Pulmonary Artery Banding
Indications and Results in Infants and Children

By Allan Goldblatt, M.D., William F. Bernhard, M.D.,
Alexander S. Nadas, M.D., and Robert E. Gross, M.D.

Banding of the pulmonary artery has been proposed as a therapeutic procedure for patients with a large left-to-right shunt and pulmonary artery hypertension not amenable to complete correction. It was theorized that by increasing the resistance to outflow from the right ventricle, and thus lowering the pulmonary artery pressure, the size of the left-to-right shunt would diminish, the high output failure state would improve, and the pulmonary arterioles might be protected from developing progressive intimal changes.

The original proposal by Muller and Dammann was reported in 1952, at a time when surgery with the pump oxygenator was not available. It had been assumed that, with the introduction of cardiopulmonary bypass, this palliative procedure would be outmoded and discarded, and all left-to-right shunts would be repaired in a one-step open-heart procedure.

The experiences of the past few years have demonstrated, at least to us, that despite the technical progress, the pulmonary artery banding procedure is still applicable in patients who have a ventricular septal defect under these specific situations: (1) young infants with large left-to-right shunts and intractable congestive heart failure who are too small to be operated upon by means of cardiopulmonary bypass; (2) children with left-to-right shunts and severe obstructive pulmonary artery hypertension in whom the pulmonary vascular changes raise the operative mortality to prohibitive levels; and (3) patients with a presently inoperable anatomic situation in whom the decrease of pulmonary blood flow by means of banding might improve congestive heart failure.

The present report has been prompted by the paucity of reported series of any sizable number of patients treated by means of pulmonary artery banding. It was thought that by analysis of the results in a large series of patients, indications for the procedure and operative risks might be clarified.

Material and Methods

All patients who underwent banding of the pulmonary artery at the Children’s Hospital Medical Center between 1957 and June 30, 1964, comprise the series. There was a total of 69 patients, 31 male and 38 female. Within recent years, with improvement in surgical technics and increased interest in the surgery in infants, more patients were submitted to this palliative procedure and thus approximately 70 per cent of the cases were operated upon since 1962.

All of the patients had a complete clinical evaluation, including physical examination, x-rays, and electrocardiograms, and were examined by one of the authors in addition to other members of the Cardiology Department. Sixty-seven patients had cardiac catheterization and cineangiography performed according to the well-established technics. In addition, three patients have undergone postoperative cardiac catheterization. Autopsy reports were available on 19 patients.

The operative technic consisted of banding the main pulmonary artery with wide Nylon tape to reduce its size to approximately a third of its original diameter. Until 1963, all patients were operated upon in the main operating room of the Children’s Hospital Medical Center under normal atmospheric conditions. With the introduction of hyperbaric surgery at our institution, 14 patients were operated upon in the hyperbaric chamber at pressures of 3.0 and 4.0 atmospheres.
PULMONARY ARTERY BANDING

absolute (30 to 44 pounds per square inch). The effectiveness of the constriction was estimated by systemic arterial oxygen saturations in 19 patients, or by pressures in the main pulmonary artery, distal to the banding, as well as in the right ventricular body in 34 patients measured before and after operation. In 16 patients it was not possible, for technical reasons, to verify the effectiveness of the procedure other than by inspection and palpation of the pulmonary artery.

Results

The patients, all having a ventricular septal defect, were, for the purpose of this analysis, arbitrarily divided into two major groups. Group I consisted of patients with a left-to-right intracardiac shunt, pulmonary artery hypertension, and normal great vessels. This group will be discussed in some detail. Group II included patients who, in addition to a left-to-right intracardiac shunt and pulmonary artery hypertension, also had anomalies of the great arteries. This critically ill group of patients, with a very high operative mortality, will be discussed as a whole, since in the majority no postoperative follow-up is available.

Group I

Patients with left-to-right shunts, pulmonary artery hypertension and no great vessel abnormalities.

