Coil Embolization to Occlude Aortopulmonary Collateral Vessels and Shunts in Patients With Congenital Heart Disease

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Gianturco coils were used to embolize 77 vessels in 54 patients: 58 aortopulmonary collateral vessels, 14 Blalock-Taussig shunts, 3 arteries involved in pulmonary sequestrations and 2 venae cavae. Embolization resulted in total occlusion in 53 (69%), subtotal occlusion in 19 (25%) and partial occlusion in 3 (1 intentional). Two embolizations failed to reduce flow. Thus, 72 (95%) of 76 embolizations in which complete occlusion was the intended result resulted in total or subtotal occlusion. Analysis of the results demonstrates that completely occluded collateral vessels were longer and had a smaller diameter than did incompletely occluded vessels.

Several workers (1-11) have demonstrated the feasibility of transcatheter closure of abnormal vessels in children with heart disease with the use of coils (1-6), foam (7) or detachable balloons (8-11). However, the number of patients reported on is small; thus, reasonable assessments of success rates, risks and the necessary technical modifications for various lesions are not available. Beginning in May 1984, we attempted transcatheter coil embolization of all unwanted important vessels in children with heart disease. We have reviewed our experience with Gianturco coil (12,13) and report on their use to embolize 77 vessels in 54 patients: 58 aortopulmonary collateral vessels, 14 Blalock-Taussig shunts, 3 arteries involved in pulmonary sequestrations and 2 venae cavae.

Complications included six cases of inadvertent embolization to the pulmonary arteries (n = 5) or the aorta (n = 1); three were retrieved and three were left without symptoms. In addition, there was a case of severe hemolysis after intentional partial occlusion of a Blalock-Taussig shunt. The results demonstrate that coil embolization can be an effective procedure for managing a wide variety of aortopulmonary collateral vessels and shunts in children with congenital heart disease.

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Methods

Study patients. Between May 1984 and January 1988, coil embolization of 77 vessels in 54 patients with congenital heart disease was attempted. Patients ranged in age from 1 month to 36 years (mean 7.0 ± 8.4 years) and in weight from 1.8 to 81 kg (mean 20 ± 17). A single vessel was embolized in 34 patients and multiple vessels in 20 patients. In 42 patients, embolization was performed during a single catheterization and in 12 during two or more catheterizations. Aortopulmonary collateral vessels were embolized in 36 patients, Blalock-Taussig shunts in 14, pulmonary sequestrations in 2 and venae cavae in 2. Records and cineangiograms were reviewed.

Aortopulmonary collateral vessels. Embolization of 58 aortopulmonary collateral vessels was performed in 36 patients between 3 months and 23 years of age (mean 7.1 ± 6.5 years). The underlying diagnosis was tetralogy of Fallot with pulmonary atresia in 26 patients, tetralogy of Fallot in 4, polysplenia or asplenia in 2, hypoplastic left heart syndrome in 2, d-transposition of the great arteries and pulmonary atresia in 1 and bronchopulmonary dysplasia in 1. Embolization was performed before corrective surgery in 12 patients, before and after corrective surgery in 7 and after corrective surgery in 17. A single vessel was embolized in 17 patients; in 2 patients the same vessel was embolized at different catheterizations. Multiple vessels were embolized
Table 1. Coil Embolization of a Blalock-Taussig Shunt in 14 Patients

