Thermodilution right ventricular ejection fraction. Catheter positioning effects.

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Right ventricular (RV) ejection fractions have been difficult to estimate clinically. It has been demonstrated recently that RV ejection fractions can be calculated by thermodilution techniques using a rapid response thermistor and computer. This method critically depends on adequate mixing of the thermal bolus and sensing of the rapid response thermistor. This study examined the effects of the thermistor position within the pulmonary artery and injectate site within the right atrium on RV thermodilution ejection fraction measurements. Ten pigs were instrumented with a RV thermodilution catheter in the pulmonary artery, an injectate catheter in the right atrium, an atrial-pacing electrode, and a systemic arterial catheter. The RV ejection fractions were determined using thermodilution in two ways: (1) with incremental increases in pulmonic valve to thermistor distance, and (2) with incremental increases in injectate port to tricuspid valve. These measurements were obtained at a paced rate of 107 ± 1 beats per minute (bpm) and then repeated with pacing-induced tachycardia (140 bpm). The highest RV ejection fraction with the lowest coefficient of variation was with the thermistor 2 cm from the pulmonic valve (50 ± 2 percent), with a significant decline from this value at 10 cm (42 ± 4 percent, p < 0.05). This reduction in RV ejection fraction values with increased pulmonic valve to thermistor distance became more pronounced with tachycardia where a significant decline in RV ejection fraction occurred at 4 cm from the valve when compared with 0 cm (38 ± 6 percent vs 47 ± 3 percent, respectively, p < 0.05). There was no significant change in RV ejection fraction at any injectate port to tricuspid valve distance at the lower heart rate. With tachycardia, however, a significant decline in RV ejection fraction occurred with the injectate port located 7 cm from the tricuspid valve (p < 0.05). These results demonstrate that RV ejection fractions can be reliably obtained using thermodilution. Positioning of the thermodilution catheter is an important consideration for obtaining optimal RV ejection fraction measurements. Care should be taken to position the catheter with the thermistor a minimal distance from the pulmonic valve and the injectate port within the central body of the right atrium.

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For editorial comment see page 1054

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(1) different venous insertion methods are employed, (2) the catheter is to be used in smaller hearts such as those in small adults and pediatric patients, and (3) it may not allow for the measurement of pulmonary capillary occlusion pressures in large hearts. With small hearts, the requirement of positioning the injectate port just proximal to the tricuspid valve would place the thermistor a large distance from the pulmonary valve and may result in underestimation of RV ejection fraction. Secondly, placement of the injectate port at the tricuspid valve in small hearts may result in spontaneous pulmonary capillary occlusion of the catheter tip. Therefore, it would be desirable to retract the catheter from the tricuspid valve into the body of the right atrium to minimize the length of catheter within the pulmonary artery. However, the effect of right atrial mixing and the distance from the tricuspid valve on thermodilution RV ejection fractions is also unknown.

The purpose of this study was to (1) examine the effect of incremental increases in the distance of the injectate port from the tricuspid valve on thermodilution RV ejection fraction measurements, and (2) more precisely characterize the effect of pulmonic valve to thermodilutor distance on these thermodilution measurements.

METHODS

Experimental Preparation

Ten Yorkshire swines (25 to 30 kg) were anesthetized with 2 percent isoflurane and 1.5 L/min of oxygen and ventilated through a nonrecirculating anesthesia circuit. All animals used in this study were treated in accordance with the National Institutes Guide for the Care and Use of Laboratory Animals. The experimental preparation is presented in Figure 1. A femoral artery and vein were exposed and an externally calibrated microtipped transducer (PGC Biomedical Systems Inc, Pleasantville, NY) was placed in the abdominal aorta for monitoring systemic blood pressure. Under fluoroscopic guidance, a thermodilution RV ejection fraction catheter (83A-401IH-7.5, Baxter Healthcare Corp, Santa Ana, CA) was mounted with a rapid response thermistor positioned in the pulmonary artery. The thermistor from this catheter was connected to a computer (REF-1, Baxter Healthcare Corp, Santa Ana, CA) where the thermodilution curve was obtained and cardiac output, RV ejection fraction, and volumes were computed. The method employed for obtaining RV ejection fractions using thermodilution is presented in the Appendix. The distal lumen of the pulmonary artery catheter was connected to a calibrated and balanced transducer (P23-ID Statham, Gould Inc, Oxnard, CA) for monitoring pulmonary artery pressure. To examine the effects of both pulmonary artery and right atrial positioning on thermodilution ejection fraction measurements, it was necessary to use two catheters of the same thermal transfer characteristics that could be moved independently. This was accomplished by positioning one thermodilution catheter with a rapid-response thermistor in the pulmonary artery via the femoral approach. A second thermodilution catheter was cut just distal to the injectate port and was advanced into the right atrium from the jugular approach (Fig 1). The distal port of this modified catheter was connected to a calibrated transducer for monitoring right atrial pressure. Pressure values and thermodilution curves were recorded using a multichannel recorder (78304A, Hewlett Packard Corp, Andover, MA). To maintain a constant heart rate throughout the experiment, the animal was atrially paced (105 to 110 beats per minute [bpm]). Under fluoroscopy, a shielded stimulating electrode was positioned into the right atrial appendage and connected to an external pacemaker (Medtronic Inc, Minneapolis, MN). Bipolar limb leads were placed and an electrocardiogram (ECG) was continuously monitored using lead 1 and the analog ECG signal was input to the ejection fraction computer (REF-1). Finally, a percutaneous cystostomy was performed to maintain urinary drainage.

