Estimation of Intracardiac Shunts in Congenital Heart Disease.
A comparison of the dy-edilution and the Fick methods

Hong Do Cha, Honggil Kim, Chung Sam Suh,
Hae Kun Park and Pill Whoon Hong

Departments of Internal Medicine, Surgery, and Cardio-Pulmonary Laboratory
Yonsei University College of Medicine, Seoul, Korea

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ABSTRACT

During cardiac catheterizations in 20 cases with congenital heart disease, intracardiac shunts were measured by two methods, dye dilution method and the Fick method, and the results were compared.

Arterial dilution curves were used for the estimation of both the right-to-left and left-to-right shunts. Venous dilution curves were used for measurement of left-to-right shunts.

In cases with a left-to-right shunt, the amount of the shunt was expressed as per cent of total pulmonary blood flow and, in cases with a right-to-left shunt, as per cent of total systemic blood flow. The following results were obtained.

1. In 8 cases with a right-to-left shunt, the amount of the shunt was 35.6±18.1% by the Fick method and 34.0±19.2% by arterial dilution curves. The difference was not statistically significant (p>0.1).

In 15 cases with a left-to-right shunt, the amount of shunt was 41.3±26.6% by the arterial dilution curve and 36.6±14.0% by the Fick method. The difference was not statistically significant (p>0.1).

Also venous dilution curve was performed in 8 cases of left-to-right shunt and the amount of the shunt was 33.0±21.0%, as compared to 35.5±17.3% by the Fick methods. The difference was not statistically significant (p>0.1).

2. Arterial dilution curves could be used to localize right-to-left shunts and venous dilution curves left-to-right shunts, whereas the Fick method was helpful only for the localization of left-to-right shunts.

3. It was possible to detect small left-to-right (less than 10%) and right-to-left (less than 5%) shunts by dye dilution curves, which was not possible with the Fick method.

4. In detection of small intracardiac shunts as well as in shunt localization, the dye dilution method was more accurate than the Fick method. The difference of the amount of the shunt estimated by the two methods was not statistically significant.

INTRODUCTION

A dye dilution curve is a plot of concentration of a dye at a given site in the circulation against time after injection of the dye at another site in the blood stream. The dye dilution curves are separated into arterial dilution curves and venous dilution curves. An arterial dilution curve is defined as a recording of the concentration of a dye from any site in the arterial circulation or from the left side of the heart. A venous dilution curve is defined as a recording of the concentration of a dye at any site in the venous circulation or right side of the heart.

Stewart was the first to use a dye dilution method for measuring cardiac output in 1897. He used a continuous infusion method and chose hypertonic saline solution as an indicator. He determined its concentration in the arterial blood by measuring the change in electrical conductivity of the blood. By applying the Fick principle, he was able to calculate the cardiac output.
In 1913 Henriques used a single injection techniques for measurement of cardiac output. He devised the formula that is used today in the single injection method and also recognized the importance of recirculation of a dye as a possible error in the method.

In 1929 Kinsman et al. developed a technique to correct for recirculation of the dye. The method proposed by them for correcting the curve depends upon plotting the curve on a semilogarithmic graph paper. On this semilogarithmic graph paper the downslope of the curve became a straight line to the point of recirculation and by continuing the straight line beyond the recirculation, they could obtain a primary curve involved in the recirculation curve. To validate this method of correction for the recirculated dye, they constructed a model and the semilog nature of the downslope of the curve was proved. Since that time, the semilog method for correcting the curve has been considered accurate.

Cardiac output measured by the dye dilution method was compared with the Fick method by several investigators (Moore et al., 1929; Hamilton et al. 1948; and Doyle et al., 1953). They proved that dye dilution was an accurate and reliable method.

After the establishment of the dye dilution method as accurate for measuring cardiac output, Kunston et al. (1950) and Nicholson et al. (1951) began to apply the arterial dilution curve in the detection of intracardiac shunts and other hemodynamic changes in patients with heart diseases. They reported that specific abnormal dilution curves were observed in congenital heart diseases with intracardiac shunts. At present, the arterial dilution curve is being used not only for the estimation of the cardiac output but also for detecting intracardiac shunts in congenital heart disease.

