunegin-Albin multiorifice catheter for initial aspiration, only 3 survived. The double-lumen multiorifice catheter was exchanged for Bunegin-Albin multiorifice catheter in those three survivors, and the second challenge was conducted. Two of those three animals survived using the double-lumen multiorifice catheter. Those two animals died during the third embolism challenge. Overall, a significantly larger percentage of the 5-ml/kg VAE could be aspirated from the double-lumen multiorifice catheter than the Bunegin-Albin catheter. In the 15 trials (12 initial plus 3 crossover) involving aspiration with the double-lumen multiorifice catheter, a mean $37.7 \pm 12.4\%$ of the air embolus was recovered. This is compared with the mean of $29.7 \pm 10.5\%$ recovered *via* the Bunegin-Albin catheter ($P = 0.042$) in 19 trials (12 initial plus 7 crossover).

For both catheters, significantly greater percentage ($P < 0.05$) of the 5-ml/kg VAE dose was retrieved from the surviving animals than for the nonsurviving animals. In animals that survived, there was no difference in retrieval of the VAE between the double-lumen multiorifice and Bunegin-Albin catheter ($46.7 \pm 6.1\%$ *vs.* 45.2 ± 3.9, $P = 0.17$). Similarly, there was no difference in the percentage retrieved from the nonsurvivors for the respective catheters either (24.2 ± 9.3 *vs.* 26.6 ± 5.3, $P = 0.21$). There were no significant differences in the physiologic data collected before the VAE for the animals with either catheter in place whether they were survivors or nonsurvivors (table 2). The changes in the end-tidal carbon dioxide and MAP are shown in figure 3.

Survival data are listed in table 3. Because of the lethal dose determination and the crossover design, 43 VAE trials were conducted at 5 ml/kg. The nine swine administered a 5-ml/kg VAE without aspiration attempts all died. This included the five used to determine the

P. D. MONGAN AND J. A. HINMAN

Table 1. Catheter Flow Characteristics

Variable	Double-lumen Multiorifice Catheter		Bunegin–Albin Multiorifice Catheter	
	Unagitated	Agitated	Unagitated	Agitated
Swine blood				
Flow rate (ml/min)	195.3 ± 1.9	136.3 ± 1.9*	196.7 ± 2.5	117.0 ± 5.9*·†
Air aspirated (%)	0.0	56.0 ± 3.6	0.0	54 ± 9.0

Data represent the flow rates (mean ± SD) calculated for the 10 trials for each catheter design in the agitated and unagitated swine blood. The flow rates were obtained by converting the time required to aspirate 50 ml into ml/min. There was no difference in the flow rate between catheters for the unagitated swine blood ($P = 0.18$). There was no difference between the volume percent of air aspirated from the agitated blood, which indicates that similar conditions existed in the fluid–gas interface during those flow rate determinations.

* Significant decrease in flow in the agitated compared with the unagitated blood for each catheter ($P < 0.005$).

† Significant difference between the catheters in the ability to aspirate the agitated swine blood ($P = 0.001$).

lethal dose and the four that survived two VAEs with resuscitation. The survival rate for the double-lumen multiorifice catheter from a 5-ml/kg VAE was 60% (9 of 15). This was significantly better than with no aspiration attempts ($P = 0.007$). The Bunegin-Albin multiorifice catheter resulted in successful resuscitation in 5 of 19 trials. This was not a significant improvement over no aspiration ($P = 0.14$). The double-lumen multiorifice catheter, however, was not statistically superior to the Bunegin-Albin catheter for survival (9/15 vs. 5/19, $P = 0.080$).

The necropsy results revealed that the distal aspiration orifice of all catheters was located in the right atrium within 1 cm of the junction with the superior vena cava in all animals. A continuous column of frothy blood from the high SVC through the distal pulmonary arteries also was noted.

