**Serial Cardiac Output and Blood Volume Studies Following Cardiac Valve Replacement**

**By Frank E. Kloster, M.D., J. David Bristow, M.D., Albert Starr, M.D., Colin W. McCord, M.D., and Herbert E. Griswold, M.D.**

**Determination** of the cardiac output during the early postoperative period following open heart surgery has been difficult due to technical problems in adapting the Fick and indicator-dilution methods to the bedside. The recent availability of a radioisotope-dilution method using precordial detection provides a simple and reliable means of measuring blood flow in the postoperative setting. In addition, this method measures the effective blood volume, which has been found to be grossly decreased in many patients following cardiopulmonary bypass. The present study was undertaken to measure the cardiac output and blood volume sequentially during the early postoperative period in patients having one or more cardiac valves replaced with Starr-Edwards prostheses.

**Methods**

The cardiac output and blood volume were studied by the radioisotope-dilution method in 45 patients after cardiac valve replacement with Starr-Edwards prostheses. Eighteen had aortic valve replacement, 10 had mitral replacement, and eight had both valves replaced. Eight patients underwent tricuspid, mitral, and aortic valve replacement, and one had tricuspid and mitral valve replacement.

In the selection of patients for study an attempt was made to include a spectrum of valvular lesions and severity of disease. All except one patient had preoperative cardiac catheterizations, and the findings for each group are listed in table 1. The sex distribution was equal overall, with men predominant in the aortic group and women in the others.

Valve replacement was performed as described previously, using a rotating disk oxygenator with roller pumps and hypothermia to 30°C. The priming volume for the extracorporeal circuit was made up of heparinized whole blood and mannitol. Careful measurements of blood and clear fluid balance were maintained throughout the entire procedure. In addition, body weights were obtained on many patients immediately before and after operation. At the end of bypass, blood was transfused to the patient from the pump until the mean left atrial pressure stabilized at 16 to 18 mm Hg. Subsequently, citrated whole blood was given at a rate estimated to keep replacement approximately 200 ml above measured blood losses. Following the patient's return to the cardiac recovery room, blood replacement was continued on the same basis; as the study progressed, however, blood replacement was sometimes altered by the results of blood volume determinations. The general postoperative care was carried out as described previously. All patients received digitalis preoperatively and postoperatively.

Preoperative determinations of cardiac output and blood volume were usually made the day before operation. Postoperative studies were performed within 2 hours after the patient returned from surgery, daily for the next 3 days, and at the end of 1 week. The final determination was made near the end of hospitalization, 2 or 3 weeks after operation. Patients were studied in the supine position, fasting, and in as nearly a basal state as could be achieved.

The principles of the radioisotope-dilution method utilizing a precordial detector have been described by others previously. A 1 ml injectate containing 15 microcuries of radioactive iodine-labeled (121I) human serum albumin (RISA) was given and was followed by a rapid flush with 10 ml of normal saline solution. Injections were made into an antecubital vein for the preoperative, 1-week, and final studies, and into an inferior vena caval catheter for the early postoperative studies. The detection system...
CARDIAC VALVE REPLACEMENT

The findings are shown in figure 2. Statistical analysis yielded a correlation coefficient of 0.80 ($P < 0.001$) and a slope and intercept of 1.02 minus 0.01. The average variation of the radioisotope method from the Fick method regardless of sign was 8.4%. Ten duplicate cardiac output studies by the RISA method, including patients during the postoperative period, showed an average difference of 3.2%. Two hundred duplicate blood volume studies were performed with an average difference of 3.5%.

**Results**

**Cardiac Output**

Two hundred ninety-two cardiac output studies were made; the results are listed in Table 2. Patients are grouped on the basis of the valve or valves replaced and the mean values, range, and number of patients observed on each day are reported. Subsequent reference to normalcy of the cardiac output refers to the normal resting value for our laboratory of greater than 2.5 L/min/m². It is acknowledged that these patients were not always in a strictly resting state.

The mean control cardiac output was slightly below normal in the aortic, mitral, and double replacement groups but was markedly lower in the triple replacement group. In most patients the control value was close to the resting cardiac output measured during the preoperative cardiac catheterization.

