Physiologic Studies Early after Repair of Tetralogy of Fallot

By Richard A. Theye, M.D., and John W. Kirklin, M.D.

Fifteen cyanotic patients with tetralogy of Fallot were studied at various times in the operating room and during the first 3 days after intracardiac repair of tetralogy of Fallot. Similar studies have not been reported previously. The accumulated data emphasize the need for precision in accomplishing the operation; allow description of the hemodynamic state, gas exchange, and acid-base profile in the postoperative period; and provide background for discussion on certain features of the management of these patients.

Material and Methods

Observations were made by methods and calculations described earlier. Recorded values usually were averages of several determinations. Indicator-dilution curves recorded at the radial artery after injection of indocyanine green into the right atrium were employed for identification of right-to-left shunts. Similar curves recorded after left atrial injection were used for calculation of cardiac output (left atrial flow) and for qualitative information on left-to-right shunts. Left-to-right shunts were quantitated by successive injections of dye into the left atrium and by sampling from the pulmonary artery (occasionally the right ventricle) and the radial artery. The area inscribed by early appearing dye (1 to 2 seconds) at former sampling site was compared with that inscribed at the radial artery by the forward triangle method. The early appearing dye did not come from the coronary sinus blood, since direct sampling from the coronary sinus showed that dye did not appear for 5 to 6 seconds after left atrial injection (in operating room, after repair of atrial septal defect). Similar appearance times in coronary sinus blood (in dogs) were reported by David and Wood. Injections of dye directly into the aortic root during operation were made via a needle inserted into the ascending aorta so that its tip lay about 1 cm. above the aortic valve; in one case the tip lay near the orifice of the innominate artery. The aortic valve seemed competent in all cases. All appearance times were corrected for the actual "dead space" time of the sampling systems used.

Cases have been categorized as to severity (table I) by criteria established earlier. Five patients (cases 2, 8, 9, 11, and 12) had functioning Blalock anastomoses; these were closed at the time of open intracardiac repair. The cases were grouped according to the method of approach to the ventricular septal defect as follows: cases 1 and 2, vertical ventriculotomy; cases 3 and 4, right atriotomy; cases 5 to 15, transverse ventriculotomy. A typical indicator-dilution curve before repair is shown in figure 1. Operations were done between January 15 and July 23, 1962.

During and after operation, patients were managed by methods previously described. The perfusate was heparinized whole blood in cases 1 and 2, and two-thirds blood and one-third 5 per cent dextrose in water in the others. Perfusion time averaged 106 minutes (range, 90 to 160 minutes). Cardiac arrest time was between 40 and 60 minutes, after cardiac cooling by means of the perfusate and saline ice sludge placed around the heart. Median sternotomy incision was used. The outflow tract was enlarged with pericardium only when valvotomy and infundibular resection failed to provide adequate relief of pulmonary stenosis. The enlargement by pericardium was always carried across the pulmonary valve ring. During the period in which some of the patients were operated on, the ventricular septal defect was closed routinely with a patch of knitted Teflon. Later, direct suture was used whenever possible; otherwise a Teflon felt or pericardial patch was used. On inspection, repair of the defect was considered excellent except in two patients (cases 2 and 3) in whom visualization of the defect was extremely difficult and the precision of repair could not be ascertained with certainty. Tracheostomy and assisted ventilation after operation were employed in only one patient (case 2), and only one patient (case 4) was given digitalis (digoxin) during the period of observation. In the latter patient, atrioventricular dissociation appeared on day 2, but it disappeared about 12 hours after prompt cessa-
Table 1
Data on 15 Patients Studied Early After Intracardiac Repair of Tetralogy of Fallot

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<th>Case</th>
<th>Age, yr.</th>
<th>Body surface area, M²</th>
<th>Severity of tetralogy</th>
<th>Repair of ventricular septal defect</th>
<th>Relief of pulmonary stenosis in addition to infundibular resection</th>
<th>After repair ratio systolic pressure, right ventricle: radial artery</th>
<th>Indicator-dilution curves after repair</th>
<th>Left atrial injection, sampling</th>
<th>Pulmonary artery injection, sampling</th>
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*Right atrial injection.
1L-R shunt, 5% with needle tip at level of innominate artery.
tion of administration of digitalis. Sinus or nodal rhythm was present in all other patients after operation.

