Relative Contribution of Blood from Each Lung to the Left-to-Right Shunt in Atrial Septal Defect

Demonstration by Indicator-Dilution Technics

By H. J. C. Swan, M.B., Peter S. Hetzel, M.D., Howard B. Burchell, M.D., and Earl H. Wood, M.D.

Arterial dilution curves of T-1824 have been recorded by oximeters after injection of T-1824 into both the right and left pulmonary arteries in patients with anomalous connections of the pulmonary veins, with atrial septal defects or with persistent common atrioventricular canals. The most extreme differences were found between the pairs of curves in the patients with the anomalous connection. These differences were less pronounced but clearly recognizable in the other conditions, and suggested a more general use of the term "anomalous pulmonary venous drainage." The findings indicate that, in the usual case of atrial septal defect, a greater proportion of the blood from the right lung passes to the right atrium than does blood from the left lung.

The term "anomalous pulmonary venous connection" has been proposed to designate the anomaly of a pulmonary vein passing to the right atrium or to a tributary thereof. Such a term also may include the condition in which a pulmonary vein communicates with the left atrium by way of an abnormal venous channel. It is thought that the term "anomalous pulmonary venous drainage" applies more appropriately to any hemodynamic situation in which blood from the pulmonary veins passes into the right atrium and is recirculated through the lungs.

Within the limits of these definitions, anomalous pulmonary venous drainage is a relatively common condition, since it includes the usual case of atrial septal defect in addition to cases of anomalous pulmonary venous connection. However, atrial septal defects frequently are found in patients who have anomalous pulmonary venous connections. Furthermore, some examples of anomalous connection are associated with a larger atrial septal defect, the posterior margin of which cannot be defined. In these cases, anomalous pulmonary veins usually pass into the lateral wall of the right atrium about midway between the superior and inferior venae cavae and lie in the plane of the inferior vena cava. Since it is probable that such an anomalous connection is a consequence of the size and location of the atrial septal defect, it has been termed "secondary anomalous pulmonary venous connection." Anomalous connections into the inferior vena cava, into the junction of the superior vena cava with the right atrium or at other positions predictable on the basis of developmental anatomy, are found and these may exist with or, less frequently, without an associated atrial septal defect. In certain examples of anomalous connection of the right pulmonary veins to the junction of the superior vena cava with the right atrium, a considerable proportion of the blood leaving the anomalously connected vein has been demonstrated to drain normally by way of an interatrial communication.

The introduction of these 2 terms, namely, "connection," with its anatomic connotation, and "drainage," with its physiologic or hemodynamic implications, has been necessitated by study of patients with arteriovenous shunts by means of indicator-dilution technics. It is possible by use of these technics to determine the presence and approximate magnitude of anomalous venous drainage in several congenital malformations of the heart. This paper is
intended to deal principally with the findings in patients with atrial septal defects but, in order to develop the interpretation of the dilution curves in these patients, curves obtained in 3 patients with anomalous pulmonary venous connections also are presented. In addition, the curves in 3 patients with common atrioventricular canals are considered.

The findings indicate that in the usual case of atrial septal defect, the greater proportion of the blood shunted from left to right across the defect is returning to the heart from the right lung. This hemodynamic situation represents a position intermediate between that of patients with anomalous pulmonary venous connections, in whom all the blood from one lung passes to the right atrium, and that of patients with ventricular septal defects or patent ductus arteriosus, in whom approximately equal contributions to the left-to-right shunt are made from each lung.

The technic of injection of Evans blue (T-1824) via cardiac catheter directly into the chambers of the heart and great vessels now makes it possible to localize the site of a right-to-left shunt with precision. The extension of this method of study to congenital cardiac disease associated with a left-to-right shunt suggested itself.

Broadbent and Wood have described the essential contour of arterial indicator-dilution curves after injection of T-1824 into a peripheral vein in certain forms of congenital cardiac disease characterized by a left-to-right shunt. The appearance and build-up times usually are normal, but the peak deflection is reduced. The return of dye toward its equilibrium value is slowed, and no peak of concentration due to indicator that has passed through the systemic capillaries and recirculated can be defined on the slope of declining concentration. These authors observed no special feature in such curves that would permit localization of the site of the shunt. When injections are made directly into the great vessels or the chambers of the heart, the resultant curves are more clearly defined and features not evident on curves following peripheral injection can be recognized. In many cases, characterized by blood flowing from a pulmonary vein to the right atrium, differences can be found between curves recorded after injection of dye into the right pulmonary artery and those noted after injection into the left pulmonary artery. These differences are not a feature of ventricular septal defect or patent ductus arteriosus, in which the curves recorded after injection of dye into each pulmonary artery are essentially similar.

