

# Positioning the Right Atrial Catheter:

## A Model for Reappraisal

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A flexible Silastic® casting of the human right atrium was developed to correspond to some *in vivo* human right atrium hemodynamic characteristics including chamber pressures, pulsatility, fluid output, and flow velocity. Using an infusion pump, air was introduced (10 ml in 30 s) into the superior vena cava of the model and aspirated via a catheter from different positions within the model atrial chamber. The tests were carried out at atrial inclinations of 60°, 80°, and 90° from the horizontal and compared the aspiration efficiency of a single-orificed 16-gauge catheter to a 16-gauge multiorificed (5 aperatures) catheter. Optimal air aspiration occurred with the multiorificed catheter tip positioned within the area 2.0 cm below the junction of the superior vena cava (SVC) and the atrial chamber at an inclination of 80°. As much as 80 per cent of the incoming air could be aspirated under these conditions. At its optimal position the single-orificed catheter gave a maximal yield of 45 to 50 per cent aspiration when the tip was positioned 3.0 cm above the SVC and atrial chamber junction. Aspiration of air from mid right atrium (4.5 cm below the SVC-atrial junction) was poor regardless of the type of catheter used or atrial inclination. These data suggest a need for reappraisal of catheter design and placement. (Key words: Anesthesia; neurosurgical. Complications: air embolism. Embolism: air. Equipment: catheters, right atrial.)

THE CORNERSTONE for the treatment of venous air embolism (VAE) was pioneered by Michenfelder *et al.*<sup>1</sup> when they advocated the prior insertion of a right atrial catheter allowing for aspiration in the event VAE is suspected. Early diagnosis of VAE was made possible by the development of Doppler ultrasonic air bubble detection by Maroon and co-workers,<sup>2</sup> such that it is now possible to detect a volume as small as 0.1 ml of air passing through the detection field. In spite of the use of early detection and treatment devices (Doppler plus prior catheter insertion and aspiration), Albin and co-workers<sup>3</sup> have recently reported positive technetium-macroaggregated albumin lung scans indicating significant amounts of air entering the pulmonary circulation during VAE. In view of these findings, it appears that the standard recommended mid atrial catheter position<sup>1,4-7</sup> may not provide for optimum aspiration of air

during VAE. We therefore felt that an evaluation of air aspiration efficiency of right atrial catheters as a function of their position in the heart chamber was necessary.

In this study, a flexible Silastic® model of the human right atrium, having comparable mechanical and anatomical properties of the *in vivo* right atrium, was developed. Using this model, catheter air aspiration efficiency was determined with the catheter tip positioned at various levels within the model right atrium. The study was further extended to evaluate the effect of atrial tilt (corresponding to mid frontal plane inclination) on the air aspiration efficiency of single and multiorificed catheters.

### Materials and Methods

A wax casting of a human right atrium along with portions of the superior and inferior vena cavae was prepared, then dipped into a diluted solution of Silastic® resin. The resin was permitted to cure and the procedure repeated until a wall thickness of 0.5 mm was achieved. The wax was removed from the interior of the Silastic® casting by heating it to 60°C and permitting the melt to drain. Residual wax was removed by washing the flexible Silastic® atrium in parasol. A tricuspid valve was sutured into a hole made in the area of the atrioventricular orifice and a ¼-in diameter tygon tube was attached to the ventricular side of the orifice for conduction of atrial fluids to an occlusive roller pump (fig. 1). The roller pump pushed normal saline to a reservoir 15 cm above the atrium. Tygon tubes, ⅜ inch in diameter, connected to a "Y" at the bottom of the reservoir directed normal saline into the superior and inferior vena cavae.

The introduction of air into the right atrial model was achieved via a port in the superior vena cava 15 cm above its confluence with the right atrium. A rate of 20 ml/min (0.35 ml·kg<sup>-1</sup>·min<sup>-1</sup> assuming a body mass of 60 kg) was maintained by a Harvard® constant infusion pump for 30 s. These parameters were chosen as a consequence of observations of Adornato *et al.* in dogs that 0.35 ml·kg<sup>-1</sup>·min<sup>-1</sup> was the lowest rate at which any consistent physiological changes occurred.<sup>8</sup> These changes were also observed to begin approximately 30 s after the initiation of air infusion. Upon Doppler activation, aspiration via the test catheter commenced for one min at a constant rate of 40 ml/min. The selected aspiration rate was determined by taking the mean of 10 aspiration

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FIG. 1. The Silastic® right atrial model with superior and inferior vena cava and fluid conduction tube joined at the atrioventricular orifice.

rates that were observed during clinical VAE episodes. The duration of aspiration was determined by aspirating for various time periods during the introduction of the preselected volume of air (10 ml/30 s). Aspiration time was varied from 30 s to 5 min. It was found that the maximum yield occurred within one minute after which almost no further air could be recovered.