Results

Relief of Pulmonary Stenosis

Pulmonary stenosis could be adequately relieved without pericardial enlargement in some cases (table 1). Even with avoidance of vertical ventriculotomy, an adequate outflow tract and pulmonary valve ring were not obtained in several other cases without pericardial enlargement. For example, in case 7 perfusion was temporarily discontinued after repair without such an enlargement and right ventricular systolic pressure exceeded that in the left ventricle. Pericardial enlargement resulted in adequate relief of the obstruction. After repair the ratio of systolic pressure in right ventricle and in radial artery (left ventricle in some cases) varied from 0.3 to 0.7. A systolic pressure gradient between right ventricle and pulmonary artery existed at this time in all patients except one (case 3). During the first 3 postoperative days, this residual pulmonary stenosis did not change in degree (table 2).

Abnormal Circulatory Pathways (Table 1)

Left-to-right shunting, found early after repair in 13 of the 15 cases, could be through a residual ventricular septal defect or the pores of a Teflon patch, through surgically created connections between the coronary vascular network and the cavity of the right ventricle, or through the well-developed aorto-pulmonary collateral connections existing in patients with tetralogy of Fallot. Shunting at atrial level was not found (left atrial in-

jection of dye, right atrial sampling). In one of the two patients for whom quantitative data are lacking (case 4), a left-to-right shunt of small magnitude was present; in the other patient (case 12) the indicator-dilution curve, which was normal, eliminated the possibility of anything more than a small shunt. One of the remaining 13 patients (case 13) had no shunt, six had insignificant shunts of less than 10 per cent (fig. 2), three had small shunts of 10 to 20 per cent (fig. 3), and three had moderate shunts of 20 to 30 per cent (fig. 4). Two of the three patients with moderate shunts were those in whom some uncertainty prevailed at operation concerning the precision of the repair. The percentage of left-to-right shunt remained unchanged during the first 3 postoperative days in all patients studied. Right-to-left shunting was absent in all cases.

Injections of dye into the aortic root and sampling from the pulmonary artery, done in four patients (table 1), indicated that most of the left-to-right shunt was of extracardiac origin in all four cases (fig. 5). Dye in similar amounts appeared early in the pulmonary artery after injection into left atrium, aortic root, and distal ascending aorta (level of in-
REPAIR OF TETRALOGY OF FALLOT

nominate artery) in case 15. This result suggests strongly that the main pathway of left-to-right shunting in this patient was

![Diagram](image1)

**Figure 3**
Indicator-dilution curves after repair of tetralogy of Fallot (case 8) recorded at the radial artery (top panel) and pulmonary artery (bottom panel) after successive injections of indocyanine green into the left atrium. The left-to-right shunt was calculated to be 12 per cent. The disappearance slope of the curve recorded at the radial artery breaks off and flattens out prematurely.

![Diagram](image2)

**Figure 4**
Indicator-dilution curves after repair of tetralogy of Fallot (case 3) recorded at the radial artery (top panel) and right ventricle (bottom panel) after successive injections of indocyanine green into the left atrium. The left-to-right shunt was calculated to be 29 per cent. The disappearance slope of the curve recorded at the radial artery has a moderate break.

![Diagram](image3)

**Figure 5**
Indicator-dilution curves after repair of tetralogy of Fallot (case 14). The bottom curve was recorded from the pulmonary artery after injection of indocyanine green into the left atrium. The left-to-right shunt was calculated to be 2 per cent. The top three curves were recorded at the left atrium, pulmonary artery, and radial artery after successive injections into the root of the aorta. With injection at this site, early appearing dye was detected in the pulmonary artery in amounts similar to the amount detected at this site after left atrial injection. This suggests an extracardiac pathway for the early appearing dye. Existence of an extracardiac pathway which enters the vascular system between the pulmonary artery and left atrium is suggested by the increment in early appearing dye detected in the left atrium over that detected in the pulmonary artery seen after aortic root injection.