Discussion

VAE is a potentially fatal complication that can occur during neurosurgical procedures. Although early detection and prevention of further air entrainment are sufficient for most procedures, an important aspect of treatment of a massive VAE is aspiration of air through a central venous catheter. In cases of hemodynamically significant VAE, central catheters have been reported to be lifesaving.[1,5] In vitro and in vivo animal studies have shown that the Bunegin-Albin multiorifice catheter is probably the most effective catheter available.[6–11] In this investigation, the new double-lumen multiorifice catheter was shown to have improved flow characteristics for the aspiration of agitated blood.

We expanded on methods of determining flow rates that were previously described.[16] When aspirating un-agitated swine blood, the flow rates through the two catheters were similar. The results were also similar to the flow rates reported by Bowdle et al.[16] for a 14-G Bunegin-Albin catheter. However, because blood mixed with air has distinctly different physical properties, we believed that the flow rates of unagitated blood may not predict aspiration capability of a blood/air mixture. The double-lumen multiorifice catheter was significantly better for the aspiration of agitated blood. Three design factors in the double-lumen multiorifice catheter design make it more effective for the aspiration of a blood/air mixture. Although the cross-sectional internal aspiration diameters are equivalent (14 G) for both catheters, the double-lumen multiorifice catheter has an orifice area of 40.5 mm^2 for aspiration. The cross-sectional orifice area of the Bunegin-Albin catheter is only 7.6 mm^2. During turbulent flow through an orifice, the flow rate is dependent on the radius of the orifice to the fifth power (r^5). Although the blood/air mixture is a non-Newtonian fluid and the application of classical physics has limitations, the increased aspiration area appears to be important. A third major factor is the distance over which the orifices are located. The double-lumen multiorifice catheter has a greater number of larger orifices located over 9 instead of 5 cm. This may allow greater access to the VAE that vortexes in the distal superior vena cava and the upper right atrium.[6]

Previous investigations with the Bunegin-Albin catheter report 60–80% air retrieval and a 60% resuscitation rate. Our results for the Bunegin-Albin catheter for air retrieval and successful resuscitation were half of the previous reports.[6–8,11] Several factors may be responsible. First, the site of VAE was different in our model. By embolizing through the distal sagittal sinus, the character of the blood/air mixture at the RA may have

Table 2. Systemic Variables before Air Injection

	No Aspiration	Double-lumen Multiorifice Catheter	Bunegin–Albin Multiorifice Catheter
First air injection	n = 5	n = 12	n = 12
Pa_{O_2} (mmHg)	454 ± 44	430 ± 41	421 ± 38
Pa_{CO_2} (mmHg)	38.7 ± 1.2	39.6 ± 2.7	38.4 ± 3.0
pH	7.43 ± 0.05	7.44 ± 0.04	7.41 ± 0.03
Base excess (mEq/L)	3.3 ± 1.2	3.4 ± 1.7	3.1 ± 1.8
Hemoglobin (g/dl)	8.6 ± 0.5	8.9 ± 0.6	8.7 ± 0.4
MAP	68.7 ± 6.1	64.1 ± 7.3	61.2 ± 9.0
CVP	3.1 ± 1.0	3.6 ± 1.1	2.8 ± 0.9
Temperature (°C)	37.9 ± 0.8	38.4 ± 0.8	38.6 ± 0.5
Survivors	0/5	7/12	3/12
Second air injection		n = 3	n = 7
Pa_{O_2} (mmHg)	—	423 ± 50	436 ± 41
Pa_{CO_2} (mmHg)	—	38.2 ± 1.4	37.7 ± 1.0
pH	—	7.43 ± 0.05	7.41 ± 0.03
Base excess (mEq/L)	—	1.8 ± 1.1	2.1 ± 1.7
Hemoglobin (g/dl)	—	8.4 ± 0.3	8.3 ± 0.9
MAP	—	66.6 ± 4.2	63.4 ± 3.9
CVP	—	4.4 ± 0.8	3.8 ± 1.2
Temperature (°C)	—	38.3 ± 0.8	38.4 ± 0.9
Survivors		2/3	2/7
Third air injection	n = 4		
Pa_{O_2} (mmHg)	448 ± 31	—	—
Pa_{CO_2} (mmHg)	39.2 ± 4.1	—	—
pH	7.44 ± 0.04	—	—
Base excess (mEq/L)	2.9 ± 1.1	—	—
Hemoglobin (g/dl)	9.1 ± 0.6	—	—
MAP	65.6 ± 8.2	—	—
CVP	3.3 ± 1.6	—	—
Temperature (°C)	38.1 ± 0.6	—	—
Survivors	0/4	—	—