The tests were carried out at right atrial tilts equivalent to mid frontal plane inclinations of 60°, 80°, and 90° from the horizontal. The performance of a single-orificed 16-gauge catheter and a 16-gauge multiorificed catheter (5 orifices spaced 6 mm apart, positioned 180° with respect to one another) (fig. 2) were compared with catheter tip positions at one centimeter intervals beginning 3.0 cm above the sinoatrial (SA) node and ending at the entrance to the right ventricle (fig. 3). Observations of the right atrial model after introduction of air indicated the formation of a vortex with its upper boundary approximately 3 cm above the SA node. Since the first discernible accumulation of air occurred 3 cm above the

SA node, we felt that this location was an obvious starting point. The SA node was arbitrarily designated as the anatomical reference and set at zero cm. The 16-gauge 21-inch single-orificed catheter was an Intracath® (Deseret Pharmaceutical) and the 16-gauge 21-inch multiorificed catheter was a specially designed catheter (Sorenson Research). The percentage of air recovered at the various catheter positions was compared to the mid atrial recovery and statistically analyzed using Student's *t* test at 18 degrees of freedom.

### Results

Appropriate adjustment of the roller pump produced a pulsating right atrium mimicking human *in vivo* pumping action. The stroke volume was found to be between 60 and 70 ml with a systolic/diastolic pressure of 16/5 torr and a fluid output of 4.5–5.0 l/min at 80 beats/min (fig. 4). The kinematic viscosity of the circulating fluid (normal saline) (abs. viscosity/density) was calculated to be 1.008 centistokes. This value compares closely to the calculated *in vivo* kinematic viscosity for whole blood,

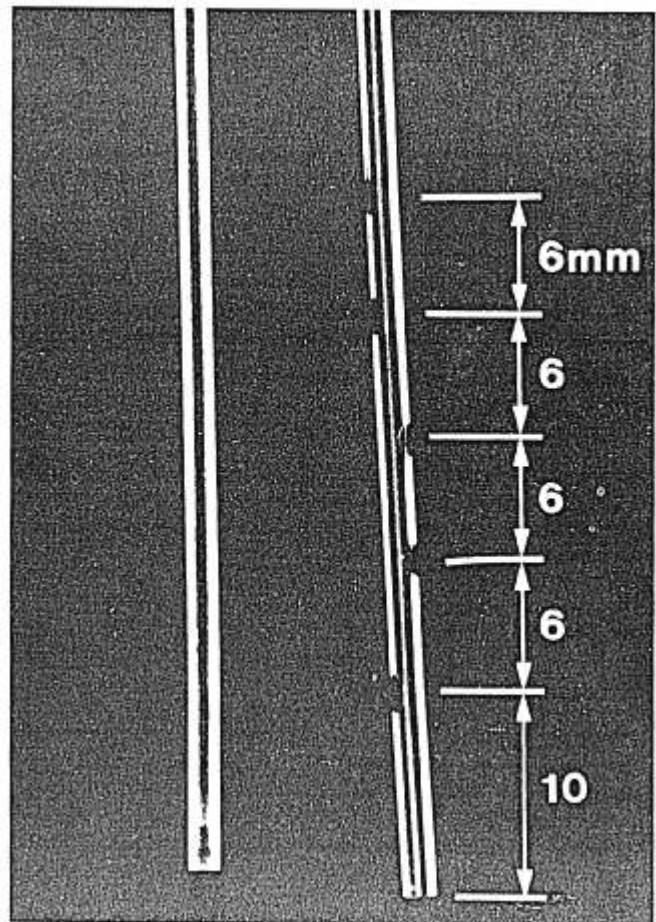


FIG. 2. Sixteen-gauge single-orificed (left) and multiorificed (right) catheters.

1.144 centistokes. Mean fluid velocity calculations in the atrial model (11.9 cm/s) appear to correlate well with previously published human right atrial mean flow velocity measurements (13.5 cm/s).<sup>9</sup> Furthermore, the pulsating right atrial model produced a Doppler audio output that was essentially indistinguishable from the Doppler sounds made by an *in vivo* human right atrium. Air entering the chamber also produced the characteristic Doppler "chirp."