**Methods**

The data presented were obtained from studies on 18 patients, 12 of whom had atrial septal defects. In 2, the defects extended posteriorly to include the orifices of the right pulmonary veins, causing "secondary" anomalous connection of these veins to the right atrium; 3 had anomalous connection of the veins from the right or left lung; and 3 had persistent common atrioventricular canals. The diagnoses were confirmed in all 14 of the patients in whom surgical correction of the defect was undertaken.*

All the patients were studied by the cardiaccatheterization procedure described previously. The locations of intracardiac shunts were determined by the withdrawal of samples of blood through a cuvette oximeter from different positions within the heart and great vessels in rapid succession. The pulmonary and systemic blood flows were obtained by the Fick method when the patient was breathing 100 per cent oxygen. The proportion of blood shunted from left to right was calculated as follows:

\[
\text{Pulmonary flow} - \text{Systemic flow} = \text{Pulmonary flow} \\
\times 100 = \text{left-to-right shunt.}
\]

Arterial indicator-dilution curves were recorded by earpiece oximeter in each of the patients after injection of T-1824 into both the right and left pulmonary artery and into other sites in the heart and great vessels. With the exception of one patient, dilution curves also were recorded simultaneously by means of a cuvette oximeter through which blood from the radial artery was allowed to flow. Quantitative measurements were made from the latter curves and are reported in a separate publication. The dilution curves from each of these sampling sites were usually similar, but the data presented in this paper have been obtained entirely by means of the ear oximeter. The time and concentration components of dilution curves characterized by a peak of concentration due to pulmonary recirculation are shown in figure 1; the symbols and

* The authors are indebted to Dr. J. W. Kirklin for use of his operative notes.
definitions used conform to those that have been proposed for normal curves.\textsuperscript{13}

**RESULTS**

*Hemodynamic findings.* The essential data with regard to pressure, flow, and shunt are given in tables 1 and 2. A high proportion of the pulmonary blood flow was found to recirculate through the lungs in the majority of the patients who had atrial septal defects.

*Contour of Dilution Curves on Central Injection.* When the dye was injected into the pulmonary trunk, the right ventricle, or the inferior or superior vena cava in these patients, it was usually possible to distinguish at least 2 separate peaks of concentration, but these were less well defined as the site of injection was moved more peripherally in each patient. The differences between curves recorded after injection of dye into the pulmonary trunk and, shortly thereafter, into the superior vena cava are noted in figure 2. Comparable changes consisting of prolongation of the time components and reduction of concentration components have been described in persons not having an intracardiac shunt when injections of dye were made at progressively more peripheral sites.\textsuperscript{13}

**Injection of Dye into Both Right and Left Pulmonary Artery in Atrial Septal Defect.** On gross inspection, the most notable characteristic of curves after injection of dye into both the right and left pulmonary artery was the great difference between them. The curves recorded after injection of dye into the left pulmonary artery were more nearly normal. The values for appearance time, *A.T.*, build-up time, *B.T.*, and peak-concentration time, *P.C.T.*, were somewhat less than those in normal persons studied in our laboratory. The build-up slope of the curve was smooth and the peak concentration *C*\textsubscript{p} of dye approached normality. The slope of declining concentration, however, was distorted by an abnormal second peak of concentration that was not clearly defined in certain cases. The interval between the initial (normal) peak and the second peak averaged 4.7 sec. (range = 4.2 to 5.9), which was much less than the normal systemic recirculation time of 20 sec. This short interval is consistent with the concept that the second peak of concentration is due to dye that has traversed a shortened vascular pathway consist
TABLE 1.—Intracardiac Pressure, Blood-Flow Data, and Circulation Time in Atrial Septal Defect: 12 Cases