In 1957, Fox and Wood began to apply venous dilution curves to localize left-to-right shunts because the arterial dilution curve did not yield information on the site of left-to-right shunts.

The amount of the shunt estimated by the dye dilution curve was compared with the Fick method by several investigators (Davis et al., 1958; Carter et al., 1960; and Swann et al., 1953), and found to correlate well.

The purpose of this article is to present our data on the estimation and comparison of intracardiac shunts determined by the dye dilution curve and Fick methods.

**MATERIAL AND METHOD**

During right heart catheterizations in 20 patients with congenital heart disease, intracardiac shunt was estimated by the two methods, Fick and dye dilution, and the shunt volume thus determined was compared. The same studies were performed in 2 patient without an intracardiac shunt.

**Fick method:**

Oxygen consumption for the Fick method was measured in a 9 liter Collins spirometer. The value was corrected to STPD. Blood samples were obtained, two in the pulmonary artery, two or three in the right ventricle, two or three in the right atrium and each one in the inferior and superior vena cava. Oxygen content was determined by the Van Slyke and Neill manometric method (1924). Because there is a normal variation of oxygen content in different locations of the same chamber and between each chamber of the right heart and pulmonary artery, a left-to-right shunt was considered to be present when the difference of oxygen between the chambers was above the normal value as shown in Table 1 (Gorlin, 1959). Right-to-left shunt was considered to be present when systemic arterial saturation was below 92%. In the Fick method, the amount of shunt was estimated by following equations.

\[ \text{Oxygen consumption (ml/min) } \times 100 \]
\[ \text{Systemic arterial O}_2 \text{ content } - \text{mixed venous O}_2 \text{ content} \]

\begin{align*}
1. \text{ Left-to-right shunt} & = \text{total pulmonary flow} \\
& - \text{effective pulmonary flow} \\
2. \text{ Right-to-left shunt} & = \text{systemic flow} \\
& - \text{effective pulmonary flow}
\end{align*}
b) Pulmonary flow = \( \frac{\text{Oxygen consumption (ml/min) × 100}}{\text{Pulmonary venous } O_2 \text{ content}} - \text{pulmonary artery } O_2 \text{ content} \) (ml/min)

c) Effective pulmonary flow (ml/min) = \( \frac{\text{Oxygen consumption (ml/min) × 100}}{\text{Pulmonary venous } O_2 \text{ content} - \text{mixed venous } O_2 \text{ content}} \)

Table 1. Normal variations in blood oxygen content in different locations of the right heart (Gorlin, 1959)

<table>
<thead>
<tr>
<th>Site</th>
<th>Maximal variations in oxygen content of successive samples v. P.C.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Within Chamber</td>
</tr>
<tr>
<td>Pulmonary Artery</td>
<td></td>
</tr>
<tr>
<td>1. Right and/or Left</td>
<td>0.4</td>
</tr>
<tr>
<td>2. Main</td>
<td></td>
</tr>
<tr>
<td>Between</td>
<td>+0.5</td>
</tr>
<tr>
<td>Right Ventricle</td>
<td></td>
</tr>
<tr>
<td>3. Below Pulmonic Valve</td>
<td>0.8</td>
</tr>
<tr>
<td>4. Mid Ventricle</td>
<td>1.8</td>
</tr>
<tr>
<td>Between</td>
<td>+0.9</td>
</tr>
<tr>
<td>Right Atrium</td>
<td></td>
</tr>
<tr>
<td>5. Lower</td>
<td>1.5</td>
</tr>
<tr>
<td>6. Mid</td>
<td>2.3</td>
</tr>
<tr>
<td>7. Upper</td>
<td></td>
</tr>
<tr>
<td>Between</td>
<td>+1.9 (Sup)</td>
</tr>
<tr>
<td>Vena Cava</td>
<td></td>
</tr>
<tr>
<td>8. Superior</td>
<td>0.6</td>
</tr>
<tr>
<td>9. Inferior</td>
<td>0.8</td>
</tr>
</tbody>
</table>

In cases with a right-to-left shunt, pulmonary venous \( O_2 \) content was assumed to be 97% of arterial \( O_2 \) capacity. Effective pulmonary flow means pulmonary flow returned to lungs via great venous system. The volume of the left-to-right shunt was expressed, not in milliliters, but as per cent of pulmonary flow and the volume of the right-to-left shunt as per cent of total systemic flow.