On the operative and first postoperative days

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*Analyzed by the formula:

$$\text{Per cent difference} = \left( \frac{\text{Study } 2 - \text{Study } 1}{\text{Study } 1} \right) \times 100.$$
A typical precordial radiocardiogram following peripheral venous injection of radioactive iodine. Radioactivity is shown on the ordinate and time on the abscissa. Passage of indicator through the right and left sides of the heart is indicated by the two peaks in $a_1$. After systemic recirculation appears, the concentration of radioactivity is extrapolated ($a_2$) based on assumed exponential washout from the left heart. The total area under the curve (A) is the sum of $a_1$ and $a_2$. See text for further explanation of the formula.

The mean cardiac output was modestly increased from the preoperative level in the aortic group. By the second day it was significantly increased over the preoperative value ($P < 0.01$) and was in the normal range in all patients except three. It then remained essentially unchanged for the remainder of the hospitalization.

Patients with triple valve replacement showed a steady rise in cardiac output from the operative day onward. There was a highly significant increase over the low preoperative level by the second day ($P < 0.001$), with all patients in the normal range except two. They then showed a continued increase in flow through the final observation ($P < 0.01$), and the final mean output for the triple group was only slightly below that for patients with aortic valve replacement.

In patients having mitral or double replacement the cardiac output was slightly decreased...
from the control level on the first 2 postoperative days, although there was considerable individual variation. It then rose slowly, but did not show a statistically significant increase until the end of the first week (P < 0.01). Patients with double valve replacement then continued to improve while those with mitral replacement showed only a small further rise after the first week.

When the final cardiac output was compared to the control value for the entire group, there was a highly significant increase (P < 0.001). The final output was greater than the control in every patient, and above 2.5 L/min/m² in all who survived except two.

**Residual Valvular Lesions**

An important factor in the slower increase in cardiac output found in patients with mitral and double valve replacement was the presence of residual valvular disease. Eleven patients in the entire series had valvular lesions which were diagnosed preoperatively or during operation, but which were not corrected because they appeared to be hemodynamically insignificant. Four had aortic insufficiency, four had tricuspid insufficiency, two had aortic stenosis, and one had relative mitral insuffi-

**Table 2**

<table>
<thead>
<tr>
<th>Cardiac Output Values*</th>
<th>No.</th>
<th>Mean</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control</td>
<td>18</td>
<td>2.47</td>
<td>1.10 - 3.83</td>
</tr>
<tr>
<td>Aortic replacement</td>
<td>16</td>
<td>2.69</td>
<td>1.69 - 3.84</td>
</tr>
<tr>
<td>Mitral replacement</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Double replacement</td>
<td>16</td>
<td>2.38</td>
<td>1.55 - 3.80</td>
</tr>
<tr>
<td>Operative day 1</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 1</td>
<td>16</td>
<td>2.38</td>
<td>1.55 - 3.80</td>
</tr>
<tr>
<td>Operative day 2</td>
<td>12</td>
<td>2.63</td>
<td>1.81 - 3.80</td>
</tr>
<tr>
<td>Postoperative day 2</td>
<td>12</td>
<td>2.63</td>
<td>1.81 - 3.80</td>
</tr>
<tr>
<td>Operative day 3</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 3</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Operative day 4</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 4</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Operative day 5</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 5</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Operative day 6</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 6</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Operative day 7</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Postoperative day 7</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
<tr>
<td>Final</td>
<td>16</td>
<td>2.46</td>
<td>1.63 - 3.84</td>
</tr>
</tbody>
</table>

*Values are reported as liters per minute per square meter of body surface area. The normal resting value for our laboratory is greater than 2.5 L/min/m².