The single-orificed, 16-gauge catheter with the tip positioned at mid atrium (4.5 cm below the SA node) permitted a maximum of 5 per cent of the incoming air to be aspirated, regardless of inclination. Optimal aspiration of air occurred at a tip position between 1 and 3 cm above the SA node for all inclinations ( $P = 0.01$ , table 1). At atrial tilts of 80° and 90° a maximum of 58 and 45 per cent, respectively, of the incoming air could be removed, while at 60° from the horizontal only a 15 per cent recovery could be demonstrated. At optimal catheter tip position (3 cm above the SA node) an inclination of 80° provided a significantly greater ( $P = 0.01$ ) air recovery than at 60° and 90° inclinations.

The multiorificed catheter tip positioned between the SA node and 2 cm below the SA node provided a significantly greater ( $P = 0.01$ ) air recovery as compared to the mid atrial position at all inclinations (table 2). Optimum aspiration (80 per cent) resulted at an inclination of 80° ( $P = 0.01$ ), while at 60° and 90°, 63 and 66 per cent of the incoming air was aspirated, respectively. Statistically there was no difference between the aspiration efficiency at 60° and 90°. Mid atrial aspiration remained low ranging between 2 and 10 per cent.

A comparison of the aspiration efficiency of the single- and multiorificed catheters positioned at their optimum locations indicates that the multiorificed catheter significantly performs better than its single-orificed counterpart (table 3).

### Discussion

These experiments indicate that right atrial catheter design and placement may be of critical importance in effective removal of air entering the right atrium and that a more precise understanding of catheter-air embolus interaction is necessary before significant improvements in right atrial catheter design are realized.

In theory, venous aspiration of air can be classified into three general categories.<sup>4,8,10-12</sup> 1) Air entering a noncollapsible vein or sinus results in large volumes (50 ml or more) being aspirated within short periods of time. Without the precaution of a right atrial catheter, an air lock may develop with the subsequent collapse of the chamber. This phenomenon has been observed in both our *in vitro* Silastic® right atrial model and in our *in*

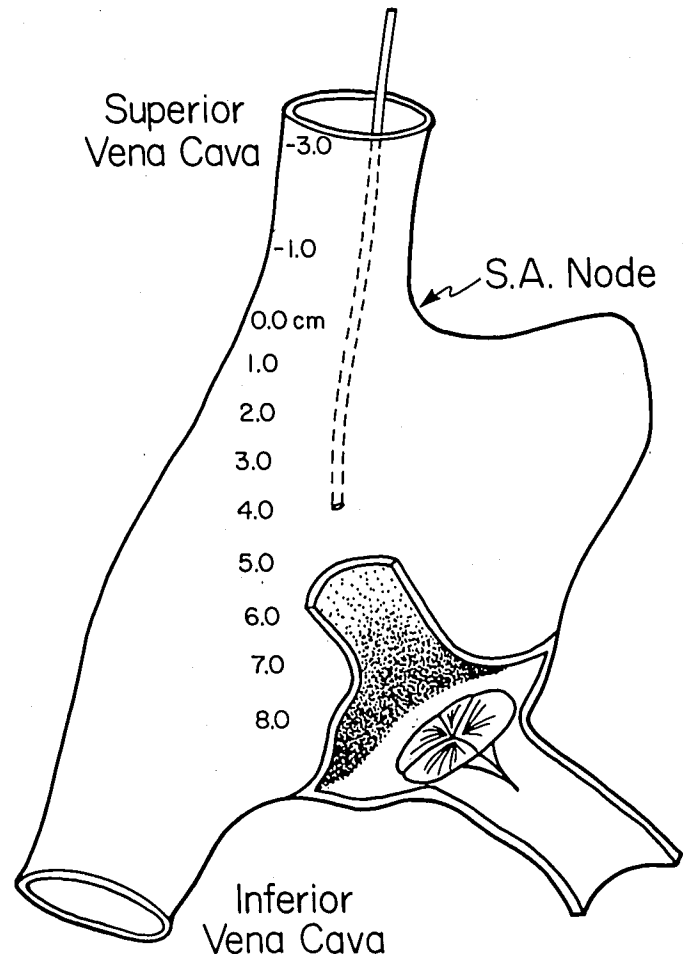


FIG. 3. Schematic of atrial model with catheter tip at the 4.0 cm (midatrial) level.