Catheter Positioning

The injection port was positioned just proximal (≤5 mm) to the tricuspid valve. This position was established by recording the pressure from the injectate port while advancing the catheter until a right ventricular 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 pulmonic valve using fluoroscopy. These catheter positions were considered the "zero" starting points for the experimental protocol described below.

Experimental Protocol

Following a 30-minute stabilization period, a triplicate set of thermodilution measurements were performed at the "zero position." The injectate catheter was then retracted in 1-cm increments from the tricuspid valve up to 5 cm with triplicate measurements performed at each position. A final set of measurements were performed at 7 cm from the tricuspid valve. All of these measurements were performed without changing the thermistor location within the pulmonary artery. Thermodilution measurements were then repeated with the catheters at the zero position. The pulmonary artery catheter was 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.
To more closely examine the effect of atrial mixing on thermodilution ejection fraction measurements, atrial filling time was reduced by increasing the heart rate to 140 bpm by atrial pacing. Following a 15-minute stabilization period at this increased rate, a set of measurements was performed with the catheters in the zero position. The injectate catheter was retracted as described above and measurements were repeated. Following completion of this sequence of measurements, the injectate catheter was placed proximal to the tricuspid valve, and thermodilution measurements were then performed with the thermistor positioned 0, 4, and 10 cm from the pulmonic valve.

**Pulmonary Artery Volumes**

On completion of the above protocol, the pulmonary artery catheter tip was placed 10 cm from the pulmonic valve, and a lethal dose of potassium chloride 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 in toto. The diameter of the pulmonary artery just above the pulmonic valve annulus was recorded and the path of the pulmonary artery catheter was carefully followed to the thermistor position and the diameter of the pulmonary artery at this location was recorded. The volume of the pulmonary artery between the pulmonic valve and the thermistor was computed for each position used in the study based on a model for a truncated cone.2

**Data Analysis**

The objective of this study was to examine changes in RV thermodilution ejection fraction measurements with respect to catheter position. In a hemodynamically steady-state model, the highest thermodilution ejection fraction measurements should reflect the best mixing characteristics and temperature sensing by the thermistor. Thus, comparisons were made with respect to the highest RV thermodilution ejection fraction measurements obtained in this study. Comparisons of thermodilution RV ejection fraction obtained at each distance from the tricuspid and pulmonic valves were performed using analysis of variance. The reproducibility of the three thermodilution RV ejection fraction measurements obtained at each distance was examined by obtaining the coefficient of variation for each set of triplicate measurements. If the analysis of variance revealed significant differences, pairwise tests of individual group means were compared using Tukey’s procedure.3

**Results**

**Pulmonary Artery Positioning**

Figure 2 presents the RV ejection fractions obtained with incremental increases in thermistor to pulmonic valve distances. The RV ejection fractions tended to increase with the thermistor positioned 2 cm from the pulmonic valve when compared with values obtained with the thermistor positioned just distal to the pulmonic valve. No statistically significant differences between RV ejection fractions at any pulmonic valve to thermistor distance were detected until the thermistor was 10 cm from the pulmonic valve. The RV ejection fractions were significantly lower at this distance when compared with the other thermistor positions used in this study (p < 0.05).