Cardiac output in patients with residual valvular lesions (11 patients) compared with that for the entire group (45 patients). Mean values are indicated for the control study (C), operative day (OD, immediately after operation), postoperative studies (1, 2, 3, 7), and final determination (F, 2 to 3 weeks after surgery).
Table 3

<table>
<thead>
<tr>
<th></th>
<th>Aortic replacement</th>
<th>Mitral replacement</th>
<th>Double replacement</th>
<th>Triple replacement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Control</td>
<td>84.9</td>
<td>63.5 — 111.7</td>
<td>93.9</td>
<td>82.1 — 126.5</td>
</tr>
<tr>
<td>Operative day</td>
<td>69.8</td>
<td>53.9 — 93.4</td>
<td>79.6</td>
<td>68.0 — 113.2</td>
</tr>
<tr>
<td>Postoperative day 1</td>
<td>74.7</td>
<td>54.5 — 105.4</td>
<td>87.8</td>
<td>68.2 — 119.6</td>
</tr>
<tr>
<td>Final</td>
<td>79.6</td>
<td>61.6 — 113.4</td>
<td>88.8</td>
<td>70.7 — 110.4</td>
</tr>
<tr>
<td></td>
<td>79.0</td>
<td>63.3 — 102.5</td>
<td>92.0</td>
<td>73.1 — 118.3</td>
</tr>
<tr>
<td></td>
<td>79.5</td>
<td>68.1 — 97.4</td>
<td>87.8</td>
<td>71.2 — 114.4</td>
</tr>
<tr>
<td></td>
<td>85.1</td>
<td>61.4 — 103.0</td>
<td>96.5</td>
<td>77.2 — 127.0</td>
</tr>
</tbody>
</table>

*Values are reported as millimeters per kilogram of body weight. The normal blood volume by our method is 73.1 ± 5.9 ml/kg (mean ± SD). The number of patients observed on each day is the same as indicated in table 2.

**Blood Volume Studies**

The blood volume findings are shown in table 3. The mean preoperative value in the aortic group was at the upper limit of normal by our method. It was somewhat higher in the other groups. The increase in blood volume generally reflected the severity of heart failure and included an elevation in both red cell mass and plasma volume as has been previously reported. Immediately after operation the mean blood volume was sharply decreased from the control levels in all groups and was lower in all patients except two. The mean decrease was 20% in the triple group, and greater than 20% in those having double valve replacement. In some individuals the reduction was dramatic.

**Circulation, Volume 33, April 1966**
as much as 42% of the preoperative value. The fall in blood volume was not consistently related to the duration of cardiopulmonary bypass, the preoperative cardiac output, the control blood volume, or the patient's weight.

The mean blood volume deficit for each group and the blood balance during cardio-

pulmonary bypass are shown in table 4. There was a marked discrepancy between the measured loss of blood during operation and the blood volume deficit determined by the dilution technique. In the aortic, double, and triple groups the blood volume dropped a liter more than could be accounted for by the measured blood loss, while in the mitral group the disparity was nearly half a liter. Preoperative and postoperative weights, which were available for about half of the patients, similarly failed to reflect the large change in measured blood volume.

The blood volume increased rapidly during the early postoperative period and approached the control level by the third day. The relationship of measured blood balance to changes in blood volume during this time is shown in table 5. On the first postoperative day there was little difference between blood volume changes and measured blood balance. A discrepancy was apparent during the second and third postoperative days, when the blood volume increased more than could be accounted for by blood replacement. This was due primarily to an increase in plasma

Table 4
Blood Balance During Cardiopulmonary Bypass*

<table>
<thead>
<tr>
<th>Group</th>
<th>No.</th>
<th>Decrease in blood volume</th>
<th>Measured blood loss, Ml</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic</td>
<td>18</td>
<td>1073</td>
<td>15.7</td>
</tr>
<tr>
<td>Mitral</td>
<td>10</td>
<td>820</td>
<td>15.2</td>
</tr>
<tr>
<td>Double</td>
<td>8</td>
<td>1424</td>
<td>23.0</td>
</tr>
<tr>
<td>Triple</td>
<td>9</td>
<td>1149</td>
<td>21.5</td>
</tr>
</tbody>
</table>

*Values reported are means for each group, expressed as milliliters of whole blood.