*vivo* animal model. 2) Aspiration by venous capillaries, venules or incompletely sealed sinus cavities may be slow to moderate with moderate to large volumes of air entering the circulation. Slow to moderate rates of air introduction into our experimental model showed that the emboli may range in size from microemboli to emboli of a few milliliters in volume. The smaller emboli are passed into the pulmonary circulation while the larger bubbles tend to float in the upper regions of the atrial chamber. 3) Aspiration through collapsible veins generally results in the entrainment of smaller volumes of air. These emboli are believed to rarely exceed a milliliter in volume and are rapidly passed through the right heart. Their detection is difficult without the use of a Doppler air bubble detector.

A catheter introduced into the right atrium for the purpose of removing air must be so positioned as to place the region of negative pressure generated at its tip within the area of greatest embolus concentration. Since we are dealing with a dynamic state, embolus concentration and

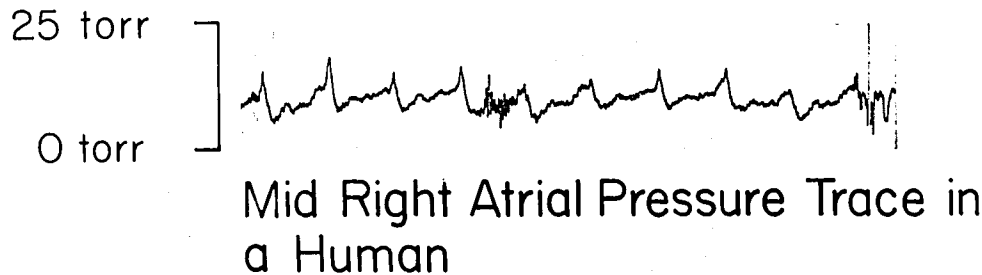
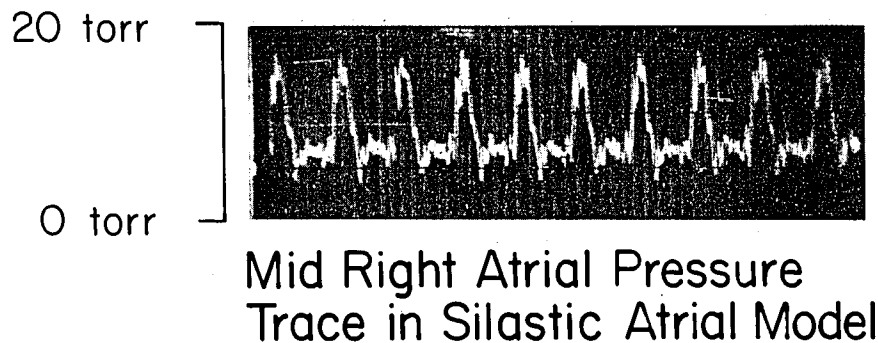


FIG. 4. A comparison of a mid right atrial pulse in the human and the mid right atrial trace in the Silastic® model.



distribution will depend on embolus size, velocity, and density of the fluid flowing through the chamber, inclination of the chamber, and the resultant forces acting on the embolus. The orientation of the catheter within the right atrium will likewise depend on the velocity and density of the fluid, and the resultant forces acting on the catheter.

The catheter is generally constructed of a plastic material (usually a polyvinyl) which is slightly denser than blood. In the upright position the axis of the atrial catheter is at a 90° angle from the horizontal. The resultant force, due to gravity acting on the catheter's center of mass, is exerted along the longitudinal axis of the chamber. Entering air emboli are buoyed up by a force equal to the weight of the fluid that they displace. This buoyancy is opposed by a force exerted on the emboli by the flowing fluid which is proportional to the surface area of the emboli, density and square of the velocity of the blood. The emboli will be passed if this force is greater than the buoyant force acting on them, otherwise, they will float upward. In view of the pulsatory flow pattern through the chamber, the development of an air-blood vortex would be expected and the air bubbles entering the vortex would subsequently be broken into tiny emboli which would be passed through the atrium at velocities approaching that of the circulating fluid. Observations in our atrial model at an atrial tilt corresponding to a mid frontal plane inclination of 90° suggest that a vortex does develop and that it is almost completely confined

within the superior vena cava just outside the atrial entrance. Also, the emboli are churned rather vigorously and rapidly reduced in size such that they are easily passed through the chamber. Positioning the aspirating port of a catheter in or very near the vortex maximizes removal efficiency.