<table>
<thead>
<tr>
<th>Case*</th>
<th>Age, yr.</th>
<th>Pressure, mm Hg</th>
<th>Blood flow, L/min./M²</th>
<th>Lt.-rt. shunt, per cent</th>
<th>Circulation time, seconds†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pulmonary artery, wedge</td>
<td>Pulmonary artery</td>
<td>Right atrium</td>
<td>Pulmonary</td>
</tr>
<tr>
<td>1</td>
<td>27</td>
<td>1.57</td>
<td>12/5</td>
<td>30/15</td>
<td>4/2</td>
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<tr>
<td>2</td>
<td>48</td>
<td>1.59</td>
<td>8/5</td>
<td>28/7</td>
<td>6/3</td>
</tr>
<tr>
<td>3</td>
<td>40</td>
<td>1.55</td>
<td>49/14</td>
<td>7/2</td>
<td>17.0</td>
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<tr>
<td>4</td>
<td>24</td>
<td>1.70</td>
<td>11/8</td>
<td>17/8</td>
<td>7/4</td>
</tr>
<tr>
<td>5</td>
<td>26</td>
<td>1.48</td>
<td>19/12</td>
<td>31/17</td>
<td>6/1</td>
</tr>
<tr>
<td>6</td>
<td>16</td>
<td>1.75</td>
<td>10/4</td>
<td>25/10</td>
<td>11/5</td>
</tr>
<tr>
<td>7</td>
<td>29</td>
<td>1.61</td>
<td>18/14</td>
<td>30/15</td>
<td>15/0</td>
</tr>
<tr>
<td>8</td>
<td>34</td>
<td>1.45</td>
<td>10/6</td>
<td>20/8</td>
<td>4/2</td>
</tr>
<tr>
<td>9</td>
<td>47</td>
<td>1.59</td>
<td>10</td>
<td>38/19</td>
<td>7/2</td>
</tr>
</tbody>
</table>

Associated “secondary” anomalous connection of right pulmonary veins

<table>
<thead>
<tr>
<th>Case</th>
<th>Age, yr.</th>
<th>Pressure, mm Hg</th>
<th>Blood flow, L/min./M²</th>
<th>Lt.-rt. shunt, per cent</th>
<th>Circulation time, seconds†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pulmonary artery, wedge</td>
<td>Pulmonary artery</td>
<td>Right atrium</td>
<td>Pulmonary</td>
</tr>
<tr>
<td>11</td>
<td>43</td>
<td>1.67</td>
<td>37/19</td>
<td>9/3</td>
<td>11.7</td>
</tr>
<tr>
<td>12</td>
<td>22</td>
<td>1.79</td>
<td>30/14</td>
<td>8/1</td>
<td>14.2</td>
</tr>
</tbody>
</table>

* The diagnosis was verified at operation in all but cases 7 and 10. The dilution curves in cases 1 through 9 are depicted in figure 3; those in case 10 are seen in figure 2B and those in cases 11 and 12 are seen in figure 4B.

† Circulation time measured by earpiece oximeter A.T., appearance time; P.C.T., peak concentration time.

TABLE 2.—Intracardiac Pressure, Blood-Flow Data, and Circulation Time in Anomalous Pulmonary Venous Connection and Persistent Common Atrioventricular Canal: 3 Cases Each

<table>
<thead>
<tr>
<th>Case*</th>
<th>Age, yr.</th>
<th>Surface area, m²</th>
<th>Pressure, mm Hg</th>
<th>Blood flow, L/min./M²</th>
<th>Lt.-rt. shunt, per cent</th>
<th>Circulation time, seconds†</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Pulmonary artery, wedge</td>
<td>Pulmonary artery</td>
<td>Right atrium</td>
<td>Pulmonary</td>
<td>Systemic</td>
</tr>
<tr>
<td>13‡</td>
<td>44</td>
<td>1.78</td>
<td>11/5</td>
<td>22/7</td>
<td>6/1</td>
<td>8.2</td>
</tr>
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<td>14∥</td>
<td>33</td>
<td>1.80</td>
<td>17/9</td>
<td>29/13</td>
<td>11/5</td>
<td>7.2</td>
</tr>
<tr>
<td>15‡</td>
<td>32</td>
<td>1.58</td>
<td>27/10</td>
<td>2</td>
<td>8.4</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Anomalous pulmonary venous connection (fig. 5B)

Persistent common atrioventricular canal (fig. 6B)