Table 5
Postoperative Blood Volume-Blood Balance Relationships*

<table>
<thead>
<tr>
<th>Group</th>
<th>Blood volume</th>
<th>Blood balance</th>
<th>Time after operation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Day 1†</td>
<td>Day 2</td>
<td>Day 3</td>
</tr>
<tr>
<td>Aortic</td>
<td>+242</td>
<td>+210</td>
<td>+253</td>
</tr>
<tr>
<td>Mitral</td>
<td>+440</td>
<td>+462</td>
<td>0</td>
</tr>
<tr>
<td>Double</td>
<td>+485</td>
<td>+521</td>
<td>+331</td>
</tr>
<tr>
<td>Triple</td>
<td>+132</td>
<td>+224</td>
<td>+731</td>
</tr>
</tbody>
</table>

*Reported as mean values for each group, expressed as milliliters of whole blood.
†The values reported are the difference between the findings on the postoperative day indicated and those of the preceding day.
volume, with little change in the red cell mass (fig. 5). By the end of the third day the blood volume approached the preoperative level in most patients, and it rose a little more through the remainder of hospitalization. On the final observation the blood volume had returned to the preoperative mean value for each group except the tricuspid, and to the preoperative level in most individual patients except those with markedly elevated preoperative volumes, the majority of whom were in the tricuspid group.

**Cardiac Output-Blood Volume Relationships**

As the magnitude of the initial blood volume deficit in some patients became apparent, blood replacement during the early postoperative period was pursued much more vigorously. It was then noted that patients with low cardiac output often had a prompt increase in output following transfusion. Subsequently, restoration of the control blood volume was specifically attempted in such patients, with the results indicated in table 6.

Twenty-one patients who had cardiac indices below 2.2 L/min/m² on the operative or first postoperative day constitute and low cardiac output group. They are divided into three subgroups on the basis of responses in cardiac output and blood volume. The values listed are the means for each subgroup. They represent the findings on the operative day or first postoperative day, whenever low output was first noted (initial), and on the second postoperative day (final).

Sixteen patients, indicated as the first two low output subgroups were given a quantity of whole blood calculated as sufficient to restore the preoperative blood volume during the first 24 to 48 hours after surgery. This resulted in an average positive blood balance of 800 ml, which increased the mean blood volume to 97% of the control value. In nine of these patients replacement of the blood volume deficit was accompanied by marked increase in cardiac output, greater than 1 L/min/m² in every patient. This represented an 80% average increase in blood flow. Each of these nine then had normal cardiac output, which was maintained for the rest of hospitalization.

![Blood volume findings (mean values) for the entire patient group. Plasma volume and red cell mass are derived from the total blood volume using the hematocrit.](image)

**Figure 5**

**Table 6**

**Response of Low Cardiac Output to Whole Blood Transfusion**

<table>
<thead>
<tr>
<th></th>
<th>Cardiac output, L/min/m²</th>
<th>Blood volume, ml/kg</th>
<th>Blood balance, ml</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial‡</td>
<td>Final§</td>
<td>Change</td>
</tr>
<tr>
<td>Low cardiac output</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output increased</td>
<td>9</td>
<td>1.77</td>
<td>3.24</td>
</tr>
<tr>
<td>Output unchanged</td>
<td>7</td>
<td>1.60</td>
<td>1.84</td>
</tr>
<tr>
<td>Control</td>
<td>5</td>
<td>1.96</td>
<td>2.11</td>
</tr>
<tr>
<td>All other patients</td>
<td>24</td>
<td>3.03</td>
<td>3.31</td>
</tr>
</tbody>
</table>

*Values reported are the means for each group.
†Net of measured whole blood gains and losses between initial and final observations.
‡Findings on day low output first occurred (operative day in 17 patients, postoperative day 1 in 4).
§Findings on postoperative day 2.
CARDIAC VALVE REPLACEMENT

The other seven patients, shown as the second low output subgroup, received a similar quantity of blood with a comparable rise in blood volume. They had no change or only modest increases in cardiac output and were still well below the lower limit of normal. They continued to have lower outputs through the remainder of hospitalization.

