CRITICAL CARE MEDICINE

Vol. 19, No. 3
Printed in U.S.A.

— Apparatus and Techniques —

Placement considerations for measuring thermodilution right ventricular ejection fractions

FRANCIS G. SPINALE, PHD; JAMES L. ZELLNER, MD; RUPAK MUKHERJEE, MS; FRED A. CRAWFORD, MD

Background and Methods: **Clinical examination of right ventricular (RV) performance has been hampered by the inability to measure easily RV volumes and ejection fraction. This study was performed to examine the effects of catheter position on thermodilution RVEF measurements. Six pigs (80 to 100 kg) were instrumented with an RV thermodilution catheter in the pulmonary artery, an injectate catheter in the right atrium, an atrial pacing electrode, and a systemic arterial catheter. RVEF measurements were determined using thermodilution in two ways: a) with incremental increases in pulmonary valve to thermistor distance; and b) with incremental increases in injectate port to tricuspid valve distance. These measurements were obtained at a paced rate of 102 ± 2 beats/min and then repeated with pacing-induced tachycardia (140 beats/min).**

Results: **There was no significant difference in thermodilution RVEF measurements with the thermistor positioned 0 to 10 cm from the pulmonary valve at either heart rate. A significant reduction in RVEF occurred with the injection port located 5 to 7 cm proximal to the tricuspid valve, with this decrease becoming more pronounced during tachycardia.**

Conclusions: **These results demonstrate that RVEF measurements can be reliably obtained using thermodilution. In these large hearts, thermodilution RVEF measurements appear to be independent of thermistor position within the pulmonary artery. However, large distances from injectate port to tricuspid valve reduced RVEF measurements. (Crit Care Med 1991; 19:417)**

KEY WORDS: **ventricular ejection fraction; stroke volume; thermodilution; heart; catheterization; pacemaker, artificial; pulmonary artery; pulmonary valve; tricuspid valve**

Clinical examination of right ventricular (RV) performance has been hampered by the inability to measure easily RV volumes and ejection fraction. Recent clinical and laboratory studies (1–4) have shown that RV volumes and RVEF can be successfully obtained using a fast response thermistor and thermodilution principles. This method obviates the need for geometric assumptions of RV shape, does not require the use of complex equipment, and allows for serial measurement of RV performance at the bedside. Several clinical studies (5–8) demonstrated the utility of the thermodilution method for monitoring RV function in critically ill patients. However, it has also been reported (4) that thermistor position within the pulmonary artery can affect thermodilution RVEF measurements. In large hearts, it may be necessary to position the distal port of the catheter, and thus the thermistor, an extended distance from the pulmonary valve to obtain measurements of pulmonary capillary occlusion pressure. The effect of thermistor position changes on thermodilution measurements of RVEF is unclear. Furthermore, in patients with enlarged hearts, the appropriate capillary occlusion position may be with the injectate port of the catheter located in the right ventricle. This approach would require repositioning the injectate port within the right atrium before thermodilution measurements. The effect of different

From Department of Surgery, Medical University of South Carolina, Charleston, SC (Drs. Spinale, Zellner, and Crawford), and the Department of Bioengineering, Clemson University, Clemson, SC (Mr. Mukherjee).

This study was supported, in part, by grants from the Baxter Healthcare Corporation and the American Heart Association, South Carolina Affiliate.

Dr. Zellner performed this work during a Research Fellowship Award from the Medical University of South Carolina, and Mr. Mukherjee during an internship from the Bioengineering Alliance of South Carolina.

0090-3493/91/1903-0417$03.00/0

injection positions within the right atrium on RVEF is unknown. The goal of this study was to examine catheter positioning effects on thermodilution measurements of RVEF in large hearts.