<table>
<thead>
<tr>
<th>Case</th>
<th>Age, yr.</th>
<th>Surface area, m²</th>
<th>Pressure, mm Hg</th>
<th>Blood flow, L/min./M²</th>
<th>Lt.-rt. shunt, per cent</th>
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<td></td>
<td>Pulmonary artery, wedge</td>
<td>Pulmonary artery</td>
<td>Right atrium</td>
<td>Pulmonary</td>
<td>Systemic</td>
</tr>
<tr>
<td>16</td>
<td>25</td>
<td>1.36</td>
<td>12/6</td>
<td>31/10</td>
<td>7/2</td>
<td>14.7</td>
</tr>
<tr>
<td>17</td>
<td>27</td>
<td>1.50</td>
<td>10/7</td>
<td>23/8</td>
<td>8/5</td>
<td>8.9</td>
</tr>
<tr>
<td>18</td>
<td>28</td>
<td>1.60</td>
<td>8/5</td>
<td>27/10</td>
<td>7/2</td>
<td>11.6</td>
</tr>
</tbody>
</table>

* The diagnosis was verified at operation in all but cases 13 and 18.

† Circulation time measured by earpiece oximeter A.T., appearance time; P.C.T., peak concentration time.

‡ Anomalous venous connection from right lung to inferior vena cava.

§ Left-to-right shunt at the atrial level.

∥ Anomalous venous connection from left lung to innominate vein.

# Total left-to-right shunt at the atrial and at the ventricular level.

The diagnosis was verified at operation in all but cases 7 and 10. The dilution curves in cases 1 through 9 are depicted in figure 3; those in case 10 are seen in figure 2B and those in cases 11 and 12 are seen in figure 4B.

† Circulation time measured by earpiece oximeter A.T., appearance time; P.C.T., peak concentration time.

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§ Left-to-right shunt at the atrial level.

∥ Anomalous venous connection from left lung to innominate vein.

# Total left-to-right shunt at the atrial and at the ventricular level.

ing of the pulmonary vessels, right atrium, and right ventricle.

The most obvious feature in the curves obtained after injection into the right pulmonary artery was the reduction in the initial peak of concentration. The magnitude of this peak varied widely between individual patients. The average appearance time for curves following
injection into the left pulmonary artery was 5.1 sec. and that following injection into the right pulmonary artery was 5.8 sec. The second peak of concentration, which was poorly defined on the declining slope of the curve after injection into the left pulmonary artery, appeared as a much larger deflection when dye was injected into the right pulmonary artery (fig. 3). The secondary deflection in this series of patients was usually somewhat greater than the initial peak of concentration.

In 2 cases (11 and 12 in table 1) in which the interior of the right atrium was explored at operation, the right pulmonary veins appeared to enter directly into the chamber of the right atrium, giving rise to a "secondary" anomalous connection. The most abnormal pairs of curves of the group studied were obtained in these 2 cases (fig. 4). The dilution curve obtained in each of these cases after injection of indicator into the left pulmonary artery was abnormal, with a reduced peak concentration and a prolonged disappearance slope. The curves following injection into the right pulmonary artery were even more abnormal. In case 12 (fig. 4B) there was a very small initial deflection followed by a large secondary deflection, while in case 11 (same figure) the appearance of dye was delayed 3.6 sec. when compared to the dilution curve recorded following injection into the left pulmonary artery. This is a greater difference than that seen between any pair of curves in the other patients with atrial septal defect, and its significance is considered below.

Anomalous Pulmonary Venous Connection. This anomaly was present in 3 cases (fig. 5). In cases 13 and 15 (fig. 5B), the veins from the right lung connected to the inferior vena cava below the diaphragm, whereas in case 14 the veins from the left lung connected with the left innominate vein. The interatrial septum was thought to be intact in case 13, while an atrial septal defect coexisted in cases 14 and 15. In each of these cases, one of the dilution curves showed a nearly normal peak concentration, but the slopes of declining concentration were abnormal in cases 14 and 15. In contrast, the dilution curves recorded after injection into the other pulmonary artery were grossly ab-

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**FIG. 2.** The path taken by indicator dye after its injection into both the right and left pulmonary artery and the resultant dilution curves recorded in the systemic arterial system in a case of atrial septal defect (case 10).

A. Diagrammatic representation of the central circulation. The thick solid lines within the diagram represent the circulatory route taken by the indicator after its injection. The relative thickness of these lines represents the fraction of indicator passing to different locations from the left atrium. The small inserts above each diagram represent the general contour of a dilution curve from each site of injection, with the instant of injection indicated by the arrow. Note the proximity of the right pulmonary veins to the location of the septal defect, which is evident from pathologic anatomic studies of this condition.