It is of interest to examine these seven further. Four had residual valvular lesions. Two others were patients with triple valve replacement who had postoperative hemodynamic or postmortem evidence of severe myocardial disease. The seventh was a 76-year-old man who improved very slowly after aortic valve replacement and was thought to have reversible myocardial insufficiency. Thus, all of the seven who failed to respond to blood replacement with an increased cardiac output had either a residual valvular lesion or evidence of myocardial disease.

Five patients with low output serve as a small control group. They were given blood transfusions according to the schedule followed for all other patients, aimed at keeping blood replacement 200 ml above measured losses, and all had a slight rise in blood volume. They showed only a small increase in cardiac output on the second day. By the end of the first week they had had a gradual rise in cardiac output into the normal range and in blood volume to near the preoperative level.

**Pressure Data**

The systemic arterial pressure was usually moderately elevated immediately after operation, with the mean pressure frequently 100 mm Hg or greater and occasionally as high as 140 mm Hg.* This was typically associated with signs of moderate to intense peripheral vasoconstriction and appeared to be the result of endogenous adrenergic activity. The arterial pressure did not reflect either the cardiac output or the blood volume with any sensitivity. On subsequent days the systemic arterial pressure usually stabilized at a mean value of 80 to 90 mm Hg, and evidence of vasoconstriction disappeared as the cardiac output increased and the blood volume expanded. The systemic vascular resistance was greater than 2,000 dynes seconds centimeters\(^{-5}\) in half the patients on the operative day, then decreased through the remainder of hospitalization and was 1,500 dynes seconds centimeters\(^{-5}\) or lower at the time of discharge.

The systemic venous pressure was recorded through a polyethylene catheter positioned in the inferior vena cava during the first 2 or 3 postoperative days. It was usually highest on the operative day, was somewhat higher in patients with low cardiac output, and tended to decrease as the output improved. However, the venous pressure showed no consistent relationship to the cardiac output, the blood volume deficit, or the response to blood replacement. It was useful in ensuring that rapid or large volume blood transfusion did not result in systemic venous congestion but was otherwise of questionable value in the management of patients, as others have also reported.\(^{16, 17}\)

**Discussion**

The prompt increase in cardiac output in patients following aortic valve replacement was not unexpected. They have been the easiest of the patients with valve replacement to manage postoperatively, with infrequent problems of low cardiac output and a lower mortality rate. Physiologically they usually have an isolated mechanical problem of left ventricular outflow obstruction or volume overload, and with correction of the problem the previously compromised ventricle might be expected to re-

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*Mean arterial pressure was determined by electrical damping of pressure recorded through a polyethylene catheter in the radial artery or from the brachial artery pressure measured with a sphygmomanometer, using the formula:

\[
\text{Mean arterial pressure} = \text{Diastolic pressure} + \frac{3}{\text{Pulse pressure}}.
\]

*Circulation, Volume XXXIII, April 1966

*Calculated from the formula:

\[
\text{Resistance} = \frac{\text{Mean arterial pressure (mm Hg)} \times 80}{\text{Cardiac output (L/min)}}
\]

with resistance units expressed in dynes seconds centimeters\(^{-5}\).\(^{15}\)
spond well. By the second postoperative day, the mean cardiac output for the group was well into the normal range, and only three patients had cardiac indices somewhat below 2.5 L/min/m. All of these had prolonged heart failure preoperatively, and one had relative mitral insufficiency.

The patients undergoing tricuspid, mitral, and aortic valve replacement are of particular interest, representing truly end-stage rheumatic heart disease. All were functional class III or IV with severe heart failure, and seven of the nine had control cardiac indices below 2.0 L/min/m. They are unique in having successful tricuspid valve replacement, an infrequently reported procedure. Most showed prompt improvement clinically and in cardiac output after operation, and by the second postoperative day all except two had cardiac indices in the normal range. One of these two died on the third postoperative day of myocardial failure. The other continues to have fluid retention and gross cardiomegaly, with no evidence of dysfunction of the prostheses during postoperative cardiac catheterization, and presumably has myocardial disease. The remaining patients have all had excellent clinical results.