Shunts of larger magnitude may occur through these connections but were not
### Table 2

**Hemodynamics in the Operating Room and during the Postoperative Period after Intracardiac Repair of Tetralogy of Fallot**

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REPAIR OF TETRALOGY OF FALLOT

Hemodynamics in the Operating Room and during the Postoperative Period after Intracardiac Repair of Tetralogy of Fallot

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<th>Pulmonary vascular resistance, dynes sec. cm.²</th>
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<tr>
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<td>During operation, min. after repair</td>
<td>Arterial</td>
<td>Right</td>
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<tr>
<td></td>
<td>Post-operative, day</td>
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<td>Pulmonary</td>
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<tr>
<td></td>
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<td>2.6</td>
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*Corrected for left-to-right shunt (systemic flow equals left atrial flow minus flow shunted from left to right).

Hemodynamic State, Gas Exchange, and Metabolic Data

All patients survived. The systemic index was usually below normal or in the low normal range; in several patients (cases 1, 5, and 6) it reached extremely low levels (table 2). In 10 of the 11 patients with observations on days 1 and 2 the cardiac index decreased between day 1 (2 to 4 hours after operation) and day 2; in six of these patients atrial pressures were higher on the second day. A change in ventricular function relative to apparent filling pressure had occurred. In contrast to the findings after repair of atrial and ventricular sepal defects,² ³ the systemic index on the third day was sometimes (three cases) as low as on the second day. In general, cardiac index did not differ significantly either with or without pericardial enlargement of the outflow tract; it was strikingly different, however, in one patient (case 13) who had a mild defect managed without valvotomy or enlargement of the outflow tract. The heart rate usually was increased, but its inverse relation to systemic index was less striking than after repair of atrial and ventricular septal defects. Radial artery pressure was generally

*Table 2 (continued)*

*Corrected for left-to-right shunt (systemic flow equals left atrial flow minus flow shunted from left to right).*

**Contributed by**

[Author Names]

Circulation, Volume XXVIII, July 1963
in the low normal or below normal range, as was pulmonary artery pressure. Other than a mild elevation in case 6, values for calculated pulmonary vascular resistance were within the range of normal. For this calculation, pulmonary blood flow was considered to be quantitatively equal to left atrial flow.

The elevation of left atrial pressure relative to right atrial pressure immediately after perfusion and transfusion was striking in cases 1, 5, and 6 and moderate in case 3. None of these four patients had pericardial enlargement of the outflow tract. Over the next 30 to 60 minutes, left atrial pressure usually fell absolutely and relatively to right atrial pressure; right atrial pressure fell, and systemic index remained the same or rose in these patients (fig. 6). This course of events is considered to be evidence of improvement in ventricular function relative to filling pressure. In these particular patients left atrial pressure generally remained higher than right atrial pressure, although postoperatively it did not exceed right atrial pressure by more than 3 mm. of mercury. Right and left atrial pressures were similar immediately after perfusion and transfusion in cases 2, 7, and 8 (pericardial enlargement of outflow tract). It is concluded that there is a relation approaching normal between left and right ventricular performance in those patients without pericardial reconstruction and that right ventricular performance is generally diminished relative to left ventricular performance in patients with pericardial reconstruction. As in previous studies, left and right atrial pressures did not differ greatly during the postoperative period.

Arterial oxygen saturation (table 3) was normal (greater than 95 per cent) at all observations except on day 1 in cases 1 and 7. Saturation of blood from the pulmonary artery was abnormally low. Differences in arteriovenous oxygen content were abnormally high, but, in contrast to patients previously studied, did not exceed 8 volumes per cent. This may be related in part to left-to-right shunt (cases 6, 7, and 8) and to the relatively high concentrations of hemoglobin seen after repair of tetralogy of Fallot. Elevated values of carbon dioxide were not observed in the postoperative period. Mild metabolic acidosis was present immediately after operation. Spontaneous return to normal occurred by the second or third postoperative day except in two patients (cases 4 and 5). These two patients were exceptional also in having the lowest values for systemic index (1.8 or less) on these same days.