B. Systemic arterial dilution curves recorded by ear oximeter (table 1). Injections of T-1824 were made at the sites indicated to the left of the figure. The curves have been arranged vertically in relation to the instant of injection indicated by the arrow. The values for the maximal concentration of dye attained in radial arterial blood recorded simultaneously are tabulated to the right and serve to indicate the sensitivity of the instrument.
normal with regard to both time and concentration components. The peak-concentration time in each instance differed considerably between the dilution curves. In cases 13 and 15, these values for the curves following injection into the right pulmonary artery exceeded those following injection into the left pulmonary artery by 6.0 and 4.8 sec., respectively; in case 14, the value for the curve noted after injection into the left pulmonary artery exceeded that for the right pulmonary artery by 7.5 sec. The interpretation and significance of these dilution curves are considered in detail below.

**Persistent Common Atrioventricular Canal.** The dilution curves obtained in 3 instances of common atrioventricular canal (fig. 6A) are considered in this paper because this anomaly frequently may give rise to a clinical and hemodynamic picture that is extremely difficult to distinguish from that of the usual case of atrial septal defect. The most notable feature of each of these pairs of curves was the greater degree of similarity between them as contrasted to the curves already considered. However, in cases 16 and 17 (fig. 6B), the initial deflections, which corresponded to a concentration of dye of 6.6 and 5.6 mg./L., respectively, produced by dye injected into the right pulmonary artery were smaller than those obtained when dye was injected into the left pulmonary artery (7.6 and 8.5 mg./L.). The dilution curves in case 18 appeared to be identical; in this respect, this case resembled those in which a ventricular septal defect or patent ductus arteriosus is present.

**Discussion**

The features of an indicator-dilution curve are largely determined by the anatomic and dynamic conditions that pertain between the site of injection and the sampling site. The data presented can be interpreted in terms of the differing pathways traversed by the indicator from injection to sampling site and in terms of the cardiac output and the magnitude
Fig. 4. A. Diagrammatic representation of the circulatory pathway traversed by dye in a case of atrial septal defect with "secondary" anomalous connection of the right pulmonary veins (case 12). See legend to figure 2A for explanatory details. Note the entry of the right pulmonary veins into the chamber of the right atrium.

B. Indicator-dilution curves obtained in 2 cases of atrial septal defect and "secondary" anomalous connection of the right pulmonary veins (cases 11 and 12). See legend to figure 2B for explanatory details. Values for maximal concentration are not given in case 11 because dilution curves from radial arterial blood were not obtained in this instance.

of recirculation of the indicator through the lungs.

The one patient who had anomalous connection of the right pulmonary veins and no interatrial communication (case 13, fig. 5B) provides a clear-cut example of these effects on the arterial indicator-dilution curves. The curves obtained from this patient are considered in detail to facilitate the interpretation of the findings in the other patients who had inter-atrial communications in which the determining factors were more complex.

When indicator dye was injected into the left pulmonary artery, a normal arterial dilution curve was recorded at the sampling site, with an appearance time of 5.0 sec., a rapid deflec-
tion to a peak of concentration at 9.0 sec. followed by a rapid decline toward 0 concentration, and a small peak of concentration 16 sec. after the main peak. In contrast, when indicator was injected into the right pul-

monary artery, the appearance time was 10 seconds, the peak deflection was reduced to 12.2 mg./L., and the slope of declining concentration was prolonged.

The reason for the differences between these curves is evident on consideration of the diagrammatic representation of the central circulatory system in this patient (fig. 5A). Blood from the right ventricle can reach the systemic circulation only by way of the left pulmonary artery. Furthermore, all of the blood traversing the left pulmonary artery passes to the systemic circulation. Indicator injected into the anomalously connected right lung and passing to the sampling site in the arterial system traverses a path lengthened by the vascular bed of the right lung, the right atrium, ventricle, and main pulmonary artery. This results in a delayed arrival of indicator at the sampling site and hence a prolonged appearance time. In addition, only a portion (approximately 50 per cent) of the indicator that reaches the main pulmonary artery on its first recirculation from the right lung enters the left pulmonary artery; thus the magnitude of the first deflection was reduced. The remainder of the indicator again enters the right pulmonary artery and is recirculated; progressively smaller amounts (a constant fraction of the indicator remaining in the pulmonary circulation) passes to the systemic arterial system by way of the left pulmonary artery with each recirculation. This slow clearance of indicator from the central circulation caused the prolonged decline of concentration of indicator noted at the arterial sampling site. The dilution curves in this patient demonstrate that all the blood from the left pulmonary artery drained normally, while all the blood from the right lung drained anomalously. This hemodynamic situation indicated the anatomic nature of the malformation to be an anomalous connection of the right pulmonary veins, with an intact atrial septum.

