Thermal dilution measurement of pulmonary and systemic blood flow in secundum atrial septal defect, and transposition of great arteries with intact interventricular septum

Eric D. Silove, Michael J. Tynan, and A. J. Simcha
with the technical assistance of Brian Reeson and John Williams

From the Department of Clinical Physiology, The Hospital for Sick Children, Great Ormond Street, London

Thermal dilution was used to measure the outputs of the left and right ventricles separately in infants and children (1) with atrial septal defects, and (2) with transposition of the great arteries. In each patient the ratio of the ventricular outputs was compared with the ratio of pulmonary:systemic flow calculated by the arteriovenous oxygen difference method. A significant correlation was found between the thermal dilution and Fick methods of calculating these ratios. There was good reproducibility within each patient. The method has many advantages, the most important of which is its simplicity, safety, and repeatability.

The measurement of cardiac output is difficult in infants and children. In them the Fick and dye dilution methods both have distinct disadvantages. The Fick method requires cumbersome equipment, especially for measuring oxygen uptake. The dye dilution method requires the injection of a dye and the placement of an arterial catheter to sample large quantities of blood rapidly; furthermore, it is difficult to interpret the curves obtained in the presence of large shunts. Thermal dilution seems to avoid most of these problems.

Several workers have shown a significant correlation between cardiac output measurements by the thermal dilution, dye dilution, and Fick methods (Fegler, 1954; Goodyer et al., 1959; Evonuk et al., 1961; Cooper, Pinakatt, and Richardson, 1963; Branthwaite and Bradley, 1968). Silove, Cantez, and Wells (1971) described a thermal dilution method of measuring right and left ventricular outputs separately in dogs and found that it compared well with the dye dilution method. They injected small quantities of an isotonic solution at room temperature into either ventricle and recorded temperature change in the respective great artery. We have adapted this technique to study the ventricular outputs of infants and children with (1) secundum atrial septal defects, and (2) transposition of the great arteries with intact interventricular septum and no persistence of the ductus arteriosus. All patients had a communication between the systemic and pulmonary circulations at atrial level only.

Materials and methods

During diagnostic cardiac catheterization thermal dilution measurements were made in 13 patients with the diagnosis of secundum atrial septal defect and in 9 with transposition of the great arteries. In all these patients, selective angiography showed that there was no communication between the ventricles or great arteries. The ages and weights of the patients studied are shown in the Table.

Cardiac catheterization was always performed on the conscious patient. Infants under 6 months of age received no sedation or premedication. Older infants and children were given a premedication of a compound containing meperidine 25 mg, promethazine 6-25 mg, and chlorpromazine 6-25 mg for each 10 kg body weight.

Oxygen saturations were measured with the Kipp Haemoreflector M.O.I., individual calibration curves having been plotted at each cardiac catheterization. As oxygen consumption was not measured, no attempt was made to calculate the cardiac output by the Fick method. Assumed

Received 20 March 1972.

1 This study was supported by a grant from the British Heart Foundation.
TABLE Comparison of pulmonary:systemic flow ratios calculated by Fick and thermal dilution methods

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>Age (Yr) Mth</th>
<th>Weight (kg)</th>
<th>Fick method</th>
<th>Oxygen saturation %</th>
<th>Qp:Qs</th>
<th>Qp (l/min)</th>
<th>Qs (l/min)</th>
<th>(SE ±)</th>
<th>SE x 100%</th>
<th>Qs ml/min/kg</th>
<th>Qp:Qs</th>
</tr>
</thead>
<tbody>
<tr>
<td>TGA</td>
<td>1</td>
<td>37</td>
<td></td>
<td></td>
<td>1:18</td>
<td>1:02</td>
<td>(0:06)</td>
<td>5:9</td>
<td>276</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>2</td>
<td>43</td>
<td></td>
<td></td>
<td>0:65</td>
<td>0:96</td>
<td>(0:02)</td>
<td>1:8</td>
<td>222</td>
<td>0:7</td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>6</td>
<td>52</td>
<td></td>
<td></td>
<td>2:23</td>
<td>2:41</td>
<td>(0:19)</td>
<td>7:9</td>
<td>457</td>
<td>0:9</td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>4</td>
<td>62</td>
<td></td>
<td></td>
<td>0:50</td>
<td>0:75</td>
<td>(0:06)</td>
<td>8:0</td>
<td>121</td>
<td>0:7</td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>1</td>
<td>66</td>
<td></td>
<td></td>
<td>2:41</td>
<td>3:55</td>
<td>(0:02)</td>
<td>0:6</td>
<td>538</td>
<td>0:7</td>
<td></td>
</tr>
<tr>
<td>TGA</td>
<td>1</td>
<td>75</td>
<td></td>
<td></td>
<td>1:82</td>
<td>3:08</td>
<td>(0:22)</td>
<td>7:3</td>
<td>411</td>
<td>0:6</td>
<td></td>
</tr>
</tbody>
</table>