At an inclination of 80°, the vortex was observed to remain within the superior vena cava. The resultant buoyant and gravitational forces, however, no longer act along the caval axis. The vortex moves closer to the uppermost vessel wall into an area of slower flow velocity. (The Reynolds number {Rn} for flow through the vena cava under our experimental conditions was 1,964 indicating laminar flow.) The catheter on the other hand is slightly denser than the saline and sinks or moves in a direction opposite the vortex presenting itself at a slight angle to the flow lines. The streaming saline is deflected away from the underside of the catheter resulting in the catheter being lifted back to its axial position. The increased efficiency is presumably due to emboli passing through the catheter's capture zone with a slower velocity.

At an inclination of 60°, a considerably smaller vortex develops in the vena cava of our model, with the majority of incoming air accumulating in the auricle. The resultant buoyant force acting on the air emboli no longer appears to be large enough to overcome the force applied to the emboli by the moving saline. The air bubbles move along the upper surface of the vena cava into the atrial

TABLE 1. Percentage of Air Recovery by a Single-orificed Catheter at Various Atrial Inclinations and Catheter Tip Positions

Atrial Inclination	Position of Single-orificed Catheter (cm from SA node)						
	-3	-1	0.5	1.5	2.5	3.5	4.5
60°	<i>P</i> = 0.01 15.1 ± 5.8	<i>P</i> = 0.01 11.8 ± 10.7	NS 6.5 ± 3.8	NS 2.3 ± 1.2	NS 2.9 ± 1.8	NS 1.8 ± 0.6	1.5 ± 0.5
80°	<i>P</i> = 0.01 58.7 ± 13.9	<i>P</i> = 0.01 46.5 ± 17.3	NS 8.8 ± 7.1	NS 13.1 ± 10.9	NS 6.6 ± 2.5	NS 5.6 ± 4.0	2.2 ± 1.6
90°	<i>P</i> = 0.01 45.2 ± 9.6	<i>P</i> = 0.01 39.4 ± 17.4	<i>P</i> = 0.01 33.3 ± 16.0	NS 5.7 ± 2.9	NS 7.2 ± 6.1	NS 5.9 ± 5.2	NS 5.1 ± 5.9

appendage. The lift provided to the catheter by the moving saline is no longer sufficient to overcome the resultant gravitational force acting on the catheter. Deviation from its original axial position results in an increased distance between the emboli and the capture zone at the catheter tip. This situation clearly results in poor catheter efficiency.

In consideration of catheter design, it would appear intuitively that a multiorificed catheter would withdraw more air than a single-orificed catheter. This conclusion is based on the idea that the multiorificed arrangement expands the zone of negative pressure over a larger area, that is, the distance along which the openings are located. In theory, the most proximal orifice should have the greatest negative pressure with the remaining orifices becoming less negative as the distal opening is approached. Pressure measurements at each opening of a multiorificed catheter confirmed these expectations. The resulting embolus capture zone, therefore, roughly resembles a cone with its base at the proximal orifice and its point at the distal orifice. The probability therefore is that a greater number of emboli interact for a longer period of time with the capture zone. The result appears to be a trend toward increased yield. Aspiration through a single orifice, however, produces a zone of negative pressure only in the immediate area of the catheter tip. This reduces the probability of emboli interacting with the capture zone, and tends to decrease the yield. In its optimal position, the proximal port of the multiorificed catheter is positioned precisely at the optimal location

for the single-orificed catheter (between 1 and 3 cm above the SA node) while the distal port falls approximately 0.5 cm below the SA node. The most proximal port, having the greatest negative pressure, appears to aspirate air with approximately the same efficiency as the single-orificed catheter. The expanded zone of negative pressure provided by the more distal openings appears to add to the efficiency by capturing the emboli missed by the proximal orifice. Furthermore, the aspiration efficiency of a multiorificed catheter may not be as severely limited by clot formation as in a single-orificed catheter, while the possibility of suction adhesion (to the chamber wall) is virtually eliminated.