**Dye dilution method:**

Tricarbocyanine dye (cardiogreen, Fox et al., 1957) made up as 5.0 mg/ml solution was used as the indicator for dye dilution curves. One end of the calibrated plastic tube containing 1.0 ml of the dye was connected to Courand catheter and the other end to a 10.0 ml syringe containing 6.0—8.0 ml of normal saline. The dye was introduced into the desired location of the circulatory system by sudden manual injection, followed immediately by flushing with normal saline. Blood was withdrawn with a Harvard constant withdrawal pump through a Courand needle for arterial dilution curves and through a Courand catheter located in the right side of the heart for venous dilution curves.

In the arterial dilution curves, Carter's method (1960) was used for the estimation of the left-to-right shunts and Swann's method (1953) for the estimation of the right-to-left shunts. In venous dilution curves the left-to-right shunt was estimated by Wood's method (1958).

**Carter's method:**

\[
\text{Left-to-right shunt(%) = } 141 - \frac{C(P + BT)}{CP} - 42
\]

\( C; \) Peak concentration
\( C(P + BT); \) Concentration at interval after the peak concentration equal to build up time

**Swann's method:**

\[
\text{Right-to-left shunt(%) = } \frac{\Delta S}{\Delta S + \Delta P}
\]

\( \Delta S; \) an area of forward triangle formed by shunted dye
\( \Delta P; \) an area of forward triangle formed by dye taking normal pathway via pulmonary system

**Wood's method:**

\[
\text{Left-to-right shunt(%) = } \frac{A_{Pa} - Pa}{A_{Pa} - Sa}
\]

\( A_{Pa} \): The area of the forward triangle portion of the curve recorded from blood withdrawn from the main pulmonary artery after an injection into a lobar pulmonary artery
\( A_{Pa} \): The area of the forward triangle portion of the curve recorded at a systemic artery after an injection into a lobar pulmonary artery
RESULTS

The dye dilution curves were recorded in patients without an intracardiac shunt, with left-to-right shunts and with right-to-left shunts.

1. Normal dye dilution curves

Normal dye dilution curves were recorded in two persons without a shunt. The dilution curves were separated into arterial dilution curves and venous dilution curves.

a) Arterial dilution curves

Fig. 1A shows a normal dye dilution curve obtained in a patient without a shunt. Cardiogreen 5.0 mg was injected into pulmonary artery and blood was sampled in the right brachial artery.

Appearance time of the dye is rapid and ascending limb of the curve is steeper than descending limb. After concentration of the dye returned to near base line, it rises again toward the recirculation peak.

b) Normal venous dilution curves

Fig. 1 B and C was normal venous dilution curves obtained in a patient without a shunt. The cardiogreen was injected into a pulmonary artery and sampled in the right ventricle and right atrium. The venous dilution curves show a delayed appearance time and lower peak concentration as compared with normal arterial dilution curves. Also the recirculation peaks are not clear.

2. Dye dilution curves in patients with left-to-right shunts

a) Arterial dilution curves

Arterial dilution curves were obtained in 15 patients with a left-to-right shunt and a typical curve is seen in Fig. 2. The maximum concentration is lower and descending slope slower as compared with a normal arterial dilution curve. Though the recirculation peak is not clear, appearance time of the dye is normal.

The magnitude of the left-to-right shunt estimated by dye dilution curves was compared with that by the Fick method, as seen in Table 2 and Fig. 3. The mean value of the left-to-right
b) Venous dilution curves

In 8 patients with a left-to-right shunt, venous dilution curves were performed. A typical curve is seen in Fig. 4B. In the presence of a left-to-right shunt, the venous dilution curves were characterized by an early appearance time of the dye and double peaks. The earlier peak is due to shunted dye and obtained in the location of the shunt (i.e., pulmonary artery in cases with a patent ductus arteriosus) or in downstream from the shunt (pulmonary artery branch). The second peak is due to normal circulation of the dye. The normal venous dilution curve was recorded in the chambers upstream to the shunt (right atrium or right ventricle, Fig. 4 C). In a cases with a patent ductus arteriosus, normal and abnormal pathways of the dye are illustrated in Fig. 5.