Data represent the parameters recorded before air injection. There were no significant differences in recorded values between catheters or times for any of the values.

Pa_{O_2} = arterial partial pressure of oxygen; Pa_{CO_2} = arterial partial pressure of carbon dioxide; MAP = mean arterial pressure; CVP = central venous pressure.

been different from previous models. Colley and Artru[7,8] injected air directly into a catheter advanced into the left or right internal jugular vein. In our investigation, the injection of the air into a dural sinus probably results in greater mixing of the air and blood and thus fewer large pockets of air to be directly aspirated. Necropsy uniformly revealed a diffuse frothy blood/air mixture in the superior vena cava extending into the pulmonary arteries. Animal position could be a contributing difference between studies. Although the modified sitting craniotomy is performed at 45–60 degrees to the horizontal,[17] Colley and Artru,[8] in their

study, positioned animals at approximately 90 degrees to the horizontal. The natural buoyancy of air in blood with the 90-degree position may have contributed to air trapping as well. Bunegin et al.[6] and Hanna et al.[10] in silastic human heart models noted large differences in the percentage of the VAE retrieved at different inclines. In the Bunegin et al.[6] investigation, positioning the model at a 60-, 80-, and 90-degree inclination to the horizontal plane resulted in aspiration of 63%, 81%, and 66% of the VAE, respectively. Another important distinguishing design difference between our swine model and others is the criteria to initiate aspiration. Our protocol required a decrease in MAP of 10 mmHg or end-tidal carbon dioxide decrease of 5 mmHg. The previously mentioned authors waited for the first decrease of end-tidal carbon dioxide or started aspiration immediately after injection of the air.[6,8–10] This may have contributed to less passage of VAE into the pulmonary circulation in previous investigations and thus a larger return of air on aspiration.

In this investigation, the survival rate was not significantly improved with the Bunegin-Albin catheter (26%, 5 of 19 swine) compared to controls. Previous investigations have found the Bunegin-Albin catheter to be 66% effective in resuscitation after a VAE.[7,8] The decreased survival rate in this investigation could be explained by differences in animal position, injection site, timing of aspiration, and animal species. In addition, survivors in the current study were challenged
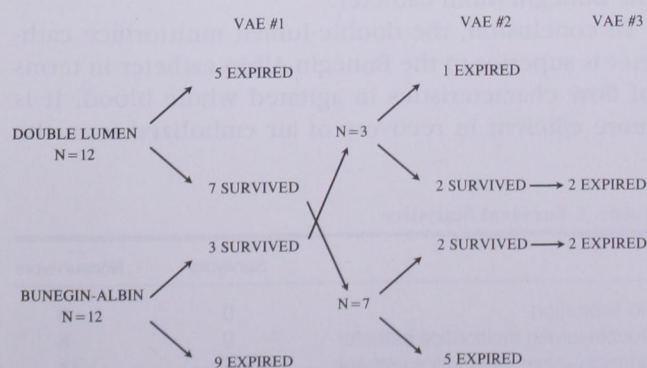