<table>
<thead>
<tr>
<th>Patient</th>
<th>Diagnosis</th>
<th>Time of Repair</th>
<th>BT Shunt</th>
<th>No. of Coils</th>
<th>Result</th>
<th>Qp:Qs</th>
<th>O₂ Sat (%)</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>ToF/CAVC</td>
<td>Post</td>
<td>Left</td>
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<td>Subtotal</td>
<td>1.5</td>
<td>96</td>
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<tr>
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<td>ToF</td>
<td>Post</td>
<td>Left</td>
<td>3</td>
<td>Complete</td>
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<td>98</td>
</tr>
<tr>
<td>3</td>
<td>TA</td>
<td>Post</td>
<td>Right</td>
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<td>Unsuccessful</td>
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<td>97</td>
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<td>ToF</td>
<td>Post</td>
<td>Right</td>
<td>5</td>
<td>Subtotal</td>
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<td>97</td>
</tr>
<tr>
<td>5</td>
<td>Fontan</td>
<td>Post</td>
<td>Left</td>
<td>1</td>
<td>Complete</td>
<td>0.7</td>
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</tr>
<tr>
<td>6</td>
<td>PS/IVS</td>
<td>Pre</td>
<td>Left</td>
<td>2</td>
<td>Complete</td>
<td>0.6</td>
<td>75</td>
</tr>
<tr>
<td>7</td>
<td>d-TGA, VSD, PA</td>
<td>Pre</td>
<td>Right</td>
<td>5</td>
<td>Partial</td>
<td>0.5</td>
<td>75</td>
</tr>
<tr>
<td>8</td>
<td>ToF/PA</td>
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<td>Left</td>
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<tr>
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<td>Pre</td>
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<td>81</td>
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<tr>
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<td>Complete</td>
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<td>97</td>
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<tr>
<td>11</td>
<td>PS</td>
<td></td>
<td>Left</td>
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<td>Complete</td>
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<td>95</td>
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<tr>
<td>12</td>
<td>PA/IVS</td>
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<td>1</td>
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<td>1.1</td>
<td>93</td>
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<tr>
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<td>Right</td>
<td>1</td>
<td>Partial</td>
<td>&gt;4</td>
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*Modified Blalock-Taussig shunt using 3 or 4 mm Gore-Tex conduit. See text for definitions of degree of occlusion. BT = Blalock-Taussig; CAVC = complete atrioventricular canal; DORV = double outlet right ventricle; d-TGA = d-transposition of the great arteries; IVS = intact ventricular septum; O₂ = oxygen; PA = pulmonary atresia; PS = pulmonary valve stenosis; Sat = systemic oxygen saturation before and after embolization; Qp:Qs = pulmonary to systemic flow ratio before and after embolization; TA = tricuspid atresia; ToF = tetralogy of Fallot; VSD = ventricular septal defect.

in 19 patients: in 5 during a single catheterization and in 9 at separate catheterizations. Review of angiograms demonstrated that 14 collateral vessels in 12 of these patients were not embolized. Records and angiograms were reviewed to determine why these collateral vessels were not embolized.

**Blalock-Taussig shunts (Table 1).** Of 14 Blalock-Taussig shunts embolized, 5 were residual shunts remaining after attempted surgical ligation (Patients 1 to 5). In Patient 1, the subclavian artery had been ligated proximal to the takeoff of a modified left Blalock-Taussig shunt, leaving residual flow through the shunt by way of the left carotid and vertebral arteries. Patient 2, treated 20 years after repair of tetralogy of Fallot and attempted ligation of a left Blalock-Taussig shunt, had had two episodes of bacterial endocarditis. Of four patients (Patients 6 to 9) who underwent shunt embolization before surgical repair, three had bilateral Blalock-Taussig shunts and the least accessible shunt was embolized to simplify the subsequent surgery. In Patient 6, who had undergone right ventricular outflow tract reconstruction and in whom catheterization demonstrated the feasibility of closing the shunt and the atrial septal defect, embolization of the shunt left only the atrial septal defect to be closed surgically. In three patients (Patients 10 to 12), embolization of the shunt eliminated the need for further surgery. Patients 10 and 12, who had valvular pulmonary atresia and intact ventricular septum, had undergone right ventricular outflow tract reconstruction and a Blalock-Taussig shunt in infancy, and an atrial septal defect or patent foramen ovale had closed spontaneously. Patient 11 had undergone surgical valvotomy for critical pulmonary stenosis and creation of a left Blalock-Taussig shunt in infancy. After embolization of the shunt, the atrial septal defect was closed with use of a Rashkind double umbrella.

After creation of a right Blalock-Taussig shunt, Patient 14, with double outlet right ventricle, complete atrioventricular (AV) canal and pulmonary stenosis, developed a pulmonary to systemic blood flow ratio >4:1 with ventricular dilation and severe AV valve regurgitation. Complete balloon occlusion of the shunt resulted in a drop in systemic oxygen saturation from 87 to 43%. Because of the difficulty of surgically decreasing the shunt size coupled with the patient’s poor condition, it was decided to attempt deliberate partial occlusion of the shunt with an oversized coil.

**Pulmonary sequestrations.** Of two patients who had embolization of pulmonary sequestrations, one had scimitar syndrome and one had tetralogy of Fallot.

**Venae cavae.** In a patient with bilateral superior venae cavae and in another with bilateral inferior venae cavae, the left-sided venae cavae, which drained to the left atrium after a Fontan procedure, were embolized.

