Thermal dilution measurement of pulmonary and systemic blood flow in secundum atrial septal defect, and transposition of great arteries with intact interventricular septum¹

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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 are 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 angiocardiography 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 Haemoreflexor 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

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TABLE Comparison of pulmonary:systemic flow ratios calculated by Fick and thermal dilution methods

Diagnosis	Age		Weight (kg)	Fick method				Thermal dilution						
	Yr	Mth		Oxygen saturation %				Qp: Qs	Qp (l./min)	Qs (l./min)	(SE±)	SE × 100%	Qs ml/min/kg	Qp: Qs
				Aorta	VC	Pul- monary veins	Pul- monary artery							
TGA		1	3.7	53	37	98	79	0.9	1.18	1.02	(0.06)	5.9	276	1.2
TGA		2	4.3	47	38	97	87	0.9	0.65	0.96	(0.02)	1.8	222	0.7
TGA		6	5.2	53	42	97	80	0.7	2.23	2.41	(0.19)	7.9	457	0.9
TGA		4	6.2	52	39	97	77	0.7	0.50	0.75	(0.06)	8.0	121	0.7
TGA	1	4	6.6	55	45	98	80	0.6	2.41	3.55	(0.02)	0.6	538	0.7
TGA	1	8	7.5	54	44	98	81	0.6	1.82	3.08	(0.22)	7.3	411	0.6
													mean 338	
													SD 157	
													SE 64	
TGA	3	6	12.6	71	58	95	87	1.6	3.93	2.33	(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)	1.4	240	2.2
ASD	8	8	20.0	92	72	93	88	4.0	12.08	3.19	(0.04)	1.3	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	4	21.8	98	67	98	85	2.4	10.89	4.22	(0.11)	2.6	194	2.6
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		24.2	100	60	96	82	2.9	8.17	4.12	(0.12)	2.9	171	2.0
ASD	11		30.8	94	72	97	85	2.0	10.08	5.32	(0.16)	3.0	172	1.9
													mean 189	
													SD 67	
													SE 17	

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: $Qp:Qs = \text{Systemic arteriovenous oxygen saturation difference} / \text{Pulmonary arteriovenous oxygen saturation difference}$, 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 (Pr160) 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:

$$Q = V_i \times (T_b - T_i) K / dT \times t$$

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:

$$K = D_i \times S_i \times 60 / D_b \times S_b \times 1000$$

where D_i = specific gravity of injectate;

S_i = specific heat of injectate;

D_b = specific gravity of blood;

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 $Q_p:Q_s$ 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 ($SE \pm 64$) and for the group 12.6 to 30.8 kg (16 patients) is 189 ml/min/kg ($SE \pm 17$).

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

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

FIG. Correlation of estimates of pulmonary:systemic flow ratio calculated by thermal dilution and Fick methods. The regression line is shown.

dilution method are its most appealing features. The technique enables frequent measurements of cardiac output to be made over a short period using small intravascular detectors which are easily calibrated. It avoids (1) the sampling of large quantities of blood; (2) the placement of catheters in more than one vessel; and (3) the problems of skin discoloration and pyrogenic reaction which may result from multiple dye injections. We had no difficulty in placing the thermistor in the pulmonary artery or aorta in patients with transposition of the great arteries or atrial septal defect. In transposition of the great arteries we found that a preformed loop at the tip of the catheter facilitated manipulation into the pulmonary artery from the left ventricle. The thermistor catheter, when passed beyond the tip of the cardiac catheter, was easily visualized with an image intensifier. A small thermistor and the newly described circuit which we used allowed the current through the thermistor to be so small that it reduced by a factor of 30 the small degree of heating that occurs with a bridge circuit (Hosie, 1962).

We had previously shown in dogs that there is no significant difference between the left and right ventricular outputs measured by the same thermal dilution technique as in the present study (Silove *et al.*, 1971). Our earlier experiments had also shown no significant difference between those thermal dilution outputs and values obtained by the conventional dye dilution method. This suggested that adequate mixing of indicator and blood occurred after a ventricular injection. Thus it might have been expected that, in the presence of interatrial shunts, the ratio of the ventricular outputs obtained in the present study should have given a reliable estimate of the pulmonary:systemic flow ratio ($Q_p:Q_s$). We did find a significant correlation between the ratio of the ventricular outputs and $Q_p:Q_s$ calculated from oxygen data. Since both methods gave similar results it is likely that they are both reasonably reliable as a guide to the relation between pulmonary and systemic blood flows. The Fick method is widely employed for calculating $Q_p:Q_s$ on a routine basis, but its value is frequently questioned. Our results suggest that it is a valid method, but we emphasize that our own oxygen data made use of the mean values of at least three measurements of oxygen saturation at each site. It is also clear that neither method accounts for bronchial blood flow; both therefore, are subject to the same error in this regard.

Several studies may be cited in which ther-

mal 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 ($SD = 157$, $SE \pm 64$) compared with a value of 232 ml/min/kg ($SD = 42$) obtained by Burnard, 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. 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.

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