Preoperative Evaluation

As indicated in table 1, there were 48 patients in this group. The ages ranged from 1 month to 6 years, with an average of 10 months. Figure 1 indicates a detailed break-down of the patients’ ages at the time of operation. All but two patients were in intractable congestive heart failure preoperatively. Severe repeated respiratory infections complicated the congestive heart failure in 26 patients. Frank pulmonary edema was present in 22. Thirty-three of the patients could not be controlled sufficiently to be discharged from the hospital. As plotted on the Children’s Hospital Medical Center anthropometric chart, 39 of the 48 patients were below the third percentile for weight (fig. 2a).

Every patient exhibited significant cardiac enlargement by chest x-ray and in 30 this was interpreted as “maximal.” In addition, 37 of the patients had “maximal” pulmonary vascular engorgement.

Table 1

<table>
<thead>
<tr>
<th>Diagnosis</th>
<th>No. patients</th>
<th>Alive</th>
<th>Operative</th>
<th>Late</th>
<th>Mortality, per cent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ventricular septal defect</td>
<td>20</td>
<td>16</td>
<td>3</td>
<td>1</td>
<td>15</td>
</tr>
<tr>
<td>Ventricular septal defect and</td>
<td>17</td>
<td>14</td>
<td>1</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>patent ductus arteriosus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ventricular septal defect and</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>atrial septal defect</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Atrioventricular canal</td>
<td>10</td>
<td>8</td>
<td>2</td>
<td>0</td>
<td>20</td>
</tr>
<tr>
<td>Totals</td>
<td>48</td>
<td>39</td>
<td>6</td>
<td>3</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Circulation, Volume XXXII, August 1965
The electrocardiogram demonstrated pure left ventricular hypertrophy in 12 patients, combined ventricular hypertrophy in 23 patients, and pure right ventricular hypertrophy in 13. In addition, left axis deviation was present in all cases of atrioventricular canal.

Medical treatment consisted of digoxin in 47 patients in conjunction with diuretics and a low-sodium diet in 35. Twenty-eight patients had been receiving antibiotics for frequent superimposed pulmonary infections.

Preoperative cardiac catheterization with cineangiography was performed on 47 patients. Forty-six had a systemic-to-pulmonary arterial systolic pressure ratio of greater than 0.75. The calculated pulmonary-to-systemic flow ratio ranged from 2.0/1 to 24.0/1, with an average of 5.6/1. Whereas the oxygen consumption had to be assumed in a significant number of these babies, the calculated flow ratios should be interpreted qualitatively, indicating a large shunt, rather than quantitatively. Without question, however, all other clinical measurements substantiated the markedly increased pulmonary blood flow in 47 of these patients. In the remaining patient, a 6-year-old girl, indication for banding was the high pulmonary vascular resistance with a small left-to-right shunt. At preoperative cardiac catheterization, the child had a calculated pulmonary vascular resistance of 5.3 mm. Hg./L./min./M.².

**Evaluation at Surgery**

The effectiveness of the pulmonary artery banding was verified, at the operating table, by systemic arterial oxygen saturations in 12 patients. Preoperatively, the average oxygen saturation was 94 per cent; after banding it was reduced by an average difference of 5 to 89 per cent.

Twenty-seven of the patients had pressures measured in the pulmonary artery before and after application of the band. The average initial systolic pressure was 76 mm. Hg, with a range from 50 to 100 mm. Hg. Immediately after the procedure, the pressure was reduced to an average of 34 mm. Hg, with a range of from 20 to 65 mm. Hg.

**Mortality and Postmortem Results**

There were six operative deaths with a resulting operative mortality of 12.5 per cent. In addition, there were three late deaths, raising the over-all mortality to 19 per cent. Since 1962, 24 patients have been operated upon with a ventricular septal defect, with or without an associated patent ductus arteriosus. There were two deaths in this latter group, or a mortality of 8 per cent.

Five of the six operative deaths were a result of cardiac arrest occurring during or immediately following surgery. In none could adequate cardiac function be restored. In none of these patients were pressure measurements obtained at surgery, possibly because of the critical condition of the patient. Postmortem examination verified the diagnosis and demonstrated the constricted pulmonary artery lumen. The effectiveness of the banding procedure could only be assumed, and it is possible that, though the pulmonary artery was decreased to what was estimated at the operating table to be a third of its original diameter, the pressures and flows were not significantly altered.

The sixth operative death occurred 10 hours postoperatively from continuing uncontrol-
lable congestive heart failure. In this patient, pressures were measured and reducing the pulmonary artery systolic pressure more than 15 mm. Hg resulted in alarming bradycardia.

Two of the three late deaths occurred 1 and 5 months postoperatively. In neither patient had pulmonary arterial pressures been measured at the time of banding. Both patients, postoperatively, had continued to exhibit signs and symptoms of congestive heart failure and in both instances superimposed pneumonia was the precipitating cause of death. The third late death occurred 1 month postoperatively. At surgery, in this patient, the pulmonary arterial systolic pressure had been reduced from 60 to 20 mm. Hg and the patient had appeared improved. Two weeks following discharge from the hospital, the patient had to be readmitted with bilateral pneumonia and died within 18 hours.

Postoperative Evaluation of the Survivors

Patients with Ventricular Septal Defect. Sixteen of the 20 patients with an isolated ventricular septal defect have survived the procedure with a follow-up ranging from 1 to 36 months. There has been marked clinical improvement in 11; the other five showed little or no significant change. It should be stressed, however, that in these five patients, the downward course of the infants was arrested and they could be maintained at home without requiring further hospitalization.

By physical examination, postoperatively, all 16 patients developed a loud ejection systolic murmur at the upper left sternal border. Nine of the patients have had no change in their electrocardiograms, whereas in the remaining seven there has been some increase in the right ventricular potentials with a concomitant decrease in left ventricular hypertrophy (fig. 3).

Postoperative chest x-rays have shown significant decrease in pulmonary vascular engorgement in 11 patients; the remaining five showed little or no change. Cardiac enlargement has persisted in all 16 patients, though in eight of them the cardiac silhouette has been interpreted to be smaller than preoperatively (fig. 4).

Five of the 16 patients no longer require any medication. The remaining 11 have been maintained on digitalis, but none has required diuretics or low-sodium diet. Two
patients have continued receiving “prophylactic” antibiotics at the discretion of their private physicians. Three of the 16 have increased their weight from below the third percentile to the thirtieth percentile, while in four others the rise has been from below the third to the tenth percentile. Of the remaining nine patients, eight have been followed for too short a time postoperatively to evaluate their growth and the remaining patient has stabilized at the third percentile.

Patients with Ventricular Septal Defect plus Patent Ductus Arteriosus. Fourteen of the 17 patients survived surgery with a follow-up ranging from 1 to 52 months. All have shown significant clinical improvement and have developed a systolic ejection murmur at the second left intercostal space. By electrocardiogram, the entire group has shown evidence of right ventricular hypertrophy and in four of the patients the degree of left ventricular hypertrophy has been significantly reduced.

The postoperative chest x-rays have shown improvement with relation to heart size and pulmonary vascular engorgement in only six of the surviving patients (fig. 5). The remaining eight have shown no significant change.

Six of the patients no longer require medication and the remaining eight are receiving only digitalis. All patients are on a normal diet and none has required diuretics or antibiotics. The growth curve in seven of the patients has increased from below the third to the tenth percentile line. The remaining seven, five of whom are but a few months postoperative, have maintained their weight at the third percentile.

Patients with Complete Atrioventricular Canal. Eight of 10 patients survived surgery and all have shown significant clinical improvement. Electrocardiographically there has been evidence of increasing right ventricular hypertrophy in four patients and there is no longer evidence of left ventricular hypertrophy in the patient with preoperative combined ventricular hypertrophy. Chest x-rays taken postoperatively have shown a significant decrease in pulmonary vascular engorgement and heart size in six of the patients while the remaining two have shown only minimal improvement. Two patients no longer require any medication. The remaining six are being maintained on digitalis but none of them requires diuretics, antibiotics, or low-sodium diet. Weight percentiles have increased from below the third to the thirtieth in four and to the tenth in three of the other four patients.

The Patient with Ventricular Septal Defect and Atrial Septal Defect. The one patient with this diagnosis has survived for 2½ years. The patient’s weight chart is unchanged in that she still is below the third percentile. Symptoms, however, have significantly improved; she has no further episodes of pneumonia and no evidence of congestive heart failure. In addition, the patient no longer requires any medication. Chest x-rays have shown a de-
crease in the pulmonary vascular engorgement as well as in the heart size.

Postoperative Cardiac Catheterization. Of the 39 patients surviving surgery, we have had the opportunity to repeat cardiac catheterization on only three. The diagnosis was ventricular septal defect in one patient, ventricular septal defect plus patent ductus arteriosus in another, and the remaining patient had an atrioventricular canal. In all three patients the pulmonary arterial systolic pressure was lowered to 50 per cent or less of the systemic pressure. Two of the three patients were studied within a month following operation.

Group II

Patients with left-to-right shunts, pulmonary artery hypertension and anomalies of the great vessels.

Preoperative Evaluation

There were 21 patients in this group. The ages ranged from 2 weeks to 11 years, with an average of 13 months. Figure 6 reveals a detailed breakdown of the patients' ages at the time of surgery. All 21 patients were in intractable congestive heart failure pre-operatively, and in 19 failure could not be adequately controlled medically to allow them to leave the hospital. Severe repeated respiratory infections complicated the congestive heart failure in 17 patients. Eighteen of the 21 patients, were below the third percentile for weight.

Every patient exhibited significant cardiac enlargement by chest x-ray, and in 14 of them this was interpreted as "maximal." In addition, 12 of the patients had "maximal" pulmonary vascular engorgement.

The electrocardiogram demonstrated pure

Figure 5

Radiographic improvement following division of patent ductus arteriosus and pulmonary artery banding.
left ventricular hypertrophy in 11 patients, combined ventricular hypertrophy in five patients, and pure right ventricular hypertrophy in five.

Medical treatment consisted of digitalis in 21 patients, in conjunction with low-sodium diet and diuretics in 16. Seventeen patients had been receiving antibiotics for frequent superimposed pulmonary infections.

Preoperative cardiac catheterization with cineangiography was performed on 20 patients in this group. All 20 had a systemic arterial, pulmonary arterial, or right ventricular systolic pressure ratio of greater than 0.75. The pulmonary to systemic flow ratio calculated for 16 of the 20 patients ranged from 2.0/1 to 8.4/1 with an average of 4.3/1. In four patients the pulmonary artery could not be entered. Here, as with the patients in group I, the same reservations should be appreciated in evaluating the figures for pulmonary blood flow.

Evaluation at Surgery

The effectiveness of pulmonary artery banding was verified at the operating table by systemic arterial oxygen saturations in seven patients. Three had transposition of the great vessels and in two of them there was no change in the systemic arterial oxygen saturation following banding. The third patient showed an increase of 16 per cent after application of the band. The remaining four patients had, preoperatively, an average oxygen saturation of 87 per cent. This was reduced after banding by an average of 17 to 70 per cent.

Seven patients had pressures measured in the pulmonary artery before and after banding. The average initial systolic pressure was 82 mm. Hg, with a range of from 55 to 100 mm. Hg. Immediately after the procedure, the pressure was reduced to an average of 41 mm. Hg, with a range of from 25 to 80 mm. Hg.

Mortality and Postmortem Results

There were 14 operative deaths, with a resulting operative mortality of 67 per cent. In addition, there were three late deaths, raising the over-all mortality to 81 per cent. Of the total of 17 deaths, pressures were measured in only six. Cardiac arrest was the major cause of operative deaths, being the precipitating factor in all the cases of ventricular septal defect, patent ductus arteriosus, and coarctation of the aorta. Both operative deaths in the group with corrected transposition of the great vessels were secondary to arrhythmia. Overwhelming infection was the cause of the late deaths in the patients with transposition and with corrected transposition of the great vessels.

Of special interest were the patients with persistent truncus arteriosus. The three operative deaths were secondary to cardiac arrest during or immediately following surgery. One late death occurred 4 months postoperatively. This was a 2½-month-old girl with a diagnosis of persistent truncus arteriosus, type II. At surgery, only the left pulmonary artery was banded because of the extreme irritability of the heart and the critical condition of the baby. Postoperatively the patient did quite well and was discharged on maintenance digoxin. Four months later this patient was readmitted in extremis with congestive heart failure and pneumonia. By both physical examination and chest x-rays the failure and infection were limited to the right lung with the left lung remaining clear (fig. 7). The patient died within 24 hours after admission and permission for postmortem examination was granted. Microscopic examination of the lungs revealed passive and active congestion of the right lung with superimposed pneumonia. There were, in addition, early intimal

Figure 7

Radiograms of the patient who underwent banding of the left pulmonary artery for truncus arteriosus, type II. Note the significant difference between the two lung fields in the postoperative film.

Circulation, Volume XXXII, August 1965
changes in the pulmonary arterioles. The left lung in contrast was free from congestion and infection. The arterioles were normal without any significant intimal changes (fig. 8).

Discussion

In 1952 Muller and Dammann^4 described the first reported case of banding of the main pulmonary artery. This was performed on a 4-month-old infant with a single ventricle. Pulmonic stenosis was created in an effort to reduce pulmonary blood flow and pulmonary artery hypertension. By decreasing the diameter of the main pulmonary artery to a third of its original size, they were able to reduce pulmonary blood flow by 50 per cent. These same authors further postulated that with the creation of pulmonic stenosis the “cardiac work load” would be significantly reduced and congestive heart failure thereby corrected. In addition, the effects of increased pulmonary blood flow and pulmonary hypertension would be arrested. Since 1952, numerous reports have emphasized the clinical benefits of pulmonary artery banding^5-13 although but few have encompassed any significant number of patients.4, 9, 13 Most of the reported patients having undergone pulmonary artery banding had, as their basic lesion, a ventricular septal defect with a large left-to-right shunt and pulmonary artery hypertension.3-9, 11-13 Only one of the 13 patients reported by Morrow and Braunwald,7 had an atrial communication as well as a ventricular septal defect. Williams et al., in an article published in 1963,16 described 12 patients who underwent pulmonary artery banding with complex cardiac defects in addition to a ventricular septal defect. Craig and Sirak^13 reported the results in 20 patients subjected to pulmonary artery banding for cardiac lesions other than pure defects in the ventricular septum. If the avowed purpose of banding the pulmonary artery is to decrease the magnitude of the left-to-right shunt, and thereby to improve the high output failure state, and hopefully to protect the pulmonary arterioles from developing progressive intimal changes, then all patients with a large left-to-right intracardiac shunt and pulmonary artery hypertension, with or without anomalies of the great vessels, should be significantly benefited as long as a defect of the ventricular septum is present. In patients with an atrial septal defect and an intact ventricular septum, banding of the main pulmonary artery could only result in an increase in right ventricular systolic and end-diastolic pressures, congestive heart failure, and death. A ventricular septal defect must therefore be proved, preoperatively, in every patient undergoing the banding procedure, since the lack of such a defect has always proven fatal.

The patients in this report were arbitrarily divided into two groups. Both had in common large intracardiac left-to-right shunts with pulmonary artery hypertension. The differen-
tiating feature was the presence or absence of associated great vessel anomalies.

Group I consisted of patients in whom there were no associated great vessel anomalies. The preoperative evaluation revealed a homogenous group of severely ill infants and children. All but two of the 48 were in intractable congestive heart failure despite vigorous long-term anticongestive measures. In addition, approximately 50 per cent of them exhibited frank pulmonary edema and repeated superimposed pulmonary infections.

One patient was subjected to the surgical procedure because of obstructive pulmonary artery hypertension. This 6-year-old girl tolerated the procedure without incident and has been followed thus far for a period of only 9 months. Cardiac catheterization has as yet not been repeated to evaluate the efficacy of this approach. Dammann et al.9 reported on eight patients with this hemodynamic picture ranging from 4 to 12 years of age. In three of these there was an "over-all right-to-left" shunt, whereas in the remaining five the shunt was "over-all left-to-right." Two patients with a predominant right-to-left shunt died. In two of those with a left-to-right shunt there was suggestive, though by no means conclusive, evidence of a decrease in the pulmonary vascular resistance. Dammann and his co-workers suggested that the medial hypertrophy, normally found during fetal life, failed to regress in the presence of an elevated pulmonary artery pressure and flow. It was on this basis that the eight patients were subjected to pulmonary artery banding.

Certain questions remain unanswered in this type of patient. How much total left-to-right shunt must exist for the patient to benefit by further decreasing pulmonary blood flow? If the shunt were "over-all right-to-left," then banding the pulmonary artery would, physiologically and hemodynamically, only increase cardiac embarrassment. With a right-to-left shunt, no longer is the pulmonary blood flow increased but only the pulmonary arterial pressure. How much can the pressure be reduced, without compromising the heart, in its attempt to perfuse a high resistant pulmonary arteriolar bed? Long-term follow-up with repeated cardiac catheterizations in addition to lung biopsies will be needed to answer these questions and to determine the validity of banding in this type of patient. For the present, however, we are not routinely subjecting these patients to pulmonary artery banding.

Further comment is warranted with regard to the specific defects included in group I. To predict the future of patients with isolated ventricular septal defects, had they not undergone banding of the pulmonary artery, is extremely difficult, if not impossible. Certainly some would have died either from infection or from intractable congestive heart failure,17,18 and others would have gone on to develop progressive pulmonary vascular obstructive disease, thereby creating a totally inoperable situation.19-21 It also seems likely that in a few instances the ventricular septal defect would have undergone spontaneous closure.22,23 Finally, in a few centers, these patients might well have undergone total correction of their defect at an early age, though surely not under 6 months.2 Therefore, one is faced with a patient who cannot be managed medically and in whom the risk of total correction, by means of cardiopulmonary bypass, is at the present time, in most institutions, at prohibitive levels.10 The place for a palliative or "first stage" procedure, such as the Blalock-Taussig operation for patients with decreased pulmonary blood flow, thus becomes apparent but has to be decided by each physician for the individual patient—taking into consideration the likelihood of the various course of events enumerated as well as the prevailing surgical skills in the particular institution.

Those patients who, in addition to a ventricular septal defect, have a patent ductus arteriosus present a unique problem. It is often extremely difficult to determine the respective percentage of increased pulmonary blood flow caused by each of these lesions. The optimal therapy for this group would appear to be the simultaneous closure of both defects. This, however, is technically difficult.
and the risk in small infants is almost prohibitive. Sasahara et al.\textsuperscript{24} showed that division of the patent ductus arteriosus alone produced little, if any, clinical improvement, failed to lower the pulmonary vascular resistance, and, in some, resulted in a “left-to-right shunt of a magnitude comparable to the preoperative one through the ventricular septal defect alone.” Therefore, in these extremely sick, small babies, division of the ductus, plus banding of the pulmonary artery, would appear to be the procedure of choice. We propose that in patients with this preoperative diagnosis, exploratory thoracotomy should be performed and the ductus divided. If, following division of the patent ductus arteriosus, there is residual, significant pulmonary artery hypertension, a banding procedure is recommended.

Of special interest in group I were those 10 patients with complete atioventricular communis defects. Williams et al.\textsuperscript{16} reported two cases in their series of 12 patients and Craig and Sirak\textsuperscript{18} had one patient in their group of 20 patients. In addition, Dammann et al.\textsuperscript{9} had one patient of 13 who, at the time of complete correction, died and was found at postmortem examination to have had a complete atioventricular canal.

At the present time the risk of complete surgical correction in this group of patients is approximately 75 per cent.\textsuperscript{25–27} Thus, with correction at prohibitive levels, a palliative procedure which could control the congestive heart failure and possibly protect the pulmonary vasculature from progressive obstructive changes should be utilized. If the principal hemodynamic burden is the left-to-right shunt with pulmonary artery hypertension and not mitral regurgitation, then the patient should benefit significantly from the procedure. The very favorable results in this group of patients suggests that this indeed is an excellent palliative approach to the problem. If, however, mitral regurgitation is the principal hemodynamic problem, banding the pulmonary artery would result in little, if any, hemodynamic improvement.

The technic of constricting the main pulmonary artery to a third of its original size has not significantly changed since it was first described.\textsuperscript{1} The method of validating the effectiveness of this procedure has been altered considerably since banding was first performed in this institution. Initially, verification was obtained either by inspection alone or by the measurement of systemic arterial oxygen saturations. Neither method, in retrospect, was found to be adequate. Five of the six patients in group I succumbed at operation and two of the three late deaths had had no pressure measurements obtained at the time of banding. The marked variability and limitations in the use of oxygen saturations and the extreme difficulty in being able to predict at the operating table the size of the pulmonary artery lumen are well known.\textsuperscript{7} As a result, pressure measurements are being obtained in the operating room on all patients before and after application of the band.

The value of pulmonary artery banding in this group of patients has been significant. No patient, postoperatively, has required either diuretics or a special diet. Only two patients are receiving antibiotics from their local physicians, not for existing infection, but rather as a “prophylactic” measure. Of the surviving 39 patients, 15 no longer require any medication. In addition to the impressive reduction in the need for medication, there has been an equally impressive increase in the rate of growth of these patients (fig. 2b). Seven patients have increased from below the third to the thirtieth percentile and 14 have moved up into the tenth. Sixteen patients have been followed for too short a period of time postoperatively to evaluate adequately the effect of the procedure on their growth.

One question still unanswered at this institution is whether, following a banding procedure, there is any increase in the risk at the time of definitive repair. To date, none of the patients has been subjected to complete repair.

Albert et al. in 1958\textsuperscript{28} described a technic for placement and subsequent removal of a pulmonary artery band in 11 dogs. They reported that the subsequent repair of the band-
ing was without difficulty and there were no deaths. Two single cases, with successful total correction, have been reported. By far the largest series to undergo definitive repair following banding was reported by Damann et al. in 1961. Their series included 13 patients undergoing complete repair with nine surviving. One of the deaths was in a patient with a complete atroventricular canal. The total reported number of reoperated patients is too small, at the present time, to make any significant statement regarding the possible increased risk at the time of total correction.

The patients with left-to-right intracardiac shunts, pulmonary artery hypertension, and anomalies of the great vessels comprise group II. In these patients with an inoperable anatomic situation, it was postulated that banding the pulmonary artery would decrease pulmonary blood flow and thereby therapeutically improve the congestive heart failure. The extremely poor results with this group, as evidenced by an over-all mortality of 81 per cent, was shocking. Williams et al. reported 12 such patients with a mortality of 58 per cent. Craig and Sirak had similar poor results in 20 patients with an over-all mortality at 65 per cent. Reasons for this great disparity between patients with and without great vessel anomalies are not clear. Though it cannot be adequately documented, these patients did appear more acutely, rather than chronically, ill. At the operating table the hearts of these patients were irritable and more prone to arrhythmias and arrest during and following the procedure.

Possible explanation for our poor results in coarctation of the aorta, with a systemic right ventricle, may be found in the documented severe pulmonary arteriolar changes. In the transposition group, the difficulties in assessing the degree of banding necessary to decrease pulmonary blood flow, without markedly reducing systemic arterial oxygen saturation, are great. Furthermore, the sudden increase in resistance to right ventricular outflow due to banding may be too stressful to the already severely malformed heart. It is likely that these hearts with multiple defects cannot be palliated adequately with a single surgically induced hemodynamic alteration.

Patients with persistent truncus arteriosus are a somewhat special group. In types II and III, without question, both pulmonary artery branches must be banded to effect any significant long-term benefit to the patient. Our poor results with this group were, in major part, the result of only unilateral banding, specifically the left pulmonary artery. All but one of the patients died at surgery. The fourth patient has already been described in detail. This case not only demonstrated the necessity for adequate banding of both pulmonary arteries but in addition lent further credence to the theory proposed by Damann, specifically, “the regression of pulmonary vascular disease after creation of pulmonic stenosis.”

The rationale for undertaking pulmonary artery banding operations in the compression chamber is based upon experimental data obtained in a series of anesthetized baboons and Rhesus monkeys. In 80 per cent of the animals included in the study, an increase in calculated pulmonary vascular resistance occurred in the compression chamber at environmental pressures of 3.0 to 4.0 atmospheres absolute (30 to 44 pounds per square inch). A small increase in pulmonary arterial pressure was noted (3.0 to 8.0 mm. Hg) with no change in simultaneously recorded left atrial pressure. Serial blood gas determinations indicated that the change in pulmonary arterial pressure (reflecting an increase in pulmonary vascular resistance) occurred when the mixed venous (pulmonary arterial) pO2 was in the range of 600 to 1,000 mm. Hg and the arterial pO2 values in the range of 1,000 to 1,800 mm. Hg. In all experiments, the values for pulmonary vascular resistance reverted to normal upon a return to standard conditions.

On the basis of this small but significant increase in pulmonary vascular resistance in normal animals under hyperbaric conditions, observations were made in a series of 14 babies with severe pulmonary plethora and pulmonary artery hypertension. In all patients
a rise in systemic arterial pressure was noted at chamber pressures of 30 and 44 pounds per square inch and this was correlated with a small rise in pulmonary arterial pressure. The mixed venous and arterial pO2 values were in the same range as the previously recorded observations in the experimental animals. The net effect of these changes in this group of severely ill infants was a transient decrease in the size of the left-to-right shunt with a concomitant increase in systemic blood flow. There were no instances of cardiac arrest or persistent arrhythmias in this consecutive series of cases, indicating an improved hemodynamic stability immediately prior to pulmonary artery banding.

**Summary and Conclusion**

A detailed analysis of 69 patients having undergone banding of the pulmonary artery is presented. The patients, all having a defect in the ventricular septum, were divided into two major groups.

Group I consisted of 48 patients with a left-to-right intracardiac shunt, pulmonary artery hypertension, and normal great vessels. There was an over-all mortality of 19 per cent. Since 1962, 24 of these patients have been subjected to this procedure with a mortality of only 8 per cent.

Group II consisted of 21 patients who, in addition to a left-to-right intracardiac shunt and pulmonary artery hypertension, had anomalies of the great vessels. The over-all mortality in this group was 81 per cent.

As a result of our review of these patients, certain statements can be made. Patients with a ventricular septal defect and a large left-to-right shunt, pulmonary artery hypertension, and no great vessel anomalies, in whom medical treatment has been unable to control congestive heart failure, have benefited significantly from the procedure. The risk of the surgery is definite but with improving technics and the use of constant pressure monitoring, this has been significantly reduced to a reasonable level during the past several years. If, in fact, as has been stated by others,9, 29, 30 there is no significant increase in morbidity or mortality at the time of total correction, it would appear, from clinical and hemodynamic measurements, that we are presenting for later definitive repair better surgical risk patients. For infants with intractable congestive heart failure due to a complete atrioventricular canal or a ventricular septal defect plus a patent ductus arteriosus, pulmonary artery banding is even more justified.

In those patients who, in addition to a large left-to-right intracardiac shunt and pulmonary arterial hypertension, have great vessel anomalies, the risk of banding is much greater. Consequently, whenever possible, these patients should be treated conservatively. Surgical palliation is justified, at the present time, only as a last resort to prevent death rather than as a maneuver for an infant who fails to improve.

**References**


8. **Albert, H. M., Fowler, R. L., Craighead, C. C.,**