Each of the remaining patients with anomalously connected veins had an associated atrial septal defect through which blood was shunting. In case 14 (fig. 5B) (connection of left pulmonary veins to innominate vein), the curve recorded after injection of dye into the
right pulmonary artery showed a slurring of the disappearance slope and the absence of a peak due to systemic recirculation, findings that are suggestive of a small left-to-right shunt of blood returning from the right lung. When indicator was injected into the left pulmonary artery, a small deflection coincided in time with the main deflection for the right pulmonary arterial curve, while the main deflection in the left pulmonary arterial curve was delayed by about 7 seconds. The small initial deflection in this curve was due to the presence of a right-to-left shunt through an interatrial communication, while the main deflection was due to anomalous drainage of blood from the left lung. Such an interpretation was substantiated by a dilution curve recorded after injection of dye into the superior vena cava. This curve (not shown), except for a slightly shorter appearance time, was identical to the curve noted after injection of dye into the left pulmonary artery, indicating that the blood from the left pulmonary veins drained into the superior vena cava, right atrium, or adjacent great veins. These dilution curves demonstrated, apart from the small quantity of blood shunted from right to left, the presence of complete anomalous drainage of the blood returning from the left lung; they also showed that, although the greater part of the blood returning from the right lung drained normally, a small fraction drained anomalously. This was indicative of anomalous connection of the left pulmonary veins and the presence of an atrial septal defect, with both right-to-left and left-to-right shunts occurring through it. By similar reasoning, the curves in case 15 (fig. 5B) were interpreted to demonstrate complete anomalous drainage of blood returning from the right lung with a moderate to severe degree of anomalous drainage of blood returning from the left lung, consistent with anomalous connection of the right pulmonary veins and an atrial septal defect.

The interpretation of the dilution curves obtained in anomalous pulmonary venous connections can be extended to include the curves in atrial septal defect. The 2 patients who had "secondary" anomalous connection of the right pulmonary veins provide a convenient tran-

tion between the groups mentioned above. The dilution curves obtained in case 11 (fig. 4B) are clearly similar to those of case 15 (fig. 5B) and were interpreted to indicate complete anomalous drainage of blood returning from the right lung associated with a considerable degree of anomalous drainage of blood returning from the left lung. Again, this finding was indicative of the anatomic diagnosis of anomalous connection of the right pulmonary veins and an atrial septal defect, a diagnosis that was substantiated at operation. Case 12 (fig. 4B) illustrates a less severe hemodynamic derangement in that not quite all the blood returning from the right lung drained anomalously, as depicted diagrammatically in figure 4A. A large atrial septal defect with a "secondary" anomalous connection to the right atrium was found in this patient at operation. Although the right pulmonary vein was connected anomalously, a small amount of blood returning from the right lung drained normally by way of the atrial septal defect. However, almost all of the blood returning from the right lung and a considerable amount of blood returning from the left lung drained anomalously. The explanation of this normal drainage of a small quantity of the blood returning from the anomalously connected right lung may be that a right-to-left shunt of blood from the right atrial chamber occurred across the atrial septal defect. Alternatively, it is possible that some of the blood returning from the right lung was shunted across the defect without having mixed with the venous blood in the right atrium. In regard to the first of these possibilities, it has been shown that small right-to-left shunts are common in cases of interatrial communication and are usually demonstrated from the inferior vena cava. No right-to-left shunt of superior vena caval blood was demonstrated in this patient but, since dye was not injected into the inferior vena cava, the possibility of a right-to-left shunt from the atrium has not been excluded. Therefore, it is not possible to be certain which interpretation is correct.