**Discussion**

The value of the present study is limited by the fact that no information was obtained on mechanisms of death, since none of the patients died. Clinical experience plus the data obtained allow some comments nonetheless.

In the earlier experience at the Mayo Clinic, some patients died 8 to 24 hours after an apparently adequate repair; death was believed to have resulted from low cardiac output. In the present study, systemic index usually fell between day 1 (2 to 4 hours after operation) and day 2 (20 hours after operation) even though atrial pressures were intentionally elevated by the administration of

**Figure 6**

Left atrial pressure in operating room after repair of tetralogy of Fallot (case 5). In this patient, 28 minutes after repair (left panel) left atrial pressure was 37/15 mm. Hg (mean, 24 mm.). At this same time right atrial pressure was 18/10 mm. Hg (mean, 15 mm.), Q was 2.6 liters per minute per square meter, and heart rate was 100 beats per minute. Twenty-six minutes later (right panel), left atrial pressure had decreased to 17/9 mm. Hg (mean, 13 mm.). At this time, right atrial pressure was 13/7 mm. Hg (mean, 10 mm.) and Q and heart rate were unchanged. These observations are consistent with a change in ventricular distensibility and contractility between the two observations.
Table 3

Oxygen Levels and Acid-Base Profile in the Postoperative Period after Intracardiac Repair of Tetralogy of Fallot

<table>
<thead>
<tr>
<th>Case</th>
<th>Day</th>
<th>Arterial blood</th>
<th>Pulmonary artery, SO₂%, mmHg</th>
<th>Hemoglobin, Gm./100 ml</th>
<th>Temp. °C</th>
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<td></td>
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<td>CO₂</td>
<td>BB⁺</td>
<td>SO₂ %</td>
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<td>7.45</td>
<td>37</td>
<td>49</td>
<td>100</td>
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</table>

*All observations made during spontaneous respiration in oxygen tent (FiO₂ 0.3-0.5) or with face mask and oxygen at 15 L/min. (cases 5 and 8) except case 2 (I.P.P.B., FiO₂ 0.4). FiO₂ = fractionated concentration of oxygen in inspired air.

†Omitted because of presence of moderate left-to-right shunt.

‡Shivering present during the study.

Blood. For the past 2 years, administration of blood has been directed toward maintenance of an adequate ventricular filling pressure rather than toward a proper blood balance or blood volume. Systemic index would have fallen to even lower, and perhaps sometimes to lethal, levels in these patients had not atrial pressures been elevated. A state of unpreparedness of the lungs and left ventricle of patients with tetralogy of Fallot has been postulated by Harris and associates, presumably on the basis of a high mortality from open repair and the histologic studies of Rich and Ferenz. The present study demonstrated normal or only slightly elevated pulmonary vascular resistance after intracardiac repair of tetralogy of Fallot. A previous study reported normal pulmonary artery pressure immediately after repair in 52 of 54 cases studied (mild elevation in two cases). Gas exchange through the lungs seemed adequate, judging from levels of oxygen and carbon dioxide in arterial blood. Except in the first 30 minutes after repair, left atrial pressure never reached levels suggesting that pulmonary edema might result. Similar values for left atrial pressure in another group of patients operated on for tetralogy...
of Fallot have been published. These data fail to support the concept that the lung and left ventricle are unable to provide adequate pulmonary gas exchange and blood flow without undue elevation of pulmonary artery or left atrial pressures after primary complete repair of the tetralogy of Fallot.

The occasional difference between the left and the right atrial pressure immediately after repair emphasizes that safety in administration of blood requires knowledge of pressures in both atria. Postoperatively, pressures in the two atria are so nearly similar as to allow measurement of only right atrial pressure in determining when blood can no longer be administered safely.

