The Assessment of Operative Results in Congenital Heart Disease by Intraoperative Indicator-Dilution Curves

By Andrew G. Morrow, M.D., H. Newland Oldham, M.D., George M. Callard, M.D., and Eugene Braunwald, M.D.

The usefulness of indicator-dilution curves in the diagnostic assessment of patients with congenital heart disease is well recognized. These technics are widely employed during preoperative cardiac catheterization to determine the presence of a circulatory shunt and, if one is present, to furnish information concerning its magnitude and sites of origin and termination.\(^1\)\(^-\)\(^4\) Similarly, when applied in the course of postoperative catheterization in patients in whom intracardiac communications have been closed, indicator-dilution curves provide a sensitive index of the completeness of the repair. At the National Heart Institute, indicator-dilution curves are recorded not only during cardiac catheterization, but also in the operating room immediately following corrective operations performed in patients with intracardiac shunts. As demonstrated by Toscano-Barboza and his associates,\(^5\) such intraoperative curves furnish an immediate indication of the completeness of the repair; these authors also found that in 14 patients the presence or absence of a residual shunt, determined from intraoperative dye curves, correlated with the presence or absence of a residual defect at necropsy. It has not been previously determined, however, whether intraoperative indicator-dilution curves provide accurate information concerning the late results of operation. In the present study, intraoperative indicator-dilution curves were recorded and analyzed in 260 patients. The presence or absence of a circulatory shunt was also determined subsequently in every patient by cardiac catheterization in the late postoperative period, or by postmortem examination. The correlations between these intraoperative and postoperative findings are described in the report that follows.

Patients and Methods

Between January 1955 and June 1963, corrective operations were performed in 372 patients with congenital malformations associated with intracardiac shunts. From this group, 260 patients were selected for study, solely on the basis that technically satisfactory indicator-dilution curves had been recorded at the termination of the operative procedure, and that the presence or absence of a residual shunt had also been established at postoperative catheterization or necropsy. Postoperative cardiac catheterization was performed in the 234 surviving patients at an average interval of 28 weeks after operation. At postoperative study, the presence or absence of a residual or recurrent right-to-left or left-to-right shunt was determined in every patient by arterial indicator-dilution curves, usually recorded after injections into the right side of the heart. Routinely, injections were made in the main pulmonary artery and the inferior vena cava, but when a residual communication permitted access to the left atrium or left ventricle, curves were recorded from these sites as well. In addition, the presence of any left-to-right shunt was determined in all patients by the application of inhaled nitrous oxide or krypton-85 tests, with pulmonary arterial or right ventricular sampling.\(^6\)\(^-\)\(^9\) Twenty-six patients died, and in them the completeness of the operative repair was determined at autopsy.

The general methods employed in recording the indicator-dilution curves at operation have previously been described in detail.\(^3\) Indocyanine green (1.25 mg./ml.) was utilized as the indicator except in early studies, which were performed with Evans-blue dye. The volume of dye ranged from 1 to 5 ml., depending upon the size of the patient and the injection site. For the detection of left-to-right shunts, dye was usually injected into a right pulmonary vein or the left atrium and, when indicated, also into the left ventricle.

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and main pulmonary artery. To determine the presence of right-to-left shunts, the sites of injection were the venae cavae, right atrium, or right ventricle. Multiple injection sites were utilized in most patients. In all patients, arterial blood was sampled from a catheter in the radial artery and withdrawn through a cuvette densitometer,* at a constant rate, by a power-driven syringe. As they were inscribed, the curves were displayed on an oscilloscope visible to the surgeon, and they were also recorded on a photographic oscillograph.

The presence or absence of a residual circulatory shunt was determined by inspection of the appearance times and contours of the recorded curves. A left-to-right shunt was indicated by an interruption of the descending limb of the curve or, after a left-sided injection, failure of the descending limb to return to the baseline before the appearance of recirculating dye. A right-to-left shunt was indicated, after right-sided injection, by the abnormally early appearance of dye and an interruption of the ascending limb of the curve. Representative curves illustrating normal and abnormal contours are reproduced in figures 1 and 2. Residual shunts evident in intraoperative indicator-dilution curves were not quantified, since it became apparent early in the study that there was poor correlation between the magnitude of the shunt determined at this time with that measured later at postoperative cardiac catheterization. For example, the intraoperative curve of the patient illustrated in figure 2 demonstrated a relatively small left-to-right shunt after pulmonary venous injection. Postoperatively, however, a significantly larger shunt was evident after pulmonary arterial injection. Such differences may indicate a change in the size of the residual communication, but more likely they reflect variations in the hemodynamic state of the patient at operation and at postoperative study. As indicated above, a small number of patients were eliminated from the study group because their intraoperative curves were unsuitable for analysis, either as the result of artifacts in the recordings or because the curves were not diagnostic due to prolongation of the circulation time.