The coefficient of variation ranged from 7 to 10 percent with no statistically significant differences between thermistor positions. The highest coefficient of variation was observed at 4 cm from the pulmonic valve (10 ± 3 percent), with the lowest obtained at 2 cm (7 ± 1 percent).

As previously stated, the highest RV ejection fractions with the lowest coefficient of variation were obtained with the thermistor positioned 2 cm from the pulmonic valve. The differences between RV ejection fractions obtained at this 2-cm thermistor position and the thermistor positioned beyond 2 cm from the pulmonic valve are shown in Figure 3. The magnitude of the difference in RV ejection fractions from the 2-cm position steadily increased with increased thermistor to pulmonic valve distance and became statistically significant at 8 and 10 cm from the pulmonic valve (p < 0.05).

Table 1 presents the hemodynamic and volumetric data obtained at each thermistor position. There was no significant difference in aortic, pulmonary artery, and right atrial pressures at any thermistor position. In addition, there was no significant difference in cardiac outputs obtained at each thermistor position. The RV end-diastolic volumes tended to increase with
increased pulmonic valve to thermistor distance with a significant increase at 10 cm (p<0.05). Since this value is computed from RV stroke volume and ejection fraction (Appendix), and RV stroke volume remained unchanged (constant heart rate and cardiac output), then changes in end-diastolic volume reflect the changes in RV ejection fraction. Pulmonary artery volumes significantly increased with each thermistor position (p<0.05) up to 8 cm distal to the pulmonic valve. Pulmonary artery diameters decreased with each thermistor position (p<0.05).

Right Atrial Positioning

Right ventricular ejection fractions obtained with increased tricuspid valve to injectate port distances are presented in Figure 2. There was an increase in RV ejection fractions with each incremental increase in injectate port distance from the tricuspid valve up to 3 cm. Right ventricular ejection fractions began to decline with the injectate port placed beyond this distance. However, none of these changes reached statistical significance. The variability within each set of triplicate RV ejection fraction measurements was similar to those obtained with pulmonary artery positioning with the coefficient of variation ranging from 7 to 12 percent.

Cardiac outputs and mean aortic, pulmonary, and right atrial pressures were very similar to those obtained with manipulation of the pulmonary artery catheter (Table 1) and did not significantly change with the incremental increases in injectate port to tricuspid valve distances.

Elevated Heart Rate

A hemodynamic summary following pacing-induced tachycardia is presented in Table 2. Cardiac output increased from the first portion of the study (p = 0.09), with no statistically significant changes in aortic, pulmonary, or right atrial pressure (p>0.50). There was no significant change in these values during manipulation of the pulmonary artery or right atrial catheters. Right ventricular ejection fractions significantly declined with increased pulmonic valve to thermistor distance (Fig 4, p<0.05). While there was no significant decline in RV ejection fractions at 4 cm during the first part of the study, increasing the heart rate resulted in a significant decline in RV ejection fractions when the thermistor was positioned at or beyond 4 cm from the pulmonic valve (p<0.05). Unlike the first portion of the study, there was a significant decrease in RV ejection fractions obtained with the

### Table 1—Hemodynamic Data Following Changes in Thermistor to Pulmonic Valve Distances

<table>
<thead>
<tr>
<th>Thermistor Distance, cm</th>
<th>0</th>
<th>2</th>
<th>4</th>
<th>6</th>
<th>8</th>
<th>10</th>
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<tr>
<td>Heart rate, bpm</td>
<td>107±1</td>
<td>107±1</td>
<td>107±1</td>
<td>107±1</td>
<td>107±1</td>
<td>107±1</td>
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<tr>
<td>Mean aortic pressure, mm Hg</td>
<td>87±4</td>
<td>89±4</td>
<td>86±3</td>
<td>90±3</td>
<td>90±4</td>
<td></td>
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<tr>
<td>Mean pulmonary artery pressure, mm Hg</td>
<td>25±2</td>
<td>26±1</td>
<td>24±1</td>
<td>25±1</td>
<td>26±2</td>
<td></td>
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<tr>
<td>Right atrial pressure, mm Hg</td>
<td>7±1</td>
<td>6±1</td>
<td>7±1</td>
<td>7±1</td>
<td>6±1</td>
<td></td>
</tr>
<tr>
<td>Cardiac output, L/min</td>
<td>3.7±0.2</td>
<td>3.8±0.2</td>
<td>3.7±0.2</td>
<td>3.8±0.2</td>
<td>3.8±0.2</td>
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<tr>
<td>Right ventricular end-diastolic volume, ml</td>
<td>74±3</td>
<td>72±3</td>
<td>73±3</td>
<td>78±3</td>
<td>81±3*</td>
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<tr>
<td>Pulmonary artery diameter, mm</td>
<td>11.4±0.8</td>
<td>8.1±0.5*</td>
<td>6.5±0.4*</td>
<td>4.8±0.3*</td>
<td>3.2±0.2*</td>
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<tr>
<td>Pulmonary artery volume, ml</td>
<td>1.74±0.13*</td>
<td>2.99±0.06*</td>
<td>3.83±0.26*</td>
<td>4.35±0.29*</td>
<td>4.63±0.30*</td>
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*Significantly different from preceding value, p<0.05, n = 10.

