Resistance to Flow of Arterial Y-Grafts 6 Months After Coronary Artery Bypass Surgery

David Glineur, MD; Philippe Noirhomme, MD; Jim Reisch, MS; Gebrine El Khoury, MD; Parla Astarci, MD; Claude Hanet, MD, PhD

Background—The use of both internal thoracic arteries (ITAs) as a Y-graft configuration has been proposed as a technique allowing complete arterial revascularization. Controversy remains, however, about the capacity of this Y-graft configuration to provide sufficient blood flow to the whole left coronary system and about possible steal phenomenon occurring during periods of maximal myocardial blood flow demand.

Methods and Results—To evaluate graft conductance 6 months after Y-graft revascularization of the left coronary system with both ITAs, 11 consecutive patients were studied during cardiac catheterization. In all of the cases, the left ITA had been connected to the left anterior descending coronary artery (LAD) territory (mean, 1.3 anastomoses), and the free right ITA was anastomosed proximally to the left ITA and distally to the left circumflex (LCX) territory (mean, 1.9 anastomoses). Pressure and fractional flow reserve (FFR) were recorded using a 0.014-inch pressure wire advanced distally in the left ITA main stem close to the proximal anastomosis of the free right ITA (ITA-stem) and in the distal part of each ITA branch at the site of their implantation to the LAD (ITA-LAD) or LCX (ITA-LCX) system. At each of these sites, the pressure gradient between aorta and the graft was measured in basal condition and during maximal hyperemia induced by intragraft bolus injection of 40 μg of adenosine. In basal conditions, the pressure gradient was minimal between the aorta and the ITA-stem (2±2 mm Hg), the ITA-LAD (3±3 mm Hg), and the ITA-LCX (3±2 mm Hg; P value was not significant versus ITA-LAD). During maximal hyperemia, the pressure gradient increased to 7±2 mm Hg in the ITA-stem, to 9±5 mm Hg in the ITA-LAD, and to 9±3 in the ITA-LCX (P value not significant versus ITA-LAD). The fractional flow reserve was 0.93±0.03 in the ITA-stem, 0.91±0.04 in the ITA-LAD, and 0.91±0.03 in the ITA-LCX.

Conclusions—A Y-graft configuration with a free right ITA attached to a pedicled left ITA allows an adequate revascularization of the whole left coronary system with an even distribution of perfusion pressure in both distal branches and minimal resistance to maximal blood flow. (Circulation. 2005;112[suppl I]:I-281–I-285.)

Key Words: surgery • adenosine • bypass • coronary disease • internal thoracic artery

The demonstrated superiority of the internal thoracic artery (ITA) over the saphenous vein (SV) coronary graft has led us to consider the use of this arterial conduit as an essential part of bypass surgery, particularly when the left anterior descending coronary artery is involved.1 The superiority of the ITA is thought to result from favorable biological properties protecting this vessel against the atherosclerotic process.2 Some of these properties are shared by other types of arterial grafts, which were proved superior to saphenous vein grafts both in patency rates and in long-term patient survival.3 In an attempt to protect the patient against the risk of vein graft failure, technical improvements, such as sequential and bilateral grafting and the use of free arterial grafts, have allowed us to achieve complete arterial myocardial revascularization in an increasing proportion of patients. Among these technical improvements, the use of both internal thoracic arteries (ITAs) in a T-graft4 or Y-graft configuration5,6 constructed by anastomosing the proximal end of the free right ITA to the side of the pedicled left ITA has been proposed to allow arterial revascularization with reduced conduit use, while preserving the left ITA to left anterior descending coronary artery graft.