A close correlation between our model and the *in vivo* situation is paramount for appropriate extrapolation to the clinical situation. From the data presented earlier in this paper, it appears that flow through the model does approach the *in vivo* state in terms of minute volume, pulse volume, and mean velocity. Since both the cross sectional diameter of the model and human atrium are the same, the flow characteristics as described by the Reynolds number are a function of the density to viscosity ratio of the circulating fluid. The use of normal saline ( $\rho/n = 99.2 \text{ g-p/cm}^3$ ) represents an 11 per cent increase over blood ( $87.4 \text{ g-p/cm}^3$ ) resulting in a value for  $\{Rn\}$  that is 11 per cent greater than would be observed clinically for that same flow. *In vivo* atrial flow is laminar with a  $\{Rn\}$  of approximately 1,770, an 11 per cent increase in  $\{Rn\}$  results in a value of approximately 1,964 which is still within the limits of laminar flow.

TABLE 2. Percentage of Air Recovery by a Multiorificed Catheter at Various Atrial Inclinations and Catheter Tip Positions

Atrial Inclination	Position of Multiorificed Catheter (cm from SA node)						
	-3	-1	0.5	1.5	2.5	3.5	4.5
60°	NS 3.3 ± 1.5	NS 16.8 ± 12.7	<i>P</i> = 0.01 63.3 ± 5.4	NS 27.6 ± 24.5	NS 4.8 ± 2.3	NS 2.7 ± 0.5	NS 2.0 ± 0.8
80°	NS 17.0 ± 2.8	NS 2.8 ± 1.7	<i>P</i> = 0.01 80.9 ± 9.5	<i>P</i> = 0.01 77.9 ± 9.7	<i>P</i> = 0.01 70.7 ± 16.2	NS 18.3 ± 9.5	9.6 ± 5.6
90°	NS 5.9 ± 1.9	NS 3.9 ± 1.1	NS 4.5 ± 3.0	<i>P</i> = 0.01 66.3 ± 8.0	NS 5.6 ± 8.0	NS 7.0 ± 4.8	1.7 ± 0.7

TABLE 3. A Comparison of Differences in Percentage Recovery from the Right Atrium between Single- and multiorificed Catheters at 60°, 80°, and 90° at Their Respective Optimum Positions

Single-orificed	Multiorificed		
	60°	80°	90°
60°	48.4 <i>P</i> = 0.01	65.8 <i>P</i> = 0.01	51.2 <i>P</i> = 0.01
80°	4.6 NS	22.2 <i>P</i> = 0.01	7.6 NS
90°	18.1 <i>P</i> = 0.01	35.7 <i>P</i> = 0.01	21.1 <i>P</i> = 0.01

Grant *et al.*, in studies of the left atrium, have demonstrated that a portion of blood transport is due to passive stretching of the atrial wall during mitral valve closure.<sup>13</sup> When the mitral valve opens, the stored energy is released even before contraction. Even though our model is made of a silicone rubber (Silastic®) material, it appears to respond much in the same way. During the period when the tricuspid valve is closed the model atrium is distended by fluid draining from the reservoir, consequently adding to the output in a manner similar to the *in vivo* situation. The major difference between the *in vivo* atrium and our model is in its ability to contract. The contractile contribution to the output of the model is zero. However, at low heart rates the contractile mechanism in the living atrium is thought to be of little physiological importance.<sup>9,14</sup> Since we feel that this model is relevant to *in vivo* conditions, it may be possible to draw clinical implications from this study, especially in terms of the sitting position used during neurosurgical procedures. Since optimal aspiration with the multiorificed catheter occurred at an inclination of 80°, the full upright position and the less steeply angled 65° position may not be optimal in terms of air removal. In addition, exact localization of the catheter tip within the upper quarter of the right atrium appears to be critical. With the conventional single-orificed catheter this can be achieved radiographically and/or by P-wave changes as described by Michenfelder *et al.*<sup>5</sup>

Placement of the multiorificed catheter into the upper right atrium of the dog is also associated with discrete P-wave changes of the EKG. Upon approach to the SA node through the SVC, notching of the negative P-wave is observed. Entry into the right atrium results in a biphasic P-wave which becomes fully upright beyond the mid atrial position. It must be emphasized that these changes were observed in the dog and may not accurately

represent the human situation. Furthermore, each orifice of the multiorificed catheter views the electrical field generated by atrial depolarization from a slightly different perspective. Since all the orifices are common to a single conductor (saline in the catheter) the resultant wave form must represent a complex combination of the electrical potentials experienced by each orifice.

Further work must be done in humans to ascertain the possibility of localization of the multiorificed catheter in order to obtain optimal aspiration. It is possible that the use of cardiac ultrasound scanning together with the ECG might be a helpful guide in establishing the precise anatomical configuration of the catheter in the SVC or heart chamber.

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