### Table 2—Hemodynamic Data with Elevated Heart Rate

<table>
<thead>
<tr>
<th>Hemodynamic Data</th>
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<tr>
<td>Heart rate, bpm</td>
<td>140±0</td>
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<tr>
<td>Mean aortic pressure, mm Hg</td>
<td>88±2</td>
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<tr>
<td>Mean pulmonary artery pressure, mm Hg</td>
<td>27±2</td>
</tr>
<tr>
<td>Right atrial pressure, mm Hg</td>
<td>9±1</td>
</tr>
<tr>
<td>Cardiac output, L/min</td>
<td>4.2±0.5</td>
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fraction measurements were obtained with the ther-

merits became more pronounced with changes in
thermistor and injectate port distances. These results
indicate that catheter positioning has a significant
effect on thermodilution RV ejection fraction
measurements in these small hearts. In our study, the
highest RV ejection fractions with the lowest coeffi-
cient of variation were obtained with the thermistor
positioned 2 cm distal to the pulmonic valve and the
injectate port located within the central body of the
right atrium.

To examine the effects thermistor and injectate port
position had on thermodilution RV ejection fraction
measurements, a hemodynamic steady-state model
was used. The animals were paced at the same heart
rate throughout the study, and aortic, pulmonary, and
right atrial pressure were carefully monitored. The
consistencies in cardiac outputs that were obtained
during catheter manipulation gave further evidence
that the animals were in a steady state, and thus,
meaningful comparisons of RV ejection fractions with
respect to catheter positioning could be made.

To examine the effect of moving the injectate port
within the right atrium more closely, right atrial filling
caracteristics were altered by elevating the heart
rate. It has been previously demonstrated that in-
creased heart rates will decrease right atrial filling
times. With tachycardia, there was a decline in RV
ejection fraction measurements with the thermistor
positioned beyond 5 cm from the tricuspid valve.
Further, tachycardia resulted in a more pronounced
decline in RV ejection fraction measurements with
increasing distances from the thermistor to the pul-
monic valve. In the first part of the study, using lower
heart rates, a significant decline in RV ejection fraction
measurements was not detected until the thermistor
was 8 cm distal to the pulmonic valve. The reason
why the decline in RV ejection fraction measurements
occurred at a shorter thermistor to pulmonic valve
distance with tachycardia is unclear, but it may be
due to alterations in flow characteristics within the
pulmonary artery.

The probable causes for changes in RV ejection
fractions with increased distances between the injec-
tate port and the tricuspid valve are as follows: (1)
incomplete mixing of the thermal bolus resulting in
an unsteady temperature change from one RV con-
traction to the next; (2) with the location of the injectate
port high in the body of the right atrium, coronary
sinus flow may significantly influence the thermal
mixing characteristics; and (3) “streaming” of the
thermal indicator may occur due to inflow from the
superior vena cavae resulting in a nonhomogeneous
mixing of the thermal indicator. With the lower heart
rates used in the first part of this study, there was an
increase in RV ejection fractions when the injectate

Figure 4A (top). A decline in right ventricular (RV) ejection fractions
with increased thermistor to pulmonic valve distance became more
pronounced with tachycardia. A significant decline in RV ejection
fractions was obtained with the thermistor 4 cm distal to the
pulmonic valve, and it significantly fell from this value at 10 cm
from the pulmonic valve. B (bottom). During tachycardia, there was
a significant decline in RV ejection fractions with the injectate port
located 7 cm proximal to the tricuspid valve. Error bars indicate
standard error of the mean (*p<0.05).