Patients having mitral or double valve replacement differed from those having aortic and triple valve replacement in showing slower initial improvement. The mitral group also had a lower mean cardiac index on the final observation. A major factor in this response was the presence of residual valvular lesions. Following mitral replacement six patients had minimal to moderate aortic valve disease and one had tricuspid insufficiency. Three patients with double valve replacement had residual tricuspid insufficiency. The cardiac outputs in patients with residual lesions were significantly below the values for the entire group throughout the postoperative period. The findings in patients undergoing mitral or double replacement who had no residual lesions were comparable to those for the entire group.

Patients with residual tricuspid insufficiency had markedly impaired cardiac function, even though the regurgitation appeared mild at the time of surgery. The cardiac index remained near or below 2 L/min/m² through the third postoperative day, associated with persistent clinical findings of low cardiac output. After discharge from the hospital, they were considerably improved over their preoperative state but continued to have signs of congestive heart failure. Two have subsequently undergone reoperation for tricuspid valve replacement. Both had increased cardiac indices after the second procedure, with outputs of 3.2 and 2.5 L/min/m² on the second postoperative day. One is now asymptomatic; the other died of a cerebral complication. A third patient also underwent reoperation but did not have tricuspid valve replacement because the hypertrophied right ventricle would not accommodate the prosthesis.

These findings support previous clinical observations that residual lesions are not well tolerated following cardiac surgery. Such patients frequently have stormy postoperative periods and unsatisfactory long-term results. Our criteria for valvular replacement have been revised since this series, and many of these patients would now have multiple valve replacement.

Although every effort was made to measure cardiac output under stable, basal conditions, this was often difficult to achieve in postoperative patients. In spite of this, the sequential values in individual patients were generally consistent. When the findings at a given observation were obviously at variance with preceding and subsequent results, the associated clinical observations were reviewed, and factors affecting the results could be identified.

Psychological stimuli, particularly anxiety or pain, were the most frequent cause of increased cardiac output. Postoperative delirium was relatively common, and cardiac output was often greater when the patient was hallucinating or overtly psychotic. Fever as high as 103° F was usually not associated with a high output. Two patients with hematocrit values of 20% had high cardiac output states, apparently due to the anemia, but numerous patients...
CARDIAC VALVE REPLACEMENT

with hematocrit readings of 28 to 32% did not show this.

Cardiac arrhythmias with ventricular rates of 120/min or greater were associated with a decreased cardiac output. This was most often due to atrial fibrillation, but also occurred with sinus and nodal tachycardia. Nodal rhythm with a moderate rate, perhaps the commonest postoperative arrhythmia, had no apparent adverse effect on the output. The stroke volume almost invariably paralleled the cardiac output in the absence of tachycardia regardless of the rhythm mechanism.

Hypovolemia was the factor most frequently related to a decreased cardiac output. This was usually due to a decreased blood volume following cardiopulmonary bypass. The occurrence of a sizable blood volume deficit following cardiopulmonary bypass was first reported in man by Litwak and co-workers\textsuperscript{17, 23} and has been attributed to perfusion with large volumes of homologous blood, although the specific mechanism has not been identified.\textsuperscript{28–25}

The blood volume deficit is believed to be due to temporary sequestration of blood in unidentified sites in the body. This is based primarily on the lack of correlation between changes in blood volume, body weight, and measured blood balance during perfusion. In addition, Litwak and associates have reported sequestration of blood during the early postoperative period.\textsuperscript{26} Berger and associates\textsuperscript{16} have found a similar blood volume deficit after open heart surgery, but neither they nor Theye and Kirklin\textsuperscript{27} found evidence of sequestration of blood after operation.

The patients in this study demonstrated blood volume deficits following cardiopulmonary bypass comparable in magnitude to those reported by Berger and co-workers\textsuperscript{16} and by Litwak and associates.\textsuperscript{17, 26} Almost all patients were hypovolemic to some degree after perfusion. The deficit was not reflected in the measured blood balance or in changes in body weight, supporting the concept that the blood loss is internal. However, there was no increase in red cell mass during the first 3 days after operation not accounted for by blood replacement, certainly not of the magnitude expected if red cells sequestered during bypass were re-entering the circulation. After the first day, the increase in blood volume to the preoperative level, which occurred in most patients, was due to a rise in plasma volume. The red cell mass progressively fell, associated with an elevated serum bilirubin and reticulocyte count, most likely due to hemolysis from red cell trauma at the time of perfusion. It is possible that sufficient hemolysis occurred to mask the return of sequestered red cells. In any event, we found no evidence of significant sequestration of blood during the early postoperative period.