The dilution curves obtained from patients with atrial septal defects had certain features in common (fig. 2B and 3). In every instance, the curve recorded after injection of indicator
into the left pulmonary artery was more nearly normal in contour. The initial peak of concentration was larger and the rate of declining concentration more rapid than for the curve obtained after injection into the right pulmonary artery. For the latter site, the initial peak of concentration was not the maximal concentration, which usually occurred 4 to 6 sec. later. This has been termed “peak concentration (recirculation),” abbreviated as $P.C.R$. It corresponded in time to the small break usually seen on the declining slope of concentration of the curves recorded after injection of indicator into the left pulmonary artery. For the latter site of injection, however, this peak of concentration was poorly defined at best and frequently was represented only by a change in the slope of declining concentration.

It will be recalled that total anomalous drainage of the blood from 1 lung was clearly demonstrated in 4 of the patients who had anomalous connections of pulmonary veins (cases 11, 13, 14, and 15). In the dilution curves recorded after injection of dye into the left pulmonary artery (fig. 2A), in the patients with atrial septal defects, the large initial deflection represented the passage of a major proportion of the injected dye to the left ventricle and to the systemic circulation after its first passage through the left lung. The small break, or slurring, on the slope of declining concentration represented dye that had been shunted from left to right through the atrial septal defect and appeared at the arterial sampling site after a second circulation through the lungs. These dilution curves indicated that a large part of the blood returning from the left lung drained normally, but that a demonstrable fraction did drain anomalously. By analogous reasoning, the small initial peaks of the dilution curves after injection of dye into the right pulmonary artery are interpreted to indicate that a small portion of the blood returning from this lung drained normally. The larger secondary peak indicated that a proportionately greater amount drained anomalously. In addition, it may be noted that the greater proportion of the blood returning from the right lung that passed to the left ventricle after its first recirculation through the lungs would probably do so by way of the left pulmonary artery.

On the basis of these dilution curves and those obtained in additional surgically proved cases of atrial septal defect, it is clear that anomalous drainage of the blood returning from the right lung, greater in magnitude than the anomalous drainage of blood returning from the left lung, is a fundamental part of the hemodynamic derangement in the usual case of atrial septal defect. In 2 patients with atrial septal defects, the proportion of blood draining anomalously was equal from each lung. In each of these patients, who were in the older age group, a considerable gradient in pressure was present between the atria, and at operation the defects were found to be unusually small. The probable reason for the phenomenon found in the more usual case of atrial septal defect is the anatomic proximity of the left atrial orifices of the right pulmonary veins to the defect and the relatively distant location of the orifices of the left pulmonary veins. It is reasonable to conclude that the blood returning from the left lung passing across the left atrium to the left ventricle and to the right atrium acts as a fluid stopper in regard to the blood returning from the right lung.

The demonstration of an equal contribution from each lung to a left-to-right shunt implies that intimate mixing of the blood from each lung has occurred proximal to the location of the shunt. Thus, in those cases of patent ductus arteriosus and ventricular septal defect in which dilution curves have been recorded after injection of dye into both the right and left pulmonary artery, the contours of the dilution curves indicated contributions of equal magnitude from each lung to the left-to-right shunt. Complete mixing must also be assumed to have occurred in the 2 cases with small atrial defects referred to in the preceding paragraph. This situation existed in 1 of the 3 cases of persistent common atrioventricular canal (case 18, fig. 6B) but the dilution curves in the other 2 cases of this anomaly indicated that a greater proportion of the blood returning from the right lung was shunted to the right side of the heart. This difference between the contribution from each lung was less that seen in
the usual case of atrial septal defect. Of the total left-to-right shunt, a greater proportion was calculated to have occurred at the ventricular level in case 18 than in either of the other 2 cases. It is possible that the location of the interatrial communication, which is farther removed from the left atrial orifices of the right pulmonary veins, may permit a more intimate degree of mixing to occur before the streams of blood reach the defect, and may allow for anomalous drainage more nearly equal in magnitude from each lung.

The location of the tip of the catheter at the time of injection of dye is clearly of fundamental importance in determining the presence and degree of anomalous drainage from one or the other lung. The placement of the catheter in the correct position may be difficult at times, and certainty of the exact location of its tip requires radiologic confirmation before and immediately after the injection. The main trunk of each pulmonary artery is short and, in patients with increased pulmonary flow, widely dilated. The injection into either the right or the left pulmonary artery must be made close to its origin from the main pulmonary artery. This is essential because anomalous drainage of differing magnitudes has been demonstrated from the lobes of the lung in patients with atrial septal defects, and in dogs with surgically created atrial septal defects. Frequently, however, the longitudinal motion of the catheter induced by the heartbeat may cause the tip of the catheter to move from the right pulmonary artery into the main or even the left pulmonary artery without manipulation by the physician.