**Results and Discussion**

The correlations between the analyses of the intraoperative indicator-dilution curves and the results of the postoperative evaluations are presented, in relation to specific malformations, in table 1. In 248 of the 260 patients (96 per cent), the presence or absence of a circulatory shunt, determined from the intraoperative curves, was confirmed by findings at postoperative cardiac catheterization or at necropsy. The methods by which the presence or absence of a circulatory shunt was determined at postoperative study merit discussion, since the results of these investigations were the reference standards to which the intraoperative studies were compared. In every patient, arterial indicator-dilution curves

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*Colson densitometer, Model 103, The Colson Corp., Elyria, Ohio.
ASSESSMENT OF OPERATIVE RESULTS

Table 1

<table>
<thead>
<tr>
<th>Anatomic malformation</th>
<th>No. pts.</th>
<th>No shunt on intraop. curves</th>
<th>Shunt on intraop. curves</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>No shunt postop.</td>
<td>Shunt postop. (recurrence)</td>
</tr>
<tr>
<td>Atrial septal defect</td>
<td>111*</td>
<td>96</td>
<td>1</td>
</tr>
<tr>
<td>Ventricular septal defect</td>
<td>77</td>
<td>60</td>
<td>0</td>
</tr>
<tr>
<td>Tetralogy of Fallot</td>
<td>22</td>
<td>15</td>
<td>0</td>
</tr>
<tr>
<td>Varieties of A-V canal</td>
<td>22</td>
<td>17</td>
<td>2</td>
</tr>
<tr>
<td>Anomalous pulmonary venous connection</td>
<td>20</td>
<td>14</td>
<td>1‡</td>
</tr>
<tr>
<td>Miscellaneous‡</td>
<td>8</td>
<td>7</td>
<td>0</td>
</tr>
<tr>
<td>Total</td>
<td>260</td>
<td>209</td>
<td>4</td>
</tr>
</tbody>
</table>

*Eight closed under hypothermia, three of whom had positive intraop. curves.
†One patient had patent foramen ovale also. Closure may have been of foramen ovale and not closure of residual ventricular septal defect.
‡Shunt was actually present at operation, but not recognized due to improper choice of injection site.
§Includes two each of atrial plus ventricular septal defects, ruptured sinus of Valsalva aneurysm, left ventriculo-right atrial shunt, and ventricular septal defect plus corrected transposition.

were recorded, but usually the injection site was, of necessity, the main pulmonary artery or right ventricle. Under some circumstances, a small left-to-right shunt may not be evident in a curve recorded after injection into these sites. Since the intraoperative curves were universally made with left heart injections, one might theorize that a left-to-right shunt, evident on intraoperative curves, might still have been present but not detected in postoperative curves. This was not the case, however, since the presence or absence of a left-to-right shunt in the postoperative indicator-dilution curves was confirmed in all patients by the results of the nitrous oxide and krypton-85 tests which were also applied. In these tests, the foreign gas is, in fact, an indicator, but is introduced into pulmonary venous blood by inhalation rather than injection. Thus, the accuracy of the tests may be considered comparable to the extremely sensitive double catheter indicator-dilution method.2

The intraoperative curves were normal in 213 patients, and in 209 of them no shunt was evident postoperatively, Thus, in four patients, the combination of studies indicated an initial complete correction followed by recurrence of the intracardiac communication, a sequence illustrated by the curves of patient A. Q., which are reproduced in figure 3. In

Figure 3

Arterial indicator-dilution curves recorded preoperatively, intraoperatively, and at postoperative catheterization in a patient who had a recurrent shunt following complete correction of incomplete A-V canal. Preoperatively, a left-to-right shunt is evident after pulmonary artery (PA) injection (Kr85 index 34 per cent). The intraoperative curve, recorded after right superior pulmonary vein (RSPV) injection, is normal. At postoperative catheterization, a recurrent atrial septal defect was crossed by the catheter, and the curve recorded after left atrial (LA) injection indicates a recurrent shunt. The Kr85 index at the time of postoperative catheterization was 22 per cent.
this patient, who had incomplete A-V canal, the recurrent shunt is relatively small and he is asymptomatic. In the patient with atrial septal defect and in the other one with A-V canal, dehiscences of the repairs, which had been performed by direct suture, were found at reoperation and autopsy, respectively. The fourth patient had atrial septal defect and anomalous pulmonary venous connection; after the repair, no left-to-right shunt was evident on indicator-dilution curves recorded following pulmonary venous and pulmonary arterial injections. At postoperative catheterization, however, a large right-to-left shunt was found to originate from the inferior vena cava. Although tabulated as an instance of recurrence, the right-to-left shunt was undoubtedly present at the conclusion of the operation and would have been apparent if injections had been made into the vena cava (fig. 4).