**Embolization Procedure.**

The procedure has been described in detail (14). Routine precatheterization sedation with chloral hydrate or meperidine hydrochloride (Demerol) compound was used and followed by intravenous morphine or diazepam (Valium) as needed during the procedure. Intravenous heparin (100 UI/kg body weight) was given when vascular access had been obtained. Patients were given an antibiotic (usually cefazolin) before coil embolization and for 24 h after embolization.

*With four exceptions, the vessels were embolized with use*
of the femoral artery. The left axillary artery was used to
to embolize a modified Blalock-Taussig shunt (Table 1, Patient
1) and an aortopulmonary collateral vessel arising from the
left subclavian artery. The left superior vena cava was
embolized from the left subclavian vein and the left inferior
vena cava from the femoral vein.

**Type of catheter.** The type of catheter used to deliver the
coil depended on the anatomy of the vessel to be embolized,
but attempts were made to avoid acute angles in the catheter
course (which makes passage of the coil through the catheter
difficult) and to fix the position of the catheter tip during
delivery of the coil either by inflating the balloon on a
balloon-tipped catheter or by using preformed curves in the
catheter. As it is frequently necessary to try a variety of
catheters to enter, occlude and embolize a vessel, a sheath was
commonly used. Coils can be delivered through catheters as small as 3F.

**Vessel anatomy.** Vessel anatomy (length, diameter, presence of stenoses)
and flow distribution were determined from selective angiograms. We have previously found that distal
occlusion of a vessel can lead to proximal vessel distension;
this can cause migration of occlusive devices that were
chosen on the basis of unstretched diameter of the vessel.
Therefore, in short vessels, those without a distal stenosis and in veins (which are more distensible than arteries),
angiography with the vessel balloon-occluded distally was
performed to determine the stretched diameter (Fig. 1). In
the case of aortopulmonary collateral vessels, pulmonary
arteriography was performed, or previous arteriograms re-
viewed, to determine if the native pulmonary arteries also
supplied the segment of the lung supplied by the collateral
vessel (dual supply).

**Criteria for proceeding with embolization and coil selec-
tion.** Criteria included availability of an appropriately sized
coil and either a vessel length of 1.5 cm or distal stenosis.
Aortopulmonary collateral vessels were embolized if the
segment of the lung supplied by the collateral vessel ap-
peared to receive blood from the native pulmonary arteries
or if the collateral vessel supplied a relatively small segment
of lung (<0.5 lobe). Coils (Occluding Spring Emboli, Cook)
are available in two wire diameters (0.025 or 0.038 in. [0.064
or 0.097 cm]), five coiled diameters (2, 3, 5, 8, 10 and 12
mm), and five lengths (2, 2.5, 3, 4 and 5 cm). The length and
shape of the coil when embolized depend on a number of
factors including the ratio of coil to vessel diameter, the
distensibility of the vessel and the diameter of the wire in the
coil. We chose the first coil to be about 10 to 40% larger than
the vessel diameter and could theoretically embolize vessels
with a diameter of approximately 1.8 to 10 mm.

**Coil placement.** Coils were soaked for 5 to 10 min to
topical thrombin (Thrombin, Topical [Bovine], USP., Ar-
more Pharmaceutical Co.) before embolization of high flow
vessels.

Coils were extruded from the catheter with use of the soft

![Figure 1](image-url)

**Figure 1.** A, Selective contrast injection using an end-hole catheter in an aortopulmonary collateral vessel (small arrow) demonstrating distal anatomy. B, A second injection was performed with use of a Berman angiographic catheter to balloon occlude (large arrow) the vessel and demonstrate proximal anatomy (small arrow). C, After embolization, the coil (large arrow) completely occludes the vessel (small arrow). A collateral vessel to the left lung is also demonstrated.
anatomy of the vessel and the position of the previously placed coil or coils. The procedure was terminated when the vessel was completely occluded or when no space remained for additional coils.

**Definition of results of embolization.** These are defined angiographically as follows. Total occlusion = no flow past the coils. Subtotal occlusion = marked delay in washout of dye injected proximal to the coils and failure of dye flowing past the coils to opacify the distal vessels. Partial occlusion = markedly slowed washout with enough residual flow to faintly opacify the vessels distal to coils. Unsuccessful embolization = no perceptable difference in angiographic flow before and after embolization.