Fig. 2. Outcomes for the swine during the resuscitation phase of this investigation. Initially, 12 swine were randomized to have either the double-lumen multiorifice catheter or the Bunegin-Albin catheter inserted for the first venous air emboli (VAE). Survivors from the first VAE were crossed-over to the second catheter (dotted line) and rechallenged and resuscitated after a recovery period. Survivors from the second VAE were challenged a third time without resuscitation attempts to verify the lethality of the VAE.
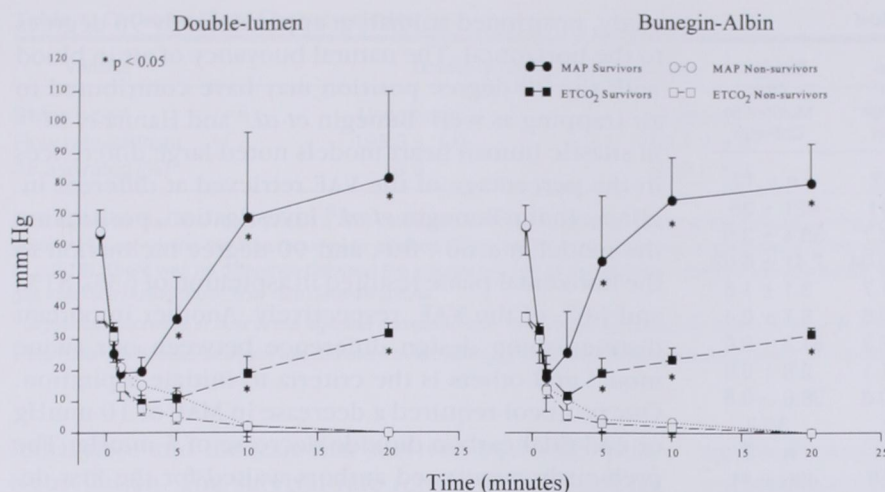
Fig. 3. The values (mean ± SD) recorded for the mean arterial pressure and arterial partial pressure of carbon dioxide after the injection of the sagittal sinus air embolism. The graphs represent the differences between survivors and nonsurvivors and the time course of recovery. There was no difference in the measured parameters when comparing survivors or nonsurvivors between the two catheter types. There were, however, significant differences ($^*P < 0.05$, analysis of variance with Tukey's test for correction of multiple comparisons) when comparing survivors and nonsurvivors within the catheter groups.

with a final VAE to assure the lethality of the dose administered. In previous investigations, the surviving animals were not challenged to determine the lethality in each animal.[7,8] The study by Colley *et al.*[8] does not report the results for the control animals (n = 6) administered a 5-ml/kg VAE. In that study, at least one animal had survived a 5-ml/kg VAE in the dose determination phase of the study. Although the Bunegin-Albin catheter has been shown to be efficient in removal of a large percentage of a VAE, the small animal numbers in the previous studies and the lack of control group lethality determinations have led to inconsistent statistically significant improvement in outcome with the Bunegin-Albin catheter.[8]

In conclusion, the double-lumen multiorifice catheter is superior to the Bunegin-Albin catheter in terms of flow characteristics in agitated whole blood. It is more efficient in recovery of air embolized from the dural sinus. The double-lumen multiorifice catheter improved survival when compared to control animals. Further studies regarding the ease of placement of this large catheter from antecubital and central vascular sites and feasibility of intravenous electrocardiographic localization using the 21-G lumen and a fluid column are needed.

Table 3. Survival Statistics

	Survivors	Nonsurvivors
No aspiration	0	9
Double-lumen multiorifice catheter	9	6
Bunegin–Albin multiorifice catheter	5	14

Data are the distribution of surviving and nonsurviving animals after a 5 ml/kg venous air embolism in the three treatment groups. The use of a multiorifice catheter significantly improved survivability (P = 0.02). The survival with the double-lumen multiorifice catheter was 60% (9 of 15). This was significantly better than no aspiration (P = 0.007). The Bunegin–Albin catheter did not significantly improve survival over no aspiration (5 of 19 *vs.* 0 of 9, P = 0.14) However, there was no definitive improvement when the double-lumen multiorifice catheter was compared with the Bunegin–Albin catheter (P = 0.08).

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