MATERIALS AND METHODS

Experimental Preparation

Six Yorkshire swine (80 to 100 kg) were anesthetized with 2% isoflurane and 1.5 L/min oxygen, and ventilated through a nonrecirculating anesthesia circuit. All animals were treated in accordance with the National Institutes of Health Guide for the Care and Use of Laboratory Animals (9) and approval of the project protocol was obtained from the Animal Review Committee at the Medical University of South Carolina. To examine the effects of both pulmonary artery and right atrial positioning on thermodilution RVEF measurements, it was necessary to use two catheters with the same thermal transfer characteristics that could be moved independently. Under fluoroscopic guidance, one RV thermodilution catheter (93A-431H-7.5, Baxter Healthcare, Irvine, CA), mounted with a rapid response thermistor, was positioned in the pulmonary artery via a femoral vein. The thermistor from this catheter was connected to a computer (REF-1, Baxter Healthcare) where the thermodilution curve was obtained and cardiac output ($\dot{Q}t$), RVEF, and volumes were computed. The theory employed in obtaining thermodilution RVEFs has been described previously (2, 4). A second thermodilution catheter divided just distal to the injectate port was advanced into the right atrium via an external jugular vein. The distal port of this injectate catheter was connected to a calibrated transducer for monitoring right atrial pressure. A microtipped transducer (7.5-Fr, PPG Biomedical Systems, Pleasantville, NY) was placed in the abdominal aorta via the femoral artery for monitoring systemic BP. Pressure values and thermodilution curves were recorded using a multichannel recorder (78304A, Hewlett-Packard, Andover, MA). In order to maintain a constant heart rate (HR) throughout the experiment, the animals were atrially paced at 100 to 104 beats/min (spontaneous anesthetized HR 90 ± 5 beats/min). A shielded stimulating electrode was positioned in the right atrial appendage and connected to an external pacemaker (5320, Medtronics, Minneapolis, MN). Bipolar limb leads were placed, an ECG was monitored continuously, and the analog ECG signal was input to the REF-1 ejection fraction computer. A percutaneous cystostomy was performed to maintain urinary drainage throughout the experiment.

Catheter Positioning

The injectate port was positioned just proximal to the tricuspid valve. This position was established by recording the pressure from the injectate port while advancing the catheter until an RV pressure trace was obtained and then slowly withdrawing the catheter until a right atrial pressure tracing was obtained. This position was then confirmed by infusing 5 mL of radiopaque dye through the injection port and visualizing the tricuspid valve. The rapid-response thermistor mounted on the pulmonary artery catheter was positioned just distal to the pulmonary valve using fluoroscopy. These catheter positions were considered the "zero" starting points for the experimental protocol.

Experimental Protocol

After a 30-min stabilization period, RVEF thermodilution measurements were performed with the thermistor and injectate port at the "zero position." The thermal indicator used was 5% dextrose in H_2O stored for 60 min to obtain a steady-state temperature of 0.0 to 1.4°C. A 10-mL bolus was delivered through the injection port at 50 psi within 2 sec using a power injector. The injections were performed at end-expiration with the exact temperature of the injectate recorded by a temperature probe located distal to the injection site (Co-set, Baxter Edwards, Irvine, CA). All thermodilution measurements were obtained in triplicate. The injectate catheter was then retracted in 1-cm increments from the tricuspid valve up to 5 cm. A final set of measurements were performed at 7 cm from the tricuspid valve. The thermistor location within the pulmonary artery was not changed during these measurements. After obtaining measurements at 7 cm proximal to the tricuspid valve, the injectate catheter was repositioned at the zero position. The pulmonary artery catheter and thermistor were then advanced in 2-cm increments up to 10 cm with measurements performed in triplicate at each position. The order in which the injectate and pulmonary artery catheters were manipulated was alternated with each animal.

In order to examine more closely the effect of atrial mixing on thermodilution ejection fraction measurements, atrial filling time was reduced by increasing the HR to 140 beats/min by atrial pacing. After a 15-min stabilization period at this increased HR, measurements were performed with the catheters in the zero position. The injectate catheter was

retracted and measurements were repeated. After completion of these measurements, the injectate catheter was placed at the zero position and thermodilution measurements were then performed with the thermistor positioned 0, 4, and 10 cm distal to the pulmonary valve.

Pulmonary Artery Volumes

On completion of the above protocol, the pulmonary artery catheter tip was placed 10 cm from the pulmonary valve, and a lethal dose of KCl was administered. A sternotomy was performed, the pulmonary artery catheter was clamped in place at the inferior vena cavae, and the heart and lungs were removed. The diameter of the pulmonary artery just above the pulmonary valve annulus was recorded and the path of the pulmonary artery catheter was carefully followed to the thermistor position; the diameter of the pulmonary artery at this location was recorded. The volume of the pulmonary artery for each thermistor position used in the study was then computed based on a model for a truncated cone (10).

Statistics

Comparisons of thermodilution RVEF and volumes obtained at each distance from the tricuspid and pulmonary valves were performed using analysis of variance (11). Pairwise tests of individual group means were compared using Tukey's procedure (11). The reproducibility of the three thermodilution RVEF measurements obtained at each distance were examined by obtaining the coefficient of variation for each set of triplicate measurements. Values of $p < .05$ were considered to be statistically significant and are reported as the mean ± SEM.