**The hemodynamic effects on the vessels embolized.** The results of embolization were assessed, when possible, in terms of systemic arterial saturation, systemic pulse pressure, pulmonary artery pressure and the ratio of pulmonary to systemic blood flow.

**Statistics.** Results are expressed as the mean value ± SD. Statistical analysis of the results was performed with use of the Student’s *t* test with a value *p* < 0.05 considered significant.

### Results

Coil embolization of 77 vessels was attempted in 54 patients. Results are presented according to the type of vessel embolized (Table 2): aortopulmonary collateral vessels, Blalock-Taussig shunts, pulmonary sequestrations or venae cavae.

**Aortopulmonary collateral vessels.** Of 58 collateral vessels, occlusion was complete in 42, subtotal in 14 and partial in 1, with 1 failed embolization. An average of 2.5 ± 1.8 (range 1 to 8) coils was used per vessel and the mean size of the largest coil used in each was 5.0 ± 1.9 mm. Nearly all coils used were standard-sized (0.038 in., 0.097 cm) with a coiled diameter of 3, 5 or 8 mm. An average of 1.6 ± 1.1 coils was used in vessels that were completely occluded (n = 34) and 3.8 ± 1.9 in vessels subtually or partially occluded (n = 12) (*p* = 0.0001). Completely occluded vessels (n = 19) had a smaller diameter (4.1 ± 1.8 versus 6.4 ± 2.8 mm) (*p* = 0.025) and were longer (3.34 ± 1.53 versus 2.22 ± 1.12 cm) (*p* = 0.029) than incompletely occluded vessels (n = 9). The mean size of the largest coils used was 4.3 ± 1.5 mm (n = 34) in completely occluded vessels and 7 ± 1.5 mm (n = 12) in incompletely occluded collateral vessels (*p* = 0.0002).

**Hemodynamic results.** Pre- and postembolization values for systemic oxygen saturation, systemic pulse pressure, mean pulmonary artery pressure, and pulmonary to systemic blood flow ratio are shown in Table 3 for three groups: 1) all collateral vessels, 2) collateral vessels embolized before corrective surgery, and 3) collateral vessels embolized after corrective surgery. The only significant change was in systemic oxygen saturation in all patients and in those undergoing embolization before corrective surgery. Similar analyses in two other groups (completely versus incompletely occluded vessels) failed to show any significant differences in pre- and postembolization values for these variables.

**Reasons for nonembolization.** In this group of 36 patients who had 58 collateral vessels embolized, a total of 72 collateral vessels were identified. Thus, 14 vessels in 12 patients were not embolized. On the basis of catheterization reports and review of angiograms, six vessels were left for "physiologic" reasons (vessels too small [n = 1], sole source of blood supply [n = 2] or necessary for oxygenation [n = 3]), and nine were left for "technical" reasons (vessels could not be entered far enough to embolize because of a sharp turn near the origin [n = 4], contrast dye limit [n = 4] and vessel injury during cannulation [n = 1]).

**Recatheterization results.** Of the 36 patients, 17 have undergone repeat catheterization and have had angiograms of 25 previously coiled vessels. The interval between embolization and recatheterization was 9.5 ± 3.9 months (range 6 days to 30 months). During follow-up, 1 of 18 completely occluded collateral vessels partly recanalized, 4 of 4 subtotaly occluded vessels closed and 3 partially occluded collateral vessels remained open (2 were reembolized). The vessel that recanalized was quite large before embolization. Recanalization was not suspected clinically but minimal flow was demonstrated at a catheterization 15 months after embolization. The four vessels that closed were recatheterized 4.5 ± 4.3 months after the embolization (Fig. 2).

**Blalock-Taussig shunts.** Of 14 shunts embolized with 1 to 5 coils, occlusion was complete in 6, subtotal in 5, partial in 2 (1 intentional) and unsuccessful in 1.

**Pulmonary sequestrations.** A patient with scimitar syndrome underwent two procedures. At the first catheterization, a single artery from the descending aorta supplied the right lower pulmonary lobe. This vessel was completely occluded with two coils and pulmonary to systemic flow ratio decreased from 2.1 to 1.7. At recatheterization 5 months later the vessel had minimally recanalized and a
second artery supplying the right lower lobe was identified. Both vessels were coil embolized and completely occluded and the shunt abolished.