Replacement of the blood volume deficit resulted in a remarkable increase in cardiac output in nine patients with low output. The increase occurred during the period when the blood was given, and there was concomitant clinical improvement. Seven other patients with low output who did not show this response to blood transfusion were found to have problems other than hypovolemia to explain their low output states; these were either residual valvular lesions or myocardial disease. Several had some increase in output (1.64 to 2.17, 0.89 to 1.67, 1.18 to 1.66, and 1.57 to 2.24 L/min/m\textsuperscript{2}) which at these low levels was undoubtedly beneficial if not as striking. Five control patients showed essentially no change in either blood volume or cardiac output when blood transfusion simply replaced measured losses.

Rehder, Kirklin, and Theye\textsuperscript{28, 29} have reported a similar increase in cardiac output following the rapid infusion of whole blood following cardiopulmonary bypass. They did not describe blood volume abnormalities but attempted to maintain right atrial pressure at 10 to 14 mm Hg by administration of blood. The most likely mechanism for the increased output is augmented ventricular diastolic filling, as they suggested.

Blood was given to our patients with caution initially while watching for evidence of overtransfusion. When this did not occur, transfusion was pursued vigorously, attempting to replace the calculated blood volume deficit within 24 hours. Close clinical observation

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of the patient and monitoring of the systemic venous pressure were maintained to assure that the rate or volume of transfusion was not excessive. The individuals who were rapidly transfused to their preoperative blood volumes remained at these levels, with no evidence of an increment of previously sequestered blood being added later. Hypervolemia was not a problem, either in the appearance of venous congestion or in the development of a blood volume excessively above the control level. Neither Berger and co-workers nor Kirklan and Theye found evidence of hypervolemia in their patients despite generous blood replacement after operation.

A potential "built-in" correlation between blood volume and cardiac output when blood flow is calculated by this method should be acknowledged. Several points indicate that this is not a significant factor. (1) The cardiac output by the RISA method correlates well with the Fick output, utilizing an entirely different principle, over a wide range of flows and blood volumes. (2) The blood volume (volume of dilution of the radioisotope) and precordial equilibrium count, Ce (concentration of the radioisotope), represent an in vivo expression of the amount of radioactive indicator injected and are inversely related to each other. Any increase in the blood volume would proportionally decrease Ce and neutralize the effect of the blood volume rise. (3) Increasing the cardiac output to the extent shown simply on the basis of an enlarged blood volume would require almost doubling the blood volume, which did not occur. (4) Numerous patients showed the opposite of the expected relationship, both an increased blood volume with a decreased cardiac output and the converse.

At present when a patient shows clinical evidence of low cardiac output following cardiopulmonary bypass, we immediately suspect hypovolemia in the absence of other obvious causes. Blood replacement is initiated promptly, vigorously, and without real fear of over-transfusion, with the aim of restoring the preoperative blood volume to achieve adequate ventricular filling pressure for optimal cardiac function. The lack of response with increased cardiac output strongly suggests that a residual valvular lesion or serious myocardial disease is present.

Summary

The cardiac output and blood volume were measured preoperatively and sequentially during the early postoperative period in 45 patients undergoing cardiac valve replacement. Most patients showed a prompt, highly significant increase in cardiac output. Those with uncorrected valvular disease, even though apparently trivial, had lower cardiac outputs. The blood volume was sharply reduced from the preoperative level in almost every patient. When this was associated with low cardiac output, replacement of the blood volume deficit was usually accompanied by a prompt increase in cardiac output. Failure to respond in this way occurred only in patients with residual valvular lesions or myocardial disease.

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Serial Cardiac Output and Blood Volume Studies Following Cardiac Valve Replacement
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