The intraoperative curves revealed a resid-

![Figure 4](image)

**Figure 4**

Arterial indicator-dilution curves recorded preoperatively, intraoperatively, and at postoperative catheterization in a patient with anomalous connection of the right upper and middle pulmonary veins and an atrial septal defect. Preoperatively, a right-to-left shunt is evident after inferior vena caval (IVC) injection, and a left-to-right shunt is also indicated by the interruption of the descending limb of the curve (Kr$^{85}$ index 43 per cent). The intraoperative curve recorded after right superior pulmonary vein injection (RSPV) shows no left-to-right shunt, but no vena caval injections were made. At postoperative catheterization, there is no left-to-right shunt (Kr$^{85}$ index 9 per cent), but a right-to-left shunt is present after inferior vena caval (IVC) injection. This right-to-left shunt probably resulted from partial diversion of inferior caval flow to the left atrium. It was undoubtedly present following closure of the defect and could have been detected at the conclusion of the operation by the proper choice of injection sites when the intraoperative indicator-dilution curves were recorded.

![Figure 5](image)

**Figure 5**

Arterial indicator-dilution curves recorded preoperatively, intraoperatively, and at postoperative catheterization in a patient who had spontaneous closure of a residual shunt after operation for anomalous connection of the right superior and middle pulmonary veins and an atrial septal defect. Preoperatively, a large left-to-right shunt is evident (Kr$^{85}$ index 65 per cent) after inferior vena caval (IVC) injection. The intraoperative curve recorded from the right middle pulmonary vein (RMPV) is normal, but the intraoperative curve recorded from the right superior pulmonary vein (RSPV) shows a residual left-to-right shunt. The postoperative curve recorded following superior vena caval (SVC) injection is normal and the Kr$^{85}$ index at this time was 5 per cent.
Eight of this repair was postoperatively, and in each an incomplete repair was found at necropsy. This mortality rate is twice that recorded among the larger number of patients without residual shunts (8.5 per cent), a difference that reflected the deleterious hemodynamic effects of a residual shunt in the immediate postoperative period, but also indicated that the specific malformations in these patients posed more difficult technical problems. Among the 39 patients who survived, postoperative catheterization revealed that 17 had persistent residual shunts comparable in magnitude to those that existed preoperatively, and second operations have been recommended or performed in them. Fourteen patients have residual shunts of lesser magnitude, and repeat operation is considered unnecessary; 12 have left-to-right shunts with pulmonary-to-systemic flow ratios averaging 1.26 to 1, and the other two have small right-to-left shunts. In the remaining eight patients, although the intraoperative curves clearly indicated that the repair was incomplete, no shunt was demonstrable at postoperative catheterization. In them, therefore, the residual communication apparently closed spontaneously after operation (fig. 5). Of possible significance is the fact that in all of the eight patients in whom spontaneous closure occurred, the residual shunt was entirely left to right.

The analysis above indicates that any residual shunt, evident at the conclusion of operation, must be considered a distinctly unfavorable finding. The risk of death in the postoperative period is increased, and if the patient survives, it is likely that the shunt will persist and will probably be of sufficient magnitude to necessitate a second attempt at repair. With these considerations, what should be the surgeon’s course when a residual shunt is detected? He will, of course, already have made every attempt to achieve a complete repair and, in the individual patient, must compare the risk of immediately reopening the cardiotomy to the risk of a possible second operation at a later time. This judgment will also be tempered by his opinion as to whether the residual shunt is occurring through the defect or defects that he has attempted to repair, or whether it may be due to another and previously unrecognized intracardiac communication. This latter possibility can often be determined by additional curves, recorded after injections at other sites.

The technics employed in recording intraoperative indicator-dilution curves are simple in principle, require little time, and the necessary instruments are neither elaborate nor expensive. At the time the present study was carried out, the photographic oscillograph utilized was not equipped with a rapid-developing attachment, and the surgeon, of necessity, interpreted the curves as they were displayed on an oscilloscope. This immediate analysis, included in the surgeon’s description of the operation, was compared to the later interpretation of the recorded curves, and in all but 12 patients was found to be correct. In each of these 12 patients, a small left-to-right shunt was not appreciated. Thus, although oscillographic visualization of the densitometer output will generally provide valid information, immediate inspection of recorded curves, now possible with improved oscillographic systems, is preferable.