Concerns have been expressed about the flow capacity of this configuration, particularly in the main stem of the left ITA, and about the theoretical possibility of a steal phenomenon resulting in a fall of perfusion pressure in one of the branches during periods of maximal myocardial blood flow demand. Although intraoperative flow measurements have suggested that the flow capacity is sufficient to meet myocardial flow requirements in the perioperative period,7 postoperative measurements of flow reserve in the proximal ITA by Doppler techniques8 and in the reperfused myocardium by positron emission tomography9 have provided conflicting results.
A limitation of these flow studies is the determinant influence of the reperfused myocardial vascular bed that precludes any inference from flow data to the notion of either graft or microvascular dysfunction. In other words, an abnormal flow reserve may reflect either an excessive resistance of the graft to blood flow or a dysfunction of resistive vessels in the myocardial territory revascularized by the graft. The present study was designed to evaluate more specifically the conductance of arterial Y-graft configurations by directly measuring the perfusion pressure in the main stem of the pedicled left ITA and in each of the ITA limbs. Measurements were done in basal conditions and during a maximal hyperemia induced by a bolus injection of adenosine. From pressure measurements obtained at each of these 3 points during hyperemia, the fractional flow reserve (FFR), calculated as the ratio of distal intragraft pressure divided by aortic pressure, was determined as an index of the resistance along the different segments of the graft.

**Methods**

**Patients**

Eleven patients (9 men, 2 women; mean±SD age, 63±9 years) were studied during cardiac catheterization. All had undergone coronary artery bypass surgery with left and right ITA in a Y-graft configuration >6 months (range, 6 to 8 months) before the study and were investigated in the context of a systematic angiographic and functional study. In all of the cases, the left ITA had been connected to the left anterior descending coronary artery (LAD) territory (mean, 1.3 anastomoses), and the free right ITA was anastomosed proximally to the left ITA and distally to the left circumflex (LCX) territory (mean, 1.9 anastomoses). Patient characteristics and distal anastomoses are given in the Table. Criteria for inclusion were the absence of major tortuosities of the graft, patency of all of the anastomoses with a good runoff flow to the grafted arterial segments, and an absence of severe wall motion abnormality in the perfusion zone.

The study protocol was approved by the Ethics Committee of our institution. All of the patients gave informed consent at the time of bypass surgery and before the angiographic investigation and completed the study protocol without complication.

**Surgical Technique**

All of the patients were operated on by median sternotomy, with cardiopulmonary bypass. The pedicled ITA was harvested together with the surrounding veins, muscle, and fascia. The cautery was always used, and the side branches were clipped. The right ITA was connected to the pedicled left ITA with end-to-side anastomosis. The Y-graft was constructed under cardiopulmonary bypass at the end of the procedure after all of the distal anastomoses were completed.

The in situ ITA was prepared at the chosen site and then clamped. A longitudinal incision was performed, 6 to 8 mm long. The free right ITA graft was prepared, opened obliquely at its tip, and then extended to the ITA. A running stitch with an 8 to 0 Prolene suture (Ethicon, Inc.), starting from the heel of the free graft, was used. The in situ ITA was then unclamped, and the proximal anastomosis was carefully checked for any bleeding.

**Study Protocol**

Patients underwent cardiac catheterization by the standard femoral approach 24 hours after interruption of all of the vasoactive medications. Selective catheterization of the ostium of the left ITA was achieved by using a 5-F guiding catheter without side holes. This catheter was connected to a fluid-filled pressure transducer zeroed at the midchest level. After intragraft administration of 1 mg of isosorbide dinitrate, a biplane angiogram of the graft was obtained. A 0.014-inch electronic sensor-tipped wire (PressureWire, Radi Medical Systems) was advanced to the tip of the guiding catheter to ensure that the pressures recorded in the ostium of the graft through the fluid-filled catheter and the pressure wire were identical. The wire was then advanced in the distal part of the left ITA main stem, close to the proximal anastomosis of the free right ITA (ITA-stem). The pressures were simultaneously measured in the ostium of the graft and in the ITA-stem under basal conditions. Coronary arteriolar vasodilation was then induced by intragraft bolus injection of 40 μg of adenosine to produce transient maximal hyperemia. Pressure signals were recorded continuously until distal pressure returned to baseline values. An example of pressure recording is illustrated in Figure 1.

The pressure wire was then successively advanced in each of the 2 ITA branches, the pressure sensor being carefully positioned within the last centimeter preceding the first distal anastomosis on the LAD (ITA-LAD) or LCX (ITA-LCX) system (Figure 2). At each measurement point, the same pressure measurements were repeated in baseline conditions and during a maximal hyperemia induced by bolus injections of adenosine. When the pressure sensor was pulsed back in the guiding catheter, pressures were checked to exclude any drift of the transducers.