After corrective surgery of tetralogy of Fallot, a patient was found to have sequestration of the left lower pulmonary lobe, and embolization, with five coils, of the artery supplying the sequestration resulted in complete occlusion. The patient had a residual pulmonary to systemic blood flow ratio of 1.8:1 due to a residual ventricular septal defect.

Venae Cavae. In the two patients, the left superior and inferior venae cavae were each completely occluded with a single coil.

Complications. A coil embolized to the pulmonary artery in five patients, three with a Blalock-Taussig shunt and two with an aortopulmonary collateral vessel. In Patient 3 (Table I), after placement of an initial coil in the Blalock-Taussig shunt, the second coil embolized to the right pulmonary artery. The coil was retrieved with a snare and the procedure terminated with essentially no change in flow through the shunt. In Patient 11, who had a 4 mm modified, left Blalock-Taussig shunt (Table I), the initial coil embolized to the left pulmonary artery. During the attempt to retrieve it, it embolized to the right pulmonary artery; it was retrieved from this artery with use of a tip-deflecting wire and the procedure was terminated (Fig. 3). Embolization was again attempted 2 months later and at that procedure, a balloon dilation catheter was placed in the left pulmonary artery and inflated to occlude the distal end of the shunt (Fig. 4). The first coil placed in the Blalock-Taussig shunt straightened and extended partially into the subclavian artery. It was snared and removed, and embolization with two coils was then performed without further complication. In Patient 13 (Table I), one of five coils placed in the modified, right Blalock-Taussig shunt embolized to the pulmonary artery and attempts to retrieve it were unsuccessful. Because of severe tricuspid regurgitation, right ventricular output was unable to provide adequate pulmonary blood flow and the systemic oxygen saturation was 37% after occlusion of the shunt. The patient was taken to the operating room and the coils were removed.

In two patients with an aortopulmonary collateral vessel, a coil embolized to the left lower pulmonary lobe and was not removed. In one of the patients, embolization of a 5 mm coil occurred after placement of an 8 mm coil. In the other patient, the first coil embolized to the left pulmonary artery and was not removed. The collateral vessel was subsequently embolized with a 5 and 3 mm coil. In all three patients in whom the coil was not removed (one Blalock-Taussig shunt, two aortopulmonary collateral vessels), pulmonary angiograms demonstrated that the embolized branch pulmonary artery remained patent. The patency presumably occurs because the plane of a coil that floats into a vessel aligns parallel with the long axis of the vessel (as demonstrated on angiograms) and flow continues on either side of the coil. None of these patients had signs or symptoms of pulmonary embolism.

In attempting to manipulate a wire and catheter from the aorta distal to the collateral vessel to the aorta proximal to
Figure 2. A, An aortogram after embolization of a collateral vessel demonstrates residual flow (small arrow) past the coil (large arrow). B, At recatheterization 3 months later, an aortogram demonstrates the vessel embolized at the first procedure (large arrow) to be completely occluded and a second collateral vessel arising superiorly (small arrow). C, The second vessel was embolized and a selective injection demonstrates complete occlusion (small arrow); the large arrow is the coil in the first collateral vessel.

the vessel in a poorly sedated patient after embolization of the collateral vessel. The catheter caught the coil and dislodged it into the descending aorta. With use of a snare, the coil was pulled into the femoral artery and removed by cutdown. The artery was closed and a subsequent angiogram demonstrated the artery to be patent.

In Patient 14 (Table 1), a Blalock-Taussig shunt was partially occluded intentionally. The systemic oxygen saturation decreased from 86 to 78% and the pulmonary to systemic blood flow ratio from >4:1 to 2:1:1 after embolization. This patient developed severe hemolytic anemia presumably due to high flow past the coil. The hemolysis did not decrease in the month after embolization and it was decided to surgically remove the coil, but fever developed and the patient died before surgery.

There were two cases of extravasation of contrast medium resulting from attempts to manipulate a catheter into a vessel, one in a collateral vessel and one in a left superior vena cava. No further attempts were made to enter the collateral vessel. The vena cava was successfully occluded at the same procedure. Neither case resulted in symptoms or required intervention.