**Summary**

Systemic arterial indicator-dilution curves have been recorded by means of oximeters after injection of T-1824 (Evans blue) into both the right and left pulmonary artery in 12 patients who had atrial septal defects, 3 patients who had anomalous connections of the veins from 1 lung, and 3 patients who had persistent common atroventricular canals.

The greatest differences in contour between the curves recorded after injection at these 2 sites were observed in anomalous pulmonary venous connection. The dilution curves obtained in these patients when dye was injected into the pulmonary artery of the lung that was connected normally either were normal or showed minimal abnormality. The dilution curves noted after injection of dye into the pulmonary artery of the other lung showed a significant increase in appearance time, a reduced peak of concentration and a much prolonged slope of declining concentration. The curves obtained after use of the former site of injection were interpreted to indicate normal drainage of all or nearly all of the blood returning from that lung. Those obtained after use of the latter site indicated complete anomalous drainage from the anomalously connected lung.

In the patients who had atrial septal defects, the dilution curves differed remarkably from one another. The curves obtained after injection into the left pulmonary artery were more nearly normal, but showed abnormalities of varying degree of the slope of declining concentration. After injection into the right pulmonary artery, the dilution curves were characterized by 2 peaks of concentration, the first of which was usually small in magnitude and coincident in time with the main deflection that resulted from injection of dye into the left pulmonary artery. The second deflection, usually the larger, followed the first by an interval of 4 to 6 sec. These dilution curves are interpreted to indicate a moderate degree of anomalous drainage of blood from the left lung and a severe degree of anomalous drainage of blood from the right lung. This anomalous drainage of relatively greater magnitude from the right lung appears to be a consistent feature in the usual case of atrial septal defect and is most probably a consequence of the juxtaposition of the atrial septal defect to the left atrial orifices of the right pulmonary veins.

**Summario in Interlingua**

Curvas de dilution de indicator in arterias systemic esseva registrate per medio de oxymetros post le injection de blau de Evans in le dextere e sinistre arteriae pulmonar de 12 pacientes con defectos del septo atrial, 3 pacientes con anormal connexiones del venas ab un del pulmones, e 3 pacientes con persistent canales atroventricular commun.

Le plus grande differentias in le curvas
obtenite post le duo injectiones eseva observate in casos de anormal connexion pulmonovenose. Le curvas de dilution obtenite in iste patientes post injectiones del colorante in le arteria pulmonar del pulmone con connexiones normal eseva normal o mostrava grados minimal de anormalitate. Le curvas de dilution obtenite post injectiones in le arteria pulmonar del altere pulmone exhibiva un significative augmento del intervallo de manifestation, un reduce maximo de concentration, e un prolongatissime descendita del concentration. Le curvas obtenite post injectiones in le prime del sitos mentionate eseva interpretate como provas de drainage normal de omne o quasi omne le sanguine retornante ab le pulmone in question. Le curvas del secunde typo eseva interpretate como provas de drainage complete anormal ab le anormalmente connectite pulmone.

In le patientes con defectos atrioseptal, le curvas de dilution differeva remarkablemente le unes ab le alteres. Le curvas obtenite post injectiones in le sinistre arteria pulmonar eseva plus tosto normal, sed illos mostrava varie grados de anormalitate in le branca de concentration descendente. Post injectiones in le dextere arteria pulmonar, le curvas de dilution eseva caracterisate per 2 culmines de concentration. Le prime de iste culmines eseva usualmente de magnitude minor e coinciedea chronologicamente con le deflexion major que resultava ab le injection de colorante in le sinistre arteria pulmonar. Le secunde deflexion, usualmente plus grande que le prime, sequava post un intervallo de inter 4 e 6 sec. Iste curvas de dilution es interpretate como signos de un moderate grado de drainage anormal de sanguine ab le pulmone sinistre e de un sever grado de drainage anormal de sanguine ab le pulmone dextere. Il pare que iste drainage anormal de relativamente plus grande amonitas de sanguine ab le pulmone dextere es un caracteristica regular in le casos commun de defecto atrioseptal. Illo es probabilissime mente un consequentia del juxtaposition del defecto atrioseptal con le orificios sinistro-atrial del dextere venas pulmonar.

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