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**Table: Characteristics of the Study Population**

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F indicates female; m, male; LADD, first-diagonal branch of the left anterior descending coronary artery; LCX1 and LCX2, first and second marginal branches of the left circumflex coronary artery; PDA, posterior descending artery.
FFR of 0.94 across this segment of the graft is recorded corresponding to a maximal blood flow. A maximal pressure drop of 6 mm Hg ing the resistance opposed by the main part of the Y-graft to adenosine-induced coronary arteriolar vasodilation, reflect-

Pressure Data Analysis

Pressures recorded at different measurement points are compared in basal condition and during maximal hyperemia. The gradient in mean intragraft pressure between the ostium of the graft and each of the 3 distal measurement points are expressed in absolute values. From pressure measurements obtained during maximal hyperemia, FFR is computed as an index of resistance to blood flow of the different segments of the graft. FFR is calculated as the ratio of distal pressure (Pd) divided by proximal intragraft (Pp) pressure as follows: FFR = Pd/Pp.10 In the absence of resistance along a vascular segment, there is no pressure decline, and FFR equals unity. The larger the resistance to blood flow of a graft segment, the greater the drop in perfusion pressure across this segment and, thus, the smaller the FFR.

Figure 1. Pressure recordings in the ostium of the left ITA (Pa) and in the ITA-stem (Pd) after intragraft injection of 40 μg of adenosine (arrow). A transient decrease in distal pressure results from adenosine-induced coronary arteriolar vasodilation, reflecting the resistance opposed by the main part of the Y-graft to maximal blood flow. A maximal pressure drop of 6 mm Hg across this segment of the graft is recorded corresponding to a FFR of 0.94

Figure 2. Angiogram of a 49-year-old patient (patient 8 of the Table), 6 months after surgery. The locations of the 3 distal measurement points are indicated: ITA-stem, in the main part of the graft immediately before the implantation of the free right ITA on the left ITA; ITA-LAD, within the last centimeter preceding the first distal anastomosis of the left ITA on the LAD vascular bed; and ITA-LCX, within the last centimeter preceding the first distal anastomosis of the free right ITA on the LCX system.

Results

In each patient, the baseline angiogram showed a patent ITA Y-graft with a complete opacification of all of the target coronary segments. Selective positioning of the pressure sensor in the ITA-stem and in both ITA branches was possible in all but 1 patient (patient 11 of the Table), in whom introduction of the pressure sensor in the ITA-LCX was unsuccessful. This failure resulted from a minor tortuosity of the ITA-stem immediately before the bifurcation causing a preferential orientation of the pressure wire to the ITA-LAD. Manipulations and reshaping of the wire did not allow progression to the adequate measurement site, and the decision was made to avoid complex manipulations in order to minimize vessel trauma. Measurements were thus, available in the ITA-stem and ITA-LAD in 11 patients and in the ITA-LCX in 10 of them.

In basal conditions, a small pressure gradient was measured between the ostium of the graft and each of the 3 measurement points. This resting gradient averaged 2±2 mm Hg in the ITA-stem, 3±3 mm Hg in the ITA-LAD (P=0.015 versus ITA-stem), and 3±2 mm Hg in the ITA-LCX (P value was not significant versus ITA-stem and not significant versus ITA-LAD).

Adenosine injection resulted in a consistent increase in pressure drop in every patient at each of the measurement points (Figure 3). The maximal pressure gradient during hyperemia averaged 7±2 mm Hg in ITA-stem. This pressure gradient additionally increased in each ITA branch, averaging 9±5 mm Hg in ITA-LAD (P=0.016 versus ITA-stem) and 9±3 mm Hg in ITA-LCX (P=0.003 versus ITA-stem and P value not significant versus ITA-LAD) (Figure 4). Comparison of the pressure gradient between the ostium and each branch of the Y-graft in every individual patient showed an even distribution of perfusion pressure between both branches of the graft, the difference in pressure drop between ITA-LAD and ITA-LCX remaining within a range of 5 mm Hg during maximal hyperemia.

