EXPANDING INDICATIONS FOR PEDIATRIC CORONARY ARTERY BYPASS

Pediatric coronary artery bypass has been done mostly for ischemic complications of Kawasaki disease. We reviewed our clinical experience between 1987 and 1994 with internal thoracic artery–coronary artery bypass in one infant and five children for varying indications. Indications for coronary bypass included Kawasaki disease (2), congenital left main coronary ostial stenosis, iatrogenic coronary cameral fistula, anomalous origin of the left coronary artery from the pulmonary artery, and single coronary artery traversing between the great arteries in a patient after cardiac transplantation. An additional cohort of 34 control patients of various ages and weights (1 day to 16.1 years, 2.6 kg to 62 kg) had angiographic measurements of the right coronary, left coronary, and left internal thoracic arteries with respect to the feasibility of performing coronary artery bypass. All six patients survived internal thoracic artery–left anterior descending coronary artery bypass without evidence of perioperative myocardial infarction. Postoperative angiographic studies in five and color Doppler echocardiography in one showed graft patency. Retrospective angiographic measurements in the 34 control patients showed that internal thoracic and coronary arteries are proportionately quite large in neonates and infants compared with those in older children and adolescents. Internal thoracic artery–coronary artery bypass should be considered for the expanding indications presented herein and when emergency intraoperative life-threatening situations present themselves. Long-term patency and reoperation rates have yet to be determined. (*J THORAC CARDIOVASC SURG* 1996;111:181-9)

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Coronary artery bypass in children has been applied mostly to patients with coronary artery aneurysms and obstructions caused by Kawasaki disease.¹⁻³ The early unsatisfactory experience with reversed saphenous vein grafts²⁻⁶ led to universal preference for internal thoracic artery bypass grafts owing to the superior rates of patency with the internal thoracic artery and its ability to grow along with the developing child.⁴⁻¹⁴ Other indications for

coronary bypass have been reported with excellent results¹⁵⁻²⁶ even in infancy.^{15-17, 20}

We have applied internal thoracic artery–coronary artery bypass grafts in six children, aged 4 months to 12 years, for various indications. The purpose of this paper is to review our clinical experience with coronary bypass in children, to discuss the expanding indications for its application, and to present angiographic measurements of coronary and internal thoracic arteries in neonates, infants, children, and adolescents with respect to the feasibility of performing coronary bypass.

Material and methods

Between 1987 and 1994 (Table I), one infant and five children with congenital and acquired heart disease underwent anastomosis of the left internal thoracic artery (LITA) to the left anterior descending (LAD) coronary artery at Children's Memorial Hospital. Five patients were female and one male; their ages ranged from 0.4 to 12.4 years. Diagnosis was established in all patients by

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Table 1. *Clinical features*

<i>Age at operation (yr)</i>	<i>Diagnosis</i>	<i>Surgical procedure [LAD size] (length of stay)</i>	<i>Postoperative findings</i>	<i>Status</i>
5.6	Anomalous LCA arising from pulmonary artery; ventricular ectopy	LITA to LAD [1.5 mm] (4 days)	Echocardiography 4 mo postop. Patent LITA graft by color Doppler echocardiography, normal ventricular function No ventricular ectopy Mild mitral insufficiency	Free of symptoms
5.5	Kawasaki disease, giant aneurysm of LAD with 75% to 80% stenosis	LITA to LAD [2 mm] (4 days)	Catheterization 13 mo postop; Well-functioning LITA graft, mildly irregular RCA Persistent giant aneurysm Echocardiography 5 yr postop. Patent LITA graft, normal ventricular function Mild mitral insufficiency	Free of symptoms
6.4	Coronary artery fistula to RV caused by iatrogenic coronary injury during remote repair of tetralogy of Fallot with anomalous origin of LAD from RCA; ventricular ectopy	Ligation of fistula, LITA to anomalous LAD [2 mm] (10 days)	Catheterization 3 days postop. No residual fistula, no shunts, normal CI Patent LITA graft Exercise Study 21 mo postop. Low HR response to exercise PVCs, no couplets, no VT runs	Free of symptoms
12.4	Kawasaki disease, multiple coronary aneurysms with critical stenosis of LAD	LITA to LAD [1.5 mm] (8 days)	Catheterization 3 days postop. Patent LITA graft Catheterization 2 yr postop. Patent LITA graft	Obesity; atypical chest pains
0.4	Critical LCA ostial stenosis; mitral regurgitation	LITA to LAD after left main pericardial patch arterioplasty [0.7 mm] (67 days)	Catheterization 52 days postop. Patent LITA graft, LCA tree hypoplastic Persistent mitral regurgitation Underwent successful mitral valvuloplasty and annular remodeling to repair mitral regurgitation at 0.6 years	Persistent mild mitral regurgitation
4.8	Single RCA giving rise to left main coronary artery with syncopal episodes; status post cardiac transplant for hypoplastic left heart syndrome; atrial arrhythmias	LITA to LAD [1.0 mm] (12 days)	Catheterization 21 days postop. Patent LITA graft, no graft CAD Normal ventricular function Atrial arrhythmias	Post-heart transplant regimen; free of symptoms

RCA, Right coronary artery; RV, right ventricle; CI, cardiac index; HR, heart rate; PVC, premature ventricular contractions; VT, ventricular tachycardia; LCA, left coronary artery; CAD, coronary artery disease.

echocardiography and cardiac catheterization. Three patients had preoperative arrhythmias: ventricular ectopy in a patient after tetralogy repair, ventricular ectopy in a child with anomalous left coronary artery, and reentrant atrial tachycardia in a patient after transplantation.

The operative procedure was an end-to-side LITA-LAD coronary artery anastomosis. The child with anomalous left coronary artery from the pulmonary artery was operated on through a left thoracotomy without cardiopulmonary bypass. The others underwent median ster-

notomy and had moderate hypothermic (28° C) cardiopulmonary bypass, antegrade administration of cold blood cardioplegic solution, and a left ventricular vent. The internal thoracic artery was dissected in the standard fashion with the use of topical papaverine to prevent spasm. In five patients, a running monofilament (7-0 and 8-0) suture technique was used. In the 4-month-old infant an interrupted 8-0 monofilament suture technique was used for the anastomosis.

Another 34 "control" patients were the subjects of

Fig. 1. **A,** Preoperative aortogram in 6.4-year-old boy who had previously undergone transatrial repair of tetralogy of Fallot with anomalous LAD from right coronary artery. Unrecognized injury to posterior LAD arterial wall resulted in depicted LAD-right ventricular fistula (*arrow*). **B,** Postoperative arteriogram showing patent and unobstructed LITA-LAD bypass graft 3 days after operation.

retrospective angiographic measurements of the mid-right coronary artery, the mid-LAD coronary artery, and the mid-LITA. The ages and weights of these patients ranged from 1 day to 16.1 years and from 2.6 kg to 62 kg. There were 9 neonates (all with transposition of the great arteries), 6 infants (5 with ventricular septal defect and 1 with Taussig-Bing syndrome), and 19 children and adolescents (all with ventricular septal defect). These subjects were chosen because they all had aortic root injections as part of an angiographic evaluation and had adequate imaging of the coronary and internal thoracic arteries. Absolute measurements (interpolation techniques based on a known control) of all three arteries were made by one of us (A.J.M.). The results were analyzed to determine the

feasibility of using these arteries for coronary bypass in infants and children (appendix).

Results

The pertinent clinical features of our patients are noted in Table I. All patients survived without electrocardiographic evidence (new Q waves) of a perioperative myocardial infarction. Postoperative cardiac catheterization studies (including cineangiography) were done in five of six patients after coronary bypass (3 days, 3 days, 21 days, 52 days, and 13 months, respectively) and demonstrated anasto-

Fig. 2. **A**, Preoperative aortogram in 4-month-old girl showing prompt antegrade filling of right coronary artery and retrograde filling of LAD and circumflex branch. Preoperative differential diagnosis was anomalous left main coronary artery arising from pulmonary artery versus congenital left main coronary artery stenosis (*arrow*). **B**, Postoperative aortogram showing antegrade filling of both right and left main coronary arteries after autologous piece of pericardium was used to patch orifice of congenitally stenosed left main coronary artery. Because child could not be weaned from cardiopulmonary bypass, LITA-LAD graft was done, which was followed by separation from cardiopulmonary bypass. **C**, Occlusion aortogram showing unobstructed LITA-LAD bypass graft. Patient later underwent successful mitral valvuloplasty because of persistent mitral regurgitation and showed marked clinical improvement.

motric patency in all patients studied without evidence of stenosis, kinking, or delayed filling (Figs. 1 through 3). The sixth patient refused angiography; however, color Doppler echocardiography documented graft patency. Preoperative arrhythmias present in three patients persisted in two after operation (Table I).

Angiographic measurements in the 34 control patients are noted in Table II. When the diameter

of the LAD and right coronary artery are normalized to the body surface area, the relative size is greatest in infants and diminishes with advancing age and growth (Fig. 4). These measurements indicate that newborn and young infants have relatively large diameters of internal thoracic and coronary arteries, which makes these arteries suitable for coronary bypass when indicated.

Fig. 3. A, Selective coronary arteriogram in 4.8-year-old girl who had orthotopic cardiac transplantation and arch reconstruction because of hypoplastic left heart syndrome at age 1 month. As noted, transplanted heart has single coronary artery with long left main coronary artery traversing between great arteries, which is condition known to be associated with sudden death.²⁷ LCA, Left coronary artery; RCA, right coronary artery. B, Selective subclavian arteriogram (lateral) showing LITA-LAD bypass graft (arrow) with both antegrade and retrograde coronary filling resulting in opacification of all three coronary arteries.

Discussion

Our experience and that of others reflect the expanding indications for internal thoracic artery-coronary artery bypass grafting in infants and children with congenital and acquired heart disease. Indications for coronary artery bypass grafting with internal thoracic artery in children include (1) Kawasaki disease with coronary artery stenosis or occlusion, (2) anomalous course of the LAD coro-

nary artery between the aorta and pulmonary artery, (3) anomalous origin of the left coronary artery from the pulmonary artery, (4) intraoperative coronary artery injury such as after arterial switch for transposition of the great arteries or during outflow repair for tetralogy of Fallot with anomalous LAD from the right coronary artery, (5) coronary ostial stenosis, and (6) transplant coronary artery disease after orthotopic cardiac transplantation.

Table II. Coronary and internal thoracic artery angiographic measurements

	Neonates (n = 9)	Infants (n = 6)	Children and adolescents (n = 19)
Age (yr)	0.0049 ± 0.0045	0.412 ± 0.167	7.66 ± 4.98
Weight (kg)	3.53 ± 0.79	5.3 ± 0.51	29.07 ± 21.44
LAD (mm)	1.21 ± 0.29	1.25 ± 0.22	1.88 ± 0.46
RCA (mm)	1.33 ± 0.18	1.39 ± 0.18	2.13 ± 0.53
LITA (mm)	1.18 ± 0.26	1.21 ± 0.27	1.79 ± 0.48
BSA (m ²)	0.21 ± 0.03	0.28 ± 0.02	0.96 ± 0.46

RCA, Right coronary artery; BSA, body surface area.

Most of the clinical data supporting the efficacy and long-term outcome of coronary artery bypass grafting in children stem from the surgical experience with Kawasaki disease. Kitamura and colleagues¹⁴ reported a long-term multicenter study of 168 patients with Kawasaki disease who underwent coronary artery bypass grafting with saphenous vein or arterial conduits (thoracic or gastroepiploic arteries), or both. Their results demonstrated that the actuarial patency rate was significantly higher for arterial grafts than for venous grafts and that this difference was even greater in children younger than 7 years old at operation. Also, the late cardiac death rate was significantly higher in the venous graft group. These results confirmed earlier reports on smaller patient populations.²⁻⁵ Age at operation was a significant risk factor for hospital and late death. The mean age at operation in the patients who died in the postoperative period was significantly younger than that in the survivors.¹⁴ This may reflect a patient population with more serious sequelae of Kawasaki disease who required earlier operation. Other indications for internal thoracic-coronary artery bypass in neonates and children seem to have better short-term outcomes, even when done under emergency and unfavorable conditions.^{15, 16, 18-20}

The prevalence of a single coronary artery is 0.024% and, although single coronary artery is usually regarded as a benign condition, it may be associated with sudden death as a result of myocardial ischemia or infarction.²⁷ This is especially cogent in cases of a single right coronary artery that gives rise to a left coronary artery coursing between the aorta and the main pulmonary artery where it may be critically compressed by these surrounding vessels.^{28, 29} Sacks and associates²³ first reported saphenous vein bypass grafting from the aorta to the left main coronary artery for an aberrant (aortic) intramural left coronary artery arising from the

anterior sinus of Valsalva. As far as we are aware, our patient with a single coronary artery traversing between the aorta and pulmonary artery, acquired at the time of orthotopic cardiac transplantation, is the first such patient to undergo coronary bypass. Another potentially lethal anatomic variant occurs when the right coronary artery originates from the left aortic sinus and courses between the aorta and pulmonary artery. Cohen and associates³⁰ have reported internal thoracic artery grafting in three patients, one with right coronary artery from the left aortic sinus and two with left coronary artery from the right coronary artery. Echocardiographic evaluations for unexplained syncope may uncover an increased premortem prevalence of anomalous coronary arteries. Clinicians can then evaluate the benefits and risks of coronary bypass in these young patients in light of the potential for sudden death.²⁸⁻³⁰

Anomalous origin of the left coronary artery from the pulmonary artery is a cause of myocardial infarction, ventricular dysfunction, mitral insufficiency, congestive heart failure, and death. We recommend establishment of a two-coronary artery system at the time of diagnosis.³¹ In our series of 20 children with this diagnosis, one child underwent LITA-LAD anastomosis with ligation of the proximal left main coronary artery. Postoperative patency was demonstrated by echocardiography and, interestingly, the child's chronic ventricular ectopy disappeared. Although direct aortic implantation is preferable for infants with this condition, LITA-LAD bypass grafting can be considered in certain circumstances, particularly when the child is older and the anomalous left coronary artery originates from the far left posterior sinus of the pulmonary artery.³²⁻³⁴

The coronary arterial system can be injured during the course of intracardiac repair of congenital lesions. An example of this is a complication of coronary transfer during arterial switch. The patient reported by Rheuban, Kron, and Bulatovic¹⁶ was 9 days old, weighed 3 kg, and had inadequate aortic tissue for the right coronary artery anastomosis. Right internal thoracic-right coronary artery bypass allowed weaning from cardiopulmonary bypass and angiography 5 months later showed a patent anastomosis. Ebels and colleagues¹⁵ reported the successful use of a LITA-left coronary artery graft when myocardial ischemia ensued after the arterial switch operation in an infant with an intramural left coronary artery.

In 7% of patients with tetralogy of Fallot, the

Fig. 4. Relative vessel sizes. Regression analysis relating normalized arterial size to body surface area (*BSA*). R^2 values for right coronary (*Cor.*) artery, left anterior (*Ant.*) descending, and left internal (*Int.*) thoracic artery were 0.674, 0.701, and 0.855, respectively.

LAD originates from the right coronary artery.^{35,36} It courses over the right ventricular outflow tract to the interventricular groove. This complicates repair of tetralogy of Fallot because the artery can be easily injured, especially if the course is intramural or is obscured by postoperative adhesions. The child in our series had injury to the LAD during transatrial/transpulmonary resection of right ventricular muscle resulting in a coronary–cameral fistula, which was subsequently repaired by fistula ligation and distal internal thoracic artery–coronary artery bypass. Cooley and associates¹⁷ reported successful internal thoracic artery grafting to an anomalous LAD coronary artery in a 16-month-old patient.

Congenital coronary ostial stenosis and left main coronary atresia are extremely rare lesions that cause myocardial ischemia.³⁷ This condition presents in a similar fashion to that in children with anomalous left coronary artery arising from the pulmonary artery.^{38–41} The patient in our series with coronary ostial stenosis was the smallest and youngest (0.4 years, 4 kg) to have successful internal thoracic artery bypass grafting for this diagnosis. Kitamura and colleagues³³ recently reported the case of a 7-year-old patient with atresia of the left main coronary trunk who had internal thoracic

artery grafting. Rosenkranz and associates²² reported patch aortoplasty and LITA–LAD anastomosis in a 5-year-old patient with congenital atresia of the left main coronary ostium and supra-avalvular aortic stenosis. Fortune, Baron, and Fitzgerald²⁰ reported successful LITA–LAD anastomosis in a 17-month-old child with atresia of the left main coronary artery and mitral insufficiency.

As more infants and children are being followed up after heart transplantation, accelerated coronary atherosclerosis is becoming recognized as a major cause of late death.⁴² Many of these patients have diffuse coronary artery disease, but occasionally a child will have isolated lesions. Internal thoracic artery bypass grafting has been reported in adults for transplant coronary artery disease.⁴³ We performed internal thoracic artery grafting in one child after orthotopic cardiac transplantation, although the indication was single coronary artery with left main coronary artery coursing between the aorta and pulmonary artery.

Perhaps the greatest impediments to performing internal thoracic artery–coronary artery bypass grafts in infants and children have been the small caliber of corresponding vessels and the lack of long-term results documenting patency and anastomotic growth.

Our retrospective angiographic measurements indicate that most coronary arteries are 1 mm or larger even in the neonatal population, with few exceptions ranging downward to 0.7 mm. These data correspond to those of a study by Yatsunami and associates,⁴⁴ who measured coronary artery size in neonates with transposition of the great arteries before and after arterial switch operation. These data and our clinical experience suggest that internal thoracic artery–coronary artery bypass appears feasible in most infants with vessels 1 mm or greater and possible in vessels as small as 0.7 mm with proper magnification and currently available microvascular suture techniques.

We conclude that internal thoracic and coronary arteries are proportionately quite large in infants and children and that internal thoracic–coronary artery bypass grafts should be considered for the indications presented herein and for emergency intraoperative life-threatening situations. The long-term patency and reoperation rates with growth and maturation are yet to be determined.

Addendum

Since submission of the manuscript, we have successfully performed bilateral ITA bypass grafts to the LAD coronary artery and the right coronary artery in a 5.9-year-old, 18 kg girl with giant aneurysms and diffuse coronary artery stenosis from Kawasaki disease. Postoperative angiographic study revealed bilateral ITA–coronary artery graft patency.

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Appendix

The diameters of the right coronary artery, LAD branch, and LITA were measured from cine projections in which these arteries were clearly defined. The right coronary artery was measured in its midportion at the angulation between the two largest marginal branches. The LAD artery was measured just before its bifurcation into diagonal and interventricular branches. The LITA was measured at midthoracic level in the proximity of the ventricles. All views, in which these vessels were clearly defined, were used. The majority were aortic root injections in right anterior oblique and left anterior oblique rotation with or without cranial angulation. The projected diameter of the catheter in the ascending aorta was used to correct for magnification. The multiple measurements were averaged and presented both as true and normalized values for body surface area.

The data were analyzed by polynomial regression (second order) and plotted as x (body surface area) and y (artery diameters/body surface area) graph ($Y = A + B \cdot X + C \cdot X^2$), where A is the right coronary artery, B is the LAD branch, and C is the LITA, expressed in millimeters and normalized to the body surface area.