Discussion

Success rate. Previous reports of the use of Gianturco coils in patients with abnormal systemic to pulmonary ves-
Figure 4. Patient 11. A, Anteroposterior and B, lateral projections of a selective contrast injection in the left Blalock-Taussig shunt (small arrows) are shown with the distal end of the shunt occluded by a balloon-dilation catheter in the left pulmonary artery (large arrow). C, Anteroposterior and D, lateral projections after embolization and removal of the balloon demonstrate complete occlusion of the shunt by the coils (arrows).

sels or congenital heart disease have demonstrated the feasibility of embolizing aortopulmonary collateral vessels, pulmonary arteriovenous malformations, Blalock-Taussig shunts, arterial supply of pulmonary sequestrations, venae cavae and patent ductus arteriosus. However, the largest series reported closure of 17 vessels in four patients, each with a different lesion (4). On the basis of these reports it is not possible to determine success rate, determinants of success, risks or need for technical modifications. We used Gianturco coils to embolize 77 vessels, 58 aortopulmonary collateral vessels, 14 Blalock-Taussig shunts, 3 pulmonary sequestrations and 2 venae cavae in 54 patients. Embolization resulted in total occlusion in 53 (69%), subtotal occlusion in 19 (25%) and partial occlusion in 3 (1 intentional) as determined by angiograms performed at the time of embolization. In two cases, embolization failed to reduce flow. Thus, 72 of 76 embolizations (95%) in which complete occlusion was the intended outcome resulted in total or subtotal occlusion.

Aortopulmonary collateral vessels. In some patients, aortopulmonary collateral vessels supply a significant portion of pulmonary blood flow. Although embolization of collateral vessels before “corrective” surgery is preferable because intracardiac blood return is decreased, this is possible only if there are other adequate sources of pulmonary blood flow. The significance of collateral blood flow in patients who have not undergone repair of intracardiac defects can be assessed by occluding the vessel with a balloon-tipped catheter and measuring the systemic oxygen saturation. Thus, even though results are biased toward small decreases in saturation, our data demonstrate that systemic oxygen saturation decreased significantly in patients undergoing embolization preoperatively. On the other hand, objective assessment of the hemodynamic significance of collateral vessels in patients who have already undergone “corrective” surgery is difficult. Thus, pulmonary to systemic blood flow ratios are inaccurate because of difficulty in obtaining adequately mixed samples. In addition, because pulmonary hypertension due to collateral vessels is unusual, significant changes in pulmonary artery pressure after occlusion of collateral vessels are uncommon. In many patients, therefore, the decision to embolize collateral vessels or close them surgically is based on the size of the vessel and, though difficult to quantify, on assessment of flow through the vessel as judged by washout on pulmonary arteriograms or after injection into the aorta or collateral vessel.

Success rate. Of the 72 aortopulmonary collateral vessels (in 36 patients) in this study, 58 were embolized, resulting in total (n = 42) or subtotal (n = 14) occlusion in 96% of cases. In comparison with collateral vessels that were incompletely occluded, those completely occluded had a smaller diameter, were longer and required smaller and fewer coils. The difficulty in completely occluding a short collateral vessel with a large diameter is probably due to the need for multiple coils to occlude the residual defect (the hole in the center of the coil) left by the large coils used initially and the fact that the number of coils that can be embolized is limited by the vessel length. Additionally, it may be that the larger, short collateral vessels have a higher flow that makes complete occlusion more difficult. We have used topical thrombin to
attempt to promote clotting and occlusion, but in this retrospective study its efficacy could not be determined. Whereas 14 of the 16 incompletely occluded collateral vessels had only minimal residual flow, it may be that other devices, such as umbrellas, would be more appropriate for closing these large, short vessels. We have used the Rashkind double umbrella to close two large collateral vessels (15).

Reasons for nonembolization. Of the 72 collateral vessels (in the 36 patients) in the study, 14 were not embolized. Of the six collateral vessels not embolized for physiologic reasons, three supplied needed pulmonary blood flow and could potentially be closed when other sources of pulmonary blood flow are established. Of the nine vessels not embolized for technical reasons, the most common reason was inability to enter the vessel far enough to safely release the coil because of a sharp turn just distal to the origin. Each of these vessels sent branches to both lungs and the acute angle occurred at the branch point. Most (but not all) of these vessels can be entered by using combinations of catheters with preformed angles and tip deflecting, torque control or J wires (with a J wire out the tip to decrease the risk of perforation, the catheter can be advanced). The three vessels that were not embolized because of contrast dye limitations can potentially be closed later. The need for multiple catheterizations to close several collateral vessels is most often due to contrast dye limitations or to lack of other adequate sources of pulmonary blood flow, i.e., vessels embolized before surgery. It is, therefore, important to use each catheterization to define the anatomy and distribution of collateral vessels and native pulmonary arteries, even if embolization is not performed at that catheterization.