The magnitude of the left-to-right shunt estimated by venous dilution curves was compared with that by the Fick method and Carter’s method as seen in Table 3. The mean value of the left-to-right shunt estimated by venous dilution curves and Fick method was $33.0 \pm 21.0\%$ and $35.5 \pm 17.3\%$, respectively. The difference of
Fig. 4. Arterial and venous dilution curves in left-to-right shunt (Case 69, F, 20-patent ductus arteriosus).
A. Arterial dilution curve
B. Venous dilution curve obtained in pulmonary artery
C. Venous dilution curve obtained in right ventricle

Sample site:

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Fig. 5. Normal and abnormal pathways of the dye with respective dye dilution curves in patent ductus arteriosus.
(Mark + -Injection site, o -Sampling site)

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Table 3. Comparison of intracardiac shunts estimated by Wood's, Carter's and Fick methods in left-to-right shunts

<table>
<thead>
<tr>
<th>No.</th>
<th>Name</th>
<th>Sex</th>
<th>Age</th>
<th>Diagnosis</th>
<th>Artery</th>
<th>Venous</th>
<th>Fick</th>
</tr>
</thead>
<tbody>
<tr>
<td>69</td>
<td>S J H</td>
<td>F</td>
<td>28</td>
<td>Patent ductus arteriosus</td>
<td>25.7</td>
<td>24.0</td>
<td>37.6</td>
</tr>
<tr>
<td>50</td>
<td>S S B</td>
<td>F</td>
<td>13</td>
<td>Ruptured aneurysm of the aortic sinus</td>
<td>10.0</td>
<td>7.0</td>
<td>0.0</td>
</tr>
<tr>
<td>95</td>
<td>L J S</td>
<td>M</td>
<td>14</td>
<td>Ventricular septal defect</td>
<td>80.0</td>
<td>75.0</td>
<td>58.7</td>
</tr>
<tr>
<td>87</td>
<td>S W H</td>
<td>F</td>
<td>25</td>
<td>Ventricular septal defect with pulmonary hypertension</td>
<td>50.0</td>
<td>33.6</td>
<td>39.5</td>
</tr>
<tr>
<td>80,0</td>
<td>L J W</td>
<td>M</td>
<td>19</td>
<td>Ventricular septal defect with pulmonary hypertension</td>
<td>42.7</td>
<td>9.0</td>
<td>39.2</td>
</tr>
<tr>
<td>76</td>
<td>H C S</td>
<td>M</td>
<td>20</td>
<td>Ventricular septal defect with pulmonary stenosis</td>
<td>14.0</td>
<td>36.8</td>
<td>21.0</td>
</tr>
<tr>
<td>94</td>
<td>P Y K</td>
<td>M</td>
<td>27</td>
<td>Ventricular septal defect with pulmonary stenosis</td>
<td>46.2</td>
<td>32.0</td>
<td>51.5</td>
</tr>
<tr>
<td>71</td>
<td>K H M</td>
<td>M</td>
<td>31</td>
<td>Cushion defect</td>
<td>37.0</td>
<td>46.6</td>
<td>35.8</td>
</tr>
</tbody>
</table>

Mean 38.2 33.0 35.5
SD 22.3 21.0 17.3
SE 8.0 7.7 6.2
Significance

artery: venous P<0.1
artery: Fick P<0.1
venous: Fick P<0.1

Arterial dilution curves were obtained in 8 patients with a right-to-left shunt and a typical curve is shown in Fig. 6B. The curve shows an early appearance time and double peaks. The first peak is due to the shunted dye taking a short pathway and the second peak shows a normal circulation of the dye. This curve was obtained when the dye was injected into the site of the shunt (right ventricle in a case of a ventricular septal defect and pulmonary hypertension), or upstream of the shunt (right atrium).