RESULTS

Pulmonary Artery Positioning

Figure 1 presents the RVEFs obtained after incremental increases in thermistor to pulmonary valve distances at HR 102 ± 2 and 140 beats/min. At the lower HR, a decrease in RVEF was observed when the thermistor was positioned >4 cm distal to the pulmonary valve; however, this decrease did not reach statistical significance. Similarly, with tachycardia, there was no significant change in RVEF observed with increased pulmonary valve to thermistor distance. The coefficient of variation was 5 ± 2% with no statistically significant differences between thermistor positions. Table 1 presents the hemodynamic and volumetric data obtained at each thermistor position. There were no significant differences in any of these hemodynamic indices measured for any thermistor position. Table 2 summarizes the hemodynamic data at an HR of 140 beats/min. There was no change in these values with different thermistor distances. Pulmonary artery volumes significantly ($p < .05$) increased at each thermistor position 8 cm distal to the pulmonary valve (Table 1).

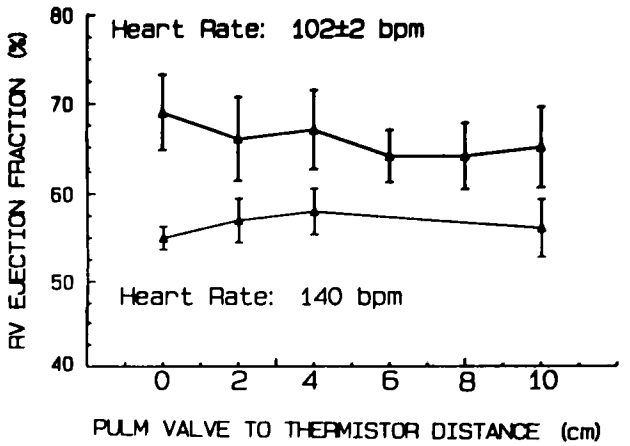

Figure 1. Thermodilution RVEF measurements with incremental increases in pulmonary valve to thermistor distance at HR 102 ± 2 beats/min (*top*), and at 140 beats/min (*bottom*). There was no significant difference in RVEF measurements at any thermistor position at either HR. *Error bars* reflect SEM.

Table 1. Hemodynamic data after changes in thermistor to pulmonary valve distances

	Thermistor Distance (cm)					
	0	2	4	6	8	10
HR (beats/min)	102 ± 2	102 ± 2	102 ± 2	102 ± 2	102 ± 2	102 ± 2
MAP (mm Hg)	92 ± 1	96 ± 2	95 ± 2	95 ± 2	96 ± 2	95 ± 3
MPAP (mm Hg)	22 ± 1	22 ± 1	22 ± 1	23 ± 1	23 ± 1	23 ± 2
Right atrial pressure (mm Hg)	7 ± 1	7 ± 1	7 ± 1	7 ± 1	7 ± 1	7 ± 1
$\dot{Q}t$ (L/min)	8.1 ± 0.5	8.07 ± 0.5	7.8 ± 0.4	7.9 ± 0.5	7.8 ± 0.5	7.9 ± 0.5
Pulmonary artery volume (mL)	—	4.07 ± 0.40[a]	7.59 ± 0.75[a]	10.6 ± 1.08[a]	13.4 ± 1.43[a]	15.8 ± 1.80[a]

[a]Significantly different from preceding value ($p < .05$, n = 6).

MAP, mean arterial pressure; MPAP, mean pulmonary artery pressure; RAP, right atrial pressure.

Table 2. Hemodynamic data with elevated HR

HR (beats/min)	140 ± 0
MAP (mm Hg)	95 ± 2
MPAP (mm Hg)	23 ± 1
RAP (mm Hg)	7 ± 1
$\dot{Q}t$ (L/min)	7.9 ± 0.3

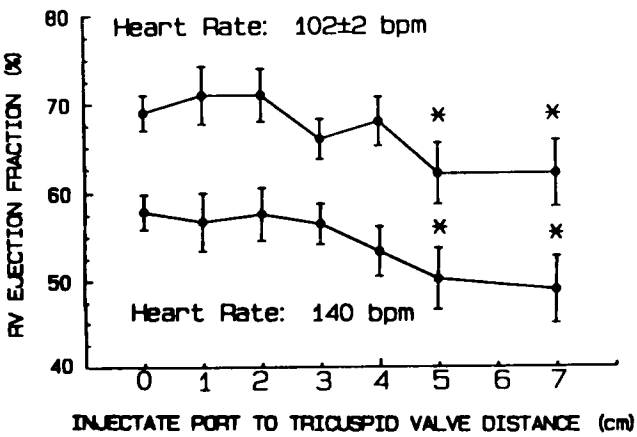

Figure 2. Thermodilution RVEF measurements with incremental increases in injectate port to tricuspid valve distance at an HR of 102 ± 2 beats/min (*top*), and at 140 beats/min (*bottom*). There was a significant ($p < .05$) reduction in RVEF measurements at 5 and 7 cm from the tricuspid valve at both HRs. *Error bars* reflect SEM.