Some comment is necessary concerning the desirable sites of injection for determining the presence or absence of residual shunts at operation. Theoretically, any significant left-to-right shunt will be evident on a curve recorded after an injection into the main pulmonary artery. In practice, however, particularly in adult patients with large hearts, such curves are often not of diagnostic quality because of an increased volume of blood between the injection and sampling sites, and a prolonged circulation time. Accordingly, a left-to-right shunt will be most easily recognized after an injection into the area or chamber immediately upstream from the site at which it originates. Thus, a normal curve after an injection into the readily accessible right upper pulmonary vein excludes the presence of any left-to-right flow after the...
closure of an interatrial or interventricular defect. If the operation has necessitated diversion of the flow from individual pulmonary veins, however, selective injections into them are also indicated (fig. 5). Selective injections at more distal (downstream) sites should be performed if an abnormal curve is obtained after pulmonary venous injection. Following closure of an interatrial communication, for example, an abnormal curve after pulmonary venous or left atrial injection may indicate a residual defect at the atrial level, or an unrecognized interventricular defect. A left ventricular injection is then indicated; if the resulting curve is normal, the origin of the residual shunt must be proximal to a competent mitral valve; if it is abnormal, an interventricular communication is indicated.

The above considerations of the detection of left-to-right shunts are also applicable to the detection of residual right-to-left shunts. Ordinarily, a normal curve after an injection into a vena cava, preferably the inferior one, indicates no abnormal right-to-left flow. If an abnormal curve results, the origin of the shunt may be localized by successive injections at downstream sites. It should be emphasized that a right-to-left shunt may be present postoperatively in a patient who had only a left-to-right one preoperatively. This may occur, for example, after incomplete closure of an atrial septal defect complicated by severe pulmonary hypertension, or from inadvertent partial diversion of caval flow to the left atrium (fig. 4).

Conclusions

In determining the advisability of operative treatment in a given patient with congenital heart disease, both the cardiologist and the cardiac surgeon must be principally guided by their past experiences with patients presenting similar clinical and hemodynamic findings. Truly objective assessments of the results of operations upon the heart cannot be confined to determinations of operative mortality and morbidity and descriptions of symptomatic improvement; they must include objective physiologic measurements indicative of the extent to which the circulatory abnormalities present before operation have been corrected. Ideally, such measurements are obtained at cardiac catheterization in the late postoperative period, but for practical reasons, elective postoperative catheterizations cannot be performed in many clinics. The results of the present study indicate an alternative method of objective evaluation applicable in the large number of patients in whom corrective operations are performed for intracardiac communications associated with circulatory shunts.

If, at the conclusion of the operation, normal arterial indicator-dilution curves are recorded after injections at appropriate sites, permanent abolition of the shunt can be expected in 98 per cent of patients, and such documentation of the operative result assumes appropriate significance. In patients with normal intraoperative curves, therefore, postoperative catheterization, merely to determine the presence or absence of a residual shunt, would seem unnecessary in the absence of clinical findings suggestive of a recurrent defect. Postoperative study may be indicated in such patients, however, when data regarding other postoperative hemodynamic changes are desirable, e.g., information concerning pulmonary vascular resistance, ventricular performance, or the results of treatment of associated stenotic or regurgitant valvular malformations. On the other hand, if intraoperative indicator-dilution curves indicate the presence of a residual shunt, it may be expected to persist in 80 per cent of surviving patients, in half of whom it will be of sufficient magnitude to indicate a second attempt at operative repair. A detailed postoperative study would seem mandatory, therefore, in every patient in whom abnormal intraoperative curves are recorded.

Summary

In 260 patients with intracardiac shunts, indicator-dilution curves were recorded immediately after corrective operations. In every patient, the effectiveness of the repair was also determined at late postoperative cardiac catheterization or necropsy. In 248 patients (96 per cent) the presence or absence of a
shunt, determined from the intraoperative curves, was confirmed by the findings at postoperative study. The intraoperative curves were normal in 213 patients, 209 of whom had no residual communication at late evaluation; in four patients, the studies indicated initial complete correction followed by recurrence of the shunt. Abnormal intraoperative curves were recorded in 47 patients, eight of whom died. In 17 of the 39 surviving patients, postoperative catheterization revealed persistent residual shunts comparable in magnitude to those present before operation. Fourteen patients had residual shunts that did not necessitate reoperation, and in eight patients, shunts present at the conclusion of the operation were shown to close in the postoperative period.

The study indicates that the recording of intraoperative indicator-dilution curves provides a reliable objective method for evaluating the effectiveness of operation in patients with circulatory shunts. If normal curves are recorded, no residual shunt may be expected in 98 per cent of patients, and postoperative catheterization may be unnecessary unless other hemodynamic data are required. If abnormal intraoperative curves are recorded, however, postoperative study is mandatory, since the shunt will persist in 80 per cent of patients, in many of whom a second operation will be indicated.

References

The Basic Attributes
They know enough who know how to learn.—Henry Adams.
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