A normal dilution curve was obtained when the dye was injected into a site downstream from the shunt (pulmonary artery), as shown in Fig. 6A. In a case of ventricular septal defect with pulmonary hypertension and a right-to-left shunt, normal and abnormal pathways of the dye are illustrated in Fig. 7. The magnitude of the
right-to-left shunt estimated by Swann’s method was compared with that by the Fick method as shown in Table 4. The mean value of the shunt estimated by two methods is 34.0±19.2% and 36.6±18.1%, respectively. The difference of the mean value was not statistically significant (p>0.1) and the correlation coefficient was 1.0.8

**DISCUSSION**

For many years, the Fick method has been used as the standard means for estimating the cardiac output and detecting intracardiac shunts in patients with congenital heart diseases. It is a simple and effective method and has served as a valuable tool in the diagnostic as well as in the hemodynamic studies of these patients. However, it is a cumbersome method involving analysis of multiple blood samples for oxygen content. Perhaps more important is the fact that the accuracy by this method is dependent upon obtaining fully mixed venous blood samples which is difficult to achieve even under ideal conditions. The not inconsiderable variation in the oxygen content of the blood sampled from the different chambers of the right heart and pulmonary artery and even from different locations in the same chamber in normal persons is well known. Thus it is impossible to detect a small left-to-right shunt by the Fick method when the step-up of oxygen content in the right side of the heart does not exceed that of the normal variation. (Warren, 1946).

Since Kunston et al. (1950) published their work on the use of the dye dilution method in the study of congenital heart disease, this method has been used extensively by others. It has been found particularly useful in the detection of small intracardiac shunts. Thus, Swann et al. (1954) reported that they were able to detect a small right-to-left shunt (less than 5%) by the dye method, which they could not with the Fick method. Similarly, Russel et al. (1958) stated that they were able to detect a small left-to-right shunt (less than 10%) with the dye method but not with the Fick method. Others reported that the sensitivity of the dye method was equal to the nitrous oxide method (Morrow et al., 1958), and the radioactive gas method (Case et al., 1958; Sanders, 1958) but it was not as sensitive as the hydrogen electrode method (Vogel et al., 1962).

In our experience also the dye dilution method was found to be more sensitive than the Fick method in detecting small intracardiac shunts. In all cases in whom there was a right-to-left shunt by the Fick method, it was possible to detect these shunts by the dye method as well. The magnitude of the shunt estimated by the
two methods was found to be equal. In addition, in a few patients with a small shunt which could not be detected with the Fick method, it was possible to detect it by the dye method. Case 32 is a good example in which the right-to-left shunt was only 2%, which was impossible to detect by the Fick method but possible with the dye method. In patients with a left-to-right shunt, the arterial dilution curve was at least as effective as the Fick method in detecting the shunt and the shunt volume calculated by the two methods was comparable. Moreover, the venous dilution curves in these patients made it possible to detect small left-to-right shunts (less than 10%), which was impossible to do with the Fick method, as shown in case 50.

In the estimation of the left-to-right shunt, there was essentially no difference among the venous dilution method, Crater’s method, and the Fick method but the correlation coefficient was poor. One of the reasons for this was the fact that it was difficult to sample the blood far enough away from the site of the shunt in a venous dilution study and therefore the blood had not been thoroughly mixed with the dye. This was illustrated in case 80 with a ventricular septal defect in which the sampling of the dye was done in the right ventricle but not in the pulmonary artery due to technical difficulties. If the dye sample had been taken sufficiently downstream from the shunt in the pulmonary artery, the correlation coefficient between Wood’s and Fick methods would have been the same as that between Swann’s and Fick method.

In the localization of the site of the intracardiac shunt, which is so important in the diagnosis as well as in the treatment of the anomalies, the dye dilution method played an important role. While it was impossible to detect the site of a left-to-right shunt by the arterial dilution method, this was readily done with the venous dilution curve. The arterial dilution curve was more effective in illustrating a right-to-left shunt which was impossible with the Fick method.

One final advantage the dye method has over the Fick method is the fact that it gives an immediate result on the monitor screen when the dye is injected. This gives the operator the necessary informations during the catheterization study which will guide him to select the next steps. Thus, the dye dilution and the Fick method complement each other in their effectiveness in detecting the shunts and determining their locations. By combining these methods, it is usually possible to diagnose the magnitude and site of the intracardiac shunts in most congenital lesions of the heart.

REFERENCES

(Quoted from Guyton’s Circulatory physiology. W. B. Saunders Company, 1963.)