INJECTATE PORT TO TRICUSPID VALVE DISTANCE (cm)

The use of thermodilution and a rapid-response
thermistor provides a means to serially monitor RV
function in the critical care setting. While thermo-
dilution provides a means to easily and safely obtain
RV ejection fractions and volumes at the bedside, the
effects of injection catheter positioning are
unknown. Therefore, the purpose of this study was
to examine the effect of changes in thermistor and
injectate port distances on RV ejection fraction
measurements in smaller hearts. The most important
findings of this study were the following: (1) with a
heart rate of 107±1 bpm, the highest RV ejection
fraction measurements were obtained with the
thermistor positioned 2 to 8 cm distal to the pulmonic
valve; (2) at this heart rate, there were no significant
differences in RV ejection fractions obtained with
the injection port located 2 to 7 cm proximal to the
tricuspid valve; and (3) at increased heart rates (140
bpm), the changes in RV ejection fraction measure-
ments became more pronounced with changes in
thermistor and injectate port distances.
obtained in this study are the same as those obtained previously by our laboratory using a similar experimental preparation.\textsuperscript{16,17}

Increased pulmonic valve to thermistor distance decreased thermodilution RV ejection fraction measurements, particularly during tachycardia. However, the variability within each set of measurements at all thermistor positions was relatively low (<12 percent). Therefore, while a statistically significant attenuation of thermodilution RV ejection fractions occurred with extended thermistor distances, these catheter positions may still be useful for serial monitoring of RV ejection fractions. Indeed, one of the important advantages of thermodilution is that it is well suited for repeated measurements over a short period. Thus, in certain patients where ideal placement of the catheter may not be possible, the RV ejection fraction measurements may not be an absolute value but rather provide valuable information on the relative changes in RV pump performance over time.

We employed relatively small animals (20 to 30 kg) for examining the positioning effects of thermodilution RV ejection fraction measurements. In these small hearts, we observed a decline in RV ejection fractions with increased distances between the thermistor and the pulmonic valve. There was no significant difference in RV ejection fractions when the thermal bolus was injected within the central body of the right atrium. With increased heart size, the pulmonary artery and right atrial volumes will be larger. Thus, optimal catheter positioning should be easier. Further, with greater pulmonary artery volumes, the attenuation of RV ejection fractions with increased pulmonary artery to thermistor distances may become inconsequential.

In summary, results from this study suggest that positioning of the thermodilution catheter is an important consideration for obtaining optimal RV ejection fraction measurements. In clinical practice, where the RV thermodilution catheter is to be used in smaller hearts, care should be taken to position the catheter with the thermistor a minimal distance from the pulmonic valve. In conjunction with these thermistor positioning requirements, the placement of the injectate port within the central body of the right atrium is also of importance.

\textbf{Appendix}

\textit{Thermodilution RV Ejection Fraction Measurements}

The rapid response thermistor, analog ECG signal, and injectate temperature probe were interfaced to the RV ejection fraction computer (REF-1). The thermal indicator used was 5 percent dextrose in water stored for 60 minutes 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 s 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, American Edwards, Santa Ana, CA). Following the injection, the thermodilution curve was plotted along with the synchronized R wave. If the time vs temperature trace did not approximate a lagged normal density curve, or the R wave triggering was incorrect, the measurement was repeated. All measurements were performed in triplicate.

The thermodilution catheter was mounted with a rapid-response thermistor (100 ms) capable of detecting beat to beat changes in pulmonary artery temperature. The thermistor response time of 100 ms refers to the time necessary to detect a 63 percent step change in temperature. The leads from the thermistor and the analog ECG signal were interfaced to the computer for signal processing. The heart rate was determined from the ECG input signal and a computer algorithm detected each R wave.

The RV ejection fraction was computed during the downslope of the thermodilution curve where it approximates a first-order exponential process. The thermodilution method is based on the principle of conservation of energy where the ratio of the temperature of the blood in the ventricle during the first systole and the temperature of the blood during the second systole are equated to an ejection fraction. The relationship between two successive temperature plateaus synchronized to the R-wave, during the thermal downslope, represents a residual fraction remaining in the ventricle and can be used to calculate an ejection fraction.

Cardiac output was determined by integrating the temperature change of the blood occurring in the pulmonary artery. The RV stroke volume was obtained by computer as the quotient of cardiac output and heart rate. With RV stroke volume and ejection fraction known, RV end-diastolic and end-systolic volumes were computed algebraically.

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