TGA 3 6 12:6 71 58 95 87 1:6 3:93 3:30 (0:14) 6:2 185 1:7
TGA 8 6 19:8 55 42 97 84 1:0 5:23 3:35 (0:11) 3:2 170 1:6
TGA 9 9 22:4 81 61 94 87 2:9 18:24 6:92 (0:26) 3:8 309 2:6
ASD 6 3 14:1 95 68 96 84 2:3 5:37 2:21 (0:06) 2:7 156 2:4
ASD 4 3 15:7 96 70 96 85 2:4 6:95 2:19 (0:06) 2:7 140 3:2
ASD 4 8 16:0 94 69 97 80 1:5 6:63 3:05 (0:22) 7:2 191 2:2
ASD 5 4 16:4 96 72 98 88 2:4 7:42 2:95 (0:15) 5:2 179 2:5
ASD 5 8 18:0 91 70 91 83 2:6 14:60 6:40 (0:48) 7:5 350 2:3
ASD 8 2 19:9 95 71 96 87 2:7 10:55 4:77 (0:07) 14 240 2:2
ASD 8 8 20:0 92 72 93 88 4:0 12:08 3:19 (0:04) 13 158 3:8
ASD 5 10 20:0 95 70 95 85 2:5 8:00 2:87 (0:13) 4:5 144 2:8
ASD 6 2 23:0 94 70 97 87 2:4 9:74 4:60 (0:12) 2:6 200 2:1
ASD 7 23:4 99 63 97 84 3:0 4:17 1:38 (0:10) 7:2 59 3:0
ASD 11 24:1 100 60 96 82 2:9 8:57 4:12 (0:12) 2:9 175 2:0
ASD 11 30:8 94 72 97 85 2:0 10:68 5:32 (0:16) 30 172 1:9

mean 338
SD 157
SE 64

Abbreviations: VC = mean value for venae cavae; Qp = pulmonary blood flow; Qs = systemic blood flow; ASD = atrial septal defect; TGA = transposition of the great arteries.

values were not used because there are conspicuous individual variations, and changes in the ambient temperature can profoundly alter the oxygen uptake of infants whether they are cyanosed or not. The ratio of pulmonary to systemic flow (Qp:Qs) was calculated from an adaptation of the Fick principle: Qp:Qs = Systemic arteriovenous oxygen saturation difference: Pulmonary arteriovenous oxygen saturation difference, where the systemic arterial, pulmonary arterial, and pulmonary venous oxygen saturations were the means of several measurements, and the systemic venous oxygen saturation was the mean of values obtained from the superior and inferior venae cavae.

For practical and technical reasons thermal dilution measurements were made after obtaining a complete set of blood samples for oxygen saturation. A radio-opaque thermistor catheter (YSI 530) was then passed through a Tuohy adaptor with a side-arm (B-D 315A) into a 6F Lehman catheter (U.S.C.I.), the tip of which had been placed into the pulmonary artery. The thermistor catheter was first advanced into a peripheral pulmonary artery and then both catheters were withdrawn together so that the thermistor lay in the main pulmonary artery or one of its primary branches, and the Lehman catheter tip lay in the ventricle below the pulmonary valve. Injections of 2-4 ml of 5 per cent dextrose in water at room temperature (20-25°C) were made into the side-arm of the Tuohy adaptor. In some instances the indicator was injected through a second cardiac catheter passed into the ventricle via the same vein. Injections were made with a B-D Cornwall continuous pipetting syringe. The volume of indicator was measured by subtracting the volume of the intravascular portion of the cardiac catheter from the injected volume. After pulmonary arterial thermal dilution curves had been obtained from this ventricular injection the same thermistor catheter was placed in the aortic arch. In patients with transposition of the great arteries the technique of placement in the aorta was similar to that described for the above pulmonary arterial placement and the injection catheter was withdrawn to the right ventricle. In patients with atrial septal defect the thermistor catheter was passed percutaneously into the femoral artery through a Seldinger needle (F160) and advanced to the aortic arch, while the injection catheter...
was placed in the left ventricle. Thermal dilution curves were then obtained from the aortic thermistor after injection of indicator into the sub-aortic ventricle.

Similar currents from similar sources were passed through both the thermistor and an offset potentiometer. The difference in voltage between the thermistor and the wiper of the potentiometer was amplified. This signal was then recorded on a potentiometric recorder (Rikadenki). The variation of resistance with temperature was made more linear by connecting in parallel with the thermistor a fixed resistor with a critical value determined by the temperature of the blood (Bryce and Hole, 1967). Thermistors were found to give a linear calibration through a range from 34° to 39°C, and the recorder was set to give a deflection of 5 to 10 cm for each 0.1°C change in temperature (full scale deflection of recorder was 25 cm). Before each injection the central blood temperature was read from the previously calibrated system. The indicator was in an open basin at room temperature, and its temperature was measured with a thermometer in the basin.