Right Atrial Positioning

RVEFs obtained with increased tricuspid valve to injectate port distances are presented in Figure 2. At the lower HR, a significant ($p < .05$) decrease in RVEF was observed with the injectate port placed 5 and 7 cm proximal to the tricuspid valve. With tachycardia, a similar decrease in RVEF was observed with the injectate port located 5 and 7 cm from the tricuspid valve ($p < .05$) (Fig. 2). The variability within each set of triplicate RVEF measurements was similar to those measurements obtained with pulmonary artery positioning with the coefficient of variation 6 ± 2%. The coefficient of variation was not significantly different between any of the injectate port positions. Hemodynamic indices were very similar to those indices obtained by manipulation of the pulmonary artery catheter (Table 1), and did not change significantly with the incremental increases in injectate port to tricuspid valve distances. $\dot{Q}t$ did not change significantly with alterations in injectate port position with a coefficient of variation ranging from 2% to 5%. With tachycardia, there was no difference in the hemodynamic indices shown in Table 2, which did not change with any injectate port to tricuspid valve distance.

DISCUSSION

The use of thermodilution and a rapid-response thermistor provides a means to monitor easily and serially the RV function in a critical care setting (1, 5–8). While thermodilution provides a means to measure RVEFs and volumes at the bedside, the effects of catheter positioning are unclear. It may be necessary to position the catheter at various locations within the pulmonary artery from patient to patient to obtain satisfactory pressure measurements. This study examined whether various catheter positions affected RVEF thermodilution measurements in large hearts. Using a large animal model with an RV geometry similar to humans (12), the most important findings of this study were: a) there was no significant change in thermodilution RVEF measurements at any pulmonary valve to thermistor distance; b) excessive injectate port to tricuspid valve distances (5 to 7 cm) resulted in a significant attenuation of RVEF measurements.

To examine the effect of thermistor and injectate port position on thermodilution RVEF measurements, a hemodynamic steady-state model was used. The animals were paced at the same HR throughout the study, and aortic, pulmonary, and right atrial pressure were carefully monitored. The consistency in $\dot{Q}t$ measurements that were obtained during catheter manipulation gave further evidence that the animals were in a steady state, and thus meaningful comparisons of RVEFs with respect to catheter positioning could be made.

This study demonstrated that in large hearts, the rapid-response thermistor mounted on the RV thermodilution catheter can be positioned over a wide range of pulmonic valve to thermistor distances without significantly affecting RVEF measurements. We (4) reported previously that in smaller swine hearts, a significant reduction in RVEF thermodilution measurements occurs with increased pulmonary valve to thermistor distance. The difference in results obtained from this current study and the previous study is most likely due to differences in heart size and pulmonary artery volumes. In our previous study, the maximal pulmonary artery volumes were 3.7 ± 0.6 mL, whereas in the current study the maximal volumes were 15.8 ± 1.8 mL. In smaller pulmonary arteries with extended pulmonary valve to thermistor distances, thermodilution RVEF measurements may be attenuated due to secondary heating of the thermistor by the vessel wall and surrounding lung parenchyma. Results from this current study suggest that with large pulmonary artery volumes,

there is no significant change in thermodilution RVEF measurements with increased pulmonary valve to thermistor distance. Thus, heart and pulmonary artery size should be taken into account when positioning the RV thermodilution catheter.

To examine more closely the effect of moving the injectate port within the right atrium, right atrial filling time, and therefore mixing characteristics, were altered by increasing the HR. Studies (13) demonstrate that increased HRs will decrease right atrial filling times. At both HRs used in this study, there was a reduction in RVEF measurements when the thermistor was positioned >4 cm from the tricuspid valve. The reduction in RVEF with increased distances between the injectate port and the tricuspid valve is probably due to inadequate mixing of the thermal bolus, resulting in an unsteady temperature change from one RV contraction to the next. This study suggests that optimal catheter positioning occurs when the injectate port is located within the main body of the right atrium. Mohammed et al. (14) reported that improved $\dot{Q}t$ measurements were obtained when the thermal bolus was injected into the central portion of the right atrium.

We did not simultaneously measure RVEF using more established methods, such as ventriculography or radionuclide techniques. However, we (3, 4) have shown that the thermodilution method is significantly correlated to ventriculographic measurements of RVEF. The focus of the present study was not to perform a comparison with other methods, but to examine intrinsic variations that may occur with the thermodilution method when thermistor and injectate positions were manipulated. In a hemodynamic steady-state model, we assumed that a higher thermodilution RVEF measurement was an indication of optimal mixing characteristics and improved response at the thermistor. The higher RVEF measurements obtained in this study are the same as those obtained previously (4, 15) by our laboratory using a similar experimental preparation.

The coefficient of variation between each set of triplicate thermodilution measurements was low. This finding suggests that the reproducibility of the thermodilution technique is high and would be useful for serial monitoring of RVEFs. Vincent and colleagues (16) reported a similar coefficient of variation within each set of triplicate thermodilution measurements obtained in patients. Distinct advantages of thermodilution are that it is well suited for repeated measurements over a short period and is not predicated on geometric assumptions of RV shape as are other methods used to measure RV function (15, 17, 18).

In summary, results from this study demonstrated that in large hearts, the insertion of the thermodilution catheter within the pulmonary artery had little effect on RVEF thermodilution measurements. However, extended injectate port to tricuspid valve distances (>5 cm) may significantly reduce RVEF measurements. In light of these findings and previous reports, heart size should be carefully considered when positioning the RV thermodilution catheter.

REFERENCES

1. Jardin F, Gueret P, Dubourg O, et al: Right ventricular volumes by thermodilution in the adult respiratory distress syndrome. A comparative study using two-dimensional echocardiography as a reference method. *Chest* 1985; 88:34
2. Kay HR, Afshari M, Barash P, et al: Measurement of ejection fraction by thermal dilution techniques. *J Surg Res* 1983; 34:337
3. Spinale FG, Smith AC, Crawford FA: Right ventricular function using thermodilution. *Surg Forum* 1988; 39:242
4. Spinale FG, Smith AC, Carabello BA, et al: Comparison of thermodilution and ventriculographic methods for determining right ventricular function. *J Thorac Cardiovasc Surg* 1990; 99:141
5. Schulman DS, Biondi JW, Matthay RA, et al: Effect of positive end-expiratory pressure on right ventricular performance. Importance of baseline right ventricular function. *Am J Med* 1988; 84:57
6. Biondi JW, Schulman DS, Soufer R, et al: The effect of incremental positive end-expiratory pressure on right ventricular hemodynamics and ejection fraction. *Anesth Analg* 1988; 67:144
7. Dhainaut J-F, Brunet F, Monsallier JF, et al: Bedside evaluation of right ventricular performance using a rapid computerized thermodilution method. *Crit Care Med* 1987; 15:148
8. Eddy AC, Rice CL, Anardi DM: Right ventricular dysfunction in multiple trauma victims. *Am J Surg* 1988; 155:712
9. National Institutes of Health. Guide for the care and use of laboratory animals. Revised Edition. Bethesda, MD, National Institutes of Health. Publication No. 85-23
10. Weast RC, Selby SM: CRC Handbook of Tables for Mathematics. Fourth Edition. Cleveland, CRC Press, 1970, pp 16–17
11. Steel RGD, Torrie JH: Principles and Procedures of Statistics: A Biometrical Approach. Second Edition. New York, McGraw-Hill, 1980, pp 1–623
12. Lumb G, Singletary HP: Blood supply to the atrioventricular node and bundle of His: A comparative study in pig, dog, and man. *Am J Pathol* 1962; 41:65
13. Little RC, Little WC (Eds): Physiology of the Heart and Circulation. Chicago, Year Book Medical Publishers, 1989, pp 165–198
14. Mohammed S, Imig CJ, Greenfield EJ, et al: Thermal indicator sampling and injection sites for cardiac output. *J Appl Physiol* 1963; 18:742
15. Spinale FG, Carabello BA, Crawford FA: Right ventricular function and three-dimensional modeling using computer aided design. *Am J Appl Physiol* 1990; 68:1707
16. Vincent JL, Thirion M, Brimioulle S, et al: Thermodilution measurements of right ventricular ejection fraction with a modified pulmonary artery catheter. *Intensive Care Med* 1986; 12:33
17. Berger HJ, Matthay R: Radionuclide right ventricular ejection fraction. Applications in valvular heart disease. *Chest* 1981; 79:497
18. Ferlinz J: Right ventricular function in adult cardiovascular disease. *Prog Cardiovasc Dis* 1982; 25:225