In the past, enlargement of the outflow tract with a prosthesis or piece of pericardium has resulted in a higher operative risk than existed when such enlargement was avoided. This study suggests that, even when the patch is carefully tailored, right ventricular performance is somewhat impaired early after repair. The impairment may be related primarily to the resulting incompetence of the pulmonary valve. A larger patch might interfere considerably more with right ventricular function.

Unusual trouble with exposure complicated the repair of the ventricular septal defect in two patients because of the use of an atrial approach in one (case 3) and because of immense intracardiac return of blood during repair in the other (case 2). These are the only patients known to have continuing moderate-sized residual shunts at the ventricular level. This emphasizes the necessity for careful planning of the operation so as to ensure optimal surgical exposure. The need for unusual attention to the details of repair is emphasized by the finding of small residual left-to-right shunts in three additional patients (cases 6, 7, and 8). The methods used in this study for detection of shunts were more sensitive than those normally employed at postoperative cardiac catheterization.

Eight of the 15 patients studied were catheterized 2 weeks after operation. In only two (cases 2 and 3) was clear evidence of left-to-right shunt obtained, and the magnitudes of the shunts were similar to those obtained in the first 3 days after operation. Of special interest is the fact that at this time no clear evidence of shunt could be found by saturation data or indicator-dilution curve (pulmonary artery injection, sampling at femoral artery) in case 10. A shunt of the magnitude present during the first 3 postoperative days would have been detected. It is concluded that the shunt was largely through pores of the Teflon felt, which was at least partly sealed over, through the coronary artery network—right ventricular connections, which closed—or through the aorticopulmonary collateral connections, which had decreased by the fourteenth postoperative day.

The detection of residual shunts at ventricular level after repair of tetralogy of Fallot is complicated by the existence of other abnormal circulatory pathways. Evidence of their existence has been obtained in this study.

The degree of residual pulmonary stenosis remained relatively constant throughout the study and gives validity to its estimation by pressure measurements in the operating room. A similar conclusion was reached by Bristow and associates. Even with a transverse ventriculotomy or an atrial approach, adequate relief of the pulmonary stenosis sometimes required enlargement of the outflow tract with pericardium. A narrow pulmonary valve ring was present in these cases, and at present constitutes about the only indication for outflow tract enlargement, a conclusion reached also by Malm and associates.

Summary

Physiologic studies have been carried out during the first 3 days after intracardiac repair of tetralogy of Fallot. All patients survived. The ratio between systolic pressure in right ventricle and a systemic artery was 0.7 or less in all cases and did not vary significantly during the period of study. Residual left-to-right shunts of moderate degree were demonstrated in three patients (repaired with
REPAIR OF TETRALOGY OF FALLOT

Teflon prostheses). In one of these three, no definite evidence of shunt could be found 2 weeks after operation. Additional abnormal circulatory pathways exist in these patients. Clear evidence was obtained of left-to-right shunting through aortopulmonary collateral connections in one case. Systemic index was usually below normal or in the low normal range. It was usually lower on the second and third postoperative days than on the first postoperative day. Left atrial pressure was sometimes strikingly higher than right atrial pressure 30 minutes after repair, but not thereafter. Pulmonary vascular resistance was normal or slightly elevated. Gas exchange and management were adequate to maintain normal or near normal oxygen and carbon dioxide levels in arterial blood. Mild metabolic acidosis existed on the first 2 days, but had generally cleared by the third day.

The implications of these data are discussed relative to ventricular function and performance, adequacy and technic of surgical repair, administration of blood after operation, and the state of preparedness in the lung and left ventricle in patients with tetralogy of Fallot.

Acknowledgment

We would like to thank Mrs. Henrietta Cranston and Mr. James Milde for their help in completing this study.

References

Physiologic Studies Early after Repair of Tetralogy of Fallot
RICHARD A. THEYE and JOHN W. KIRKLIN

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