Each thermal dilution curve was analysed by exponential extrapolation of the downslope to the baseline and measurement of the area under the curve by planimetry. The cardiac output (i.e. right or left ventricular output), Q, in litres per minute was calculated by the formula:

\[ Q = \frac{V_i \times (T_b - T_i)K}{dT \times t} \]

where \( V_i \) = volume of injectate less dead space of injecting catheter, ml;
\( T_i \) = temperature of injectate, °C;
\( T_b \) = temperature of blood in great artery, °C;
\( dT \) = average temperature change, °C;
\( t \) = duration of temperature change, sec.

The constant K is derived as follows:

\[ K = \frac{D_i \times S_i}{S_b \times 1000} \]

where \( D_i \) = specific gravity of injectate;
\( S_i \) = specific heat of injectate;
\( S_b \) = specific heat of blood.

The means of the outputs obtained by 4 or 5 injections into each ventricle were calculated. In this way the ratio of the right:left ventricular outputs in the atrial septal defect group was calculated, or the left:right in the transposition of the great arteries group. For each patient this ratio was plotted against the Qp:Qs ratio obtained from the modified Fick method (arteriovenous oxygen differences) and the coefficient of linear correlation was calculated for the pairs of results.

**Results**

There was a significant correlation between the Fick and thermal dilution methods of estimating the ratio of pulmonary:systemic blood flow \((r = 0.91, P < 0.001)\) (Table and Fig.).

The thermal dilution measurement of systemic cardiac output (left ventricle in atrial septal defect, right ventricle in transposition of the great arteries) provided a mean value of 229 ml/min/kg. If the patients are grouped according to weight, the systemic output for the group 3.7 to 7.5 kg (6 patients) is 338 ml/min/kg (SE ± 64) and for the group 12.6 to 30.8 kg (16 patients) is 189 ml/min/kg (SE ± 17).

Evidence for reproducibility of the method within each patient is obtained from the Table. The standard error of the mean value for Qs in each patient was less than 8.0 per cent of Qs in all instances, and averaged 4.4 per cent of Qs.

**Discussion**

In this study thermal dilution proved to be a safe and relatively simple method of measuring cardiac output. The relation between the outputs of the two ventricles correlated closely to the pulmonary:systemic flow ratio based on the Fick method. Absolute values for cardiac output were obtained by the thermal dilution method and were found to be reproducible within each patient.

The safety and simplicity of the thermal dilution method of estimating cardiac output should prove useful in the clinical assessment of patients with congenital heart diseases.
The thermal dilution measurement of pulmonary and systemic blood flow

The thermal dilution cardiac outputs correlated significantly with values obtained by the Fick and dye dilution methods (Fegler, 1954; Goodyer et al., 1959; Evonuk et al., 1961; Cooper et al., 1963; Branthwaite and Bradley, 1968; Silove et al., 1971). We had previously shown that reliable thermal dilution estimates of cardiac output may be made by injecting indicator into the systemic ventricle and detecting temperature change in the aorta (Silove et al., 1971). Using a similar method we calculated the systemic cardiac outputs in our patients in the present study. The values we have obtained, when expressed as ml/min/kg, are generally higher than might be expected, and there is a wide scatter. In our smaller patients the systemic output averaged 338 ml/min/kg (SD = 157, SE ± 64) compared with a value of 232 ml/min/kg (SD = 42) obtained by Bur-nard, Grauaug, and Gray (1966) in normal newborn infants. Gessner et al. (1965), using the dye dilution method, produced even lower values. However, all our smaller patients had transposition of the great arteries in which it is probable that the systemic and pulmonary blood flows are both higher than normal (Noonan et al., 1960). In the larger patients the values for systemic cardiac output are, perhaps, more acceptable and the scatter is less (average = 184 ml/min/kg, SD = 68).

We are aware of two important potential sources of error in this study. There is some small variation in the diameters of the commercially produced thermistor catheters and cardiac catheters which we used. Ordinarily these differences are unimportant. However, when the thermistor catheter has been passed through the lumen of a cardiac catheter, a ‘tight fit’ reduces the residual lumen and increases the resistance to the injection of indicator. In some instances, therefore, the injection was slow. Consequently, the heat gained by the indicator in passing through the catheter was significant and our calculated cardiac output was correspondingly falsely high. Our other question concerns the adequacy of mixing of indicator with blood. Though we have good evidence in the dog that ventricular injections resulted in suitable mixing (Silove et al., 1971), the high outputs which we obtained in our human subjects lead us to suspect the accuracy of some of our results. It has even been suggested that an injection as far upstream as the superior vena cava may not achieve complete mixing at pulmonary artery level (Lange and Botticelli, 1963). The results of other studies would dispute this (Evonuk et al., 1961; Branthwaite and Bradley, 1968; Silove et al., 1971), but we acknowledge that it is not entirely excluded as a possible source of error.
of error. If these are sources of error, they provide consistent errors within any patient, because we found that the standard error of the mean value for Qs in each patient was generally less than 5 per cent of the mean value.

The authors thank Neil Picton Robinson, A.M. I.E., for advice and encouragement in the design of the thermal dilution measuring equipment, and Dr. Gerald Graham for his encouragement and criticisms.

References


Requests for reprints to Dr. Eric D. Silove, The Hospital for Sick Children, Great Ormond Street, London WC1N 3JH.