Blalock-Taussig shunts. We report embolization of 14 Blalock-Taussig shunts resulting in total occlusion in 6 and subtotal occlusion in 5. Three of the five coils that embolized to a branch pulmonary artery did so during attempted embolization of a Blalock-Taussig shunt. Thus, the results suggest that occlusion is less likely to be complete and complications are more likely to occur when embolizing Blalock-Taussig shunts as compared with collateral vessels. We suspect this is related to differences in anatomy of the vessels, in particular the common lack of distal stenosis in shunts and the resulting higher flow. The use of distal balloon occlusion of shunts to prevent pulmonary artery embolization and to promote clotting by interrupting flow (Fig. 4) may improve results. Although subtotal occlusion can be expected to eliminate long-term risks associated with increased pulmonary blood flow, the risks of bacterial endocarditis in shunts with minimal residual flow remain to be determined. It should also be noted that three of the incompletely occluded shunts had previously undergone attempted surgical ligation and repeat surgery would have been difficult.

Complications. These included five cases of inadvertent embolization to the pulmonary arteries during attempted embolization of three Blalock-Taussig shunts and two aortopulmonary collateral vessels. This relatively high incidence of distal migration compared with that associated with use of coils to embolize neoplasms, arteriovenous malformations and aneurysms and to control hemorrhage (16) is probably largely explained by differences in vessel anatomy, that is, the relatively common lack of distal stenosis in the vessels we embolized. Despite this, we believe that distal migration should be avoidable 1) by determining stretched diameter in vessels with high flow or no distal stenosis, or both; and 2) by using distal or proximal balloon occlusion during coil release to interrupt flow and prevent coil washout until a clot has formed. Whereas two coils, early in the study, were not removed and caused no symptoms, we later attempted to retrieve coils from the pulmonary arteries, and two of three attempts were successful with use of a snare and a tip-deflecting wire. A coil was dislodged from a collateral vessel into the aorta during attempts to pass a catheter into the proximal aorta. This complication, which occurred because of inadequate sedation and patient movement, is avoidable.

Follow-up. During follow-up, we found two cases of recanalization of vessels that had been completely occluded by coils (of 20 completely occluded vessels that were recatheterized). Each of the four subtotally occluded vessels that were restudied had closed, whereas three partially occluded collateral vessels remained open. Thus, recanalization of completely occluded vessels appears unlikely and, although numbers are small, closure of vessels with minimal residual flow at the end of the procedure appears likely.

Clinical implications. This report focuses on methods of coil embolization results in terms of vessel occlusion and complications directly related to coil embolization. Exact answers regarding patient selection and indications for coil embolization of collateral vessels cannot be provided at this time for several reasons. Many of the patients with pulmonary atresia have hypoplasia and stenoses of the branch pulmonary arteries and have undergone balloon pulmonary artery dilation. Most have or will undergo surgical procedures. The timing of embolization in relation to these interventions and the results of these interventions (residual branch pulmonary artery stenosis, ventricular septal defect, or outflow tract obstruction or combinations) are variable among patients. Consequently, trying to assess the impact of embolizing individual collateral vessels in terms of patient outcome or clinical variables is difficult and beyond the scope of this report.

Assessing the impact of embolization in terms of hemodynamic variables is also difficult. Accurate measurement of pulmonary blood flow in the presence of collateral vessels is not possible with oximetry. The data demonstrate that embolization of a collateral vessel, which contributes significantly to pulmonary blood flow (as evidenced by decreased systemic oxygen saturation), is unlikely to change the pul-
monary artery pressure. Although one could be more confident about the beneficial effects of embolizing collateral vessels if the pulmonary artery pressure decreased, the converse (the lack of decrease in pulmonary artery pressure demonstrates lack of beneficial effect) is not true. Our present policy, based on the assumption that collateral flow is not beneficial (except to supply pulmonary blood flow in patients who have not undergone repair), is to embolize any collateral vessel that meets the criteria for embolization (see previous discussion of methods). Assessing this policy will require long-term follow-up of the patients involved.

Conclusions. Our results suggest that coil embolization can be used to embolize approximately 90% of aortopulmonary collateral vessels with a high success rate and few complications. Incomplete occlusion and complications appear more likely to occur when embolizing Blalock-Taussig shunts, but technical modifications are likely to improve results.

References