FFR averaged 0.93±0.03 in ITA-stem, reflecting a minimal resistance to flow during maximal hyperemia induced by adenosine. Values measured in the ITA-LAD (0.91±0.04) and in the ITA-LCX branches (0.91±0.03) were slightly but significantly smaller (P=0.016 and P=0.003, respectively) reflecting a continuous resistance to blood flow along the graft (Figure 5). There was no difference in pressure gradients measured between the graft ostium and ITA-LAD or ITA-LCX branches either in basal conditions or during maximal hyperemia and in FFR.
This study shows that a Y-graft arterial configuration with a free right ITA attached to a pedicled left ITA allows an adequate revascularization of the whole left coronary system with an even distribution of perfusion pressure in both distal branches and a minimal resistance to maximal blood flow. The resulting gradual decrease in pressure along the graft is negligible in basal conditions and remains small during a maximal hyperemia induced by intragraft injection of 40 μg of adenosine. Not surprisingly, most of the pressure drop observed during hyperemia occurs across the common part of the Y-graft where blood flow is maximal. In addition, the conductance of both branches of the Y-graft, as assessed by FFR, appears identical, which excludes the possibility of a steal phenomenon, defined as the diversion of blood flow from a high-resistance to a low-resistance branch during hyperemia.

Figure 3. Individual values of pressure gradients measured between the ostium of the Y-graft and the distal measurement points in basal conditions and during a maximal hyperemia induced by intragraft injection of 40 μg of adenosine.

Figure 4. Comparison of individual values of pressure gradients during a maximal hyperemia induced by intragraft injection of 40 μg of adenosine measured in the distal part of the ITA main stem (ITA-stem) and of ITA branches implanted to the LAD (ITA-LAD) and LCX (ITA-LCX) systems.

Previous studies have investigated the flow capacity of arterial composite Y-graft and T-graft by measuring blood flow and flow reserve either peroperatively or at different time intervals after surgery. Recently, Affleck et al recorded intraoperative flows in both limb of T-grafts. Flow reserve, computed as the ratio of completion flow on free flow, was 1.6, which was considered adequate to meet myocardial flow requirements in the early postoperative period. Wendler et al used a Doppler guide wire to measure blood flow in the proximal part of the left ITA stem of patients 1 week and 6 months after complete arterial revascularization with composite grafts. In composite grafts with the left ITA and a free right ITA, the coronary flow reserve increased from 1.85 in the early to 2.77 in the late postoperative period as a combined result of reduced baseline flow and slightly increased maximal flow. These values were comparable with those reported previously after single ITA grafting. Using a similar technique, Lemma et al reported the persistence of some flow reserve in the territory of composite Y-grafts

Figure 5. Individual values of FFR measured at different points of the Y-graft: ITA-stem, in the main part of the graft immediately before the implantation of the free right ITA on the left ITA; ITA-LAD, within the last centimeter preceding the first distal anastomosis of the left ITA on the LAD vascular bed; and ITA-LCX, within the last centimeter preceding the first distal anastomosis of the free right ITA on the LCX system.
during an increase in myocardial blood flow demand induced by atrial pacing early after surgery. The authors concluded that a Y-graft is able to fully respond to the flow demand of the whole left coronary system. Sakaguchi et al. used positron emission tomography to compare regional myocardial blood flow and flow reserve 2 weeks after coronary artery bypass grafting using arterial composite Y-graft or independent arterial grafts. Flow reserve was significantly lower in the Y-graft group than in the independent group, suggesting that Y-grafts are not as effective as independent grafts for improving flow reserve early after coronary artery bypass grafting.

A major limitation of such flow studies is their incapacity to discriminate between the relative influence of the coronary arteriolar bed and that of the graft conduit itself. Even after a successful revascularization, the presence of some myocardial areas with resistive vessel damage or dysfunction resulting from previous episodes of ischemia or from surgery itself could affect the maximal blood flow. Interestingly, the values of postoperative flow reserve reported in all of these studies are lower than those reported previously in subjects without clinical evidence of coronary artery disease. Whether this limitation of flow reserve results from the resistive characteristics of the Y-graft or from the coronary arteriolar bed is unclear. Moreover, none of these studies provides any information on the distribution of blood flow or perfusion pressure in the branches of the Y-graft during periods of maximal blood flow demand.

The concept of pressure-derived FFR has been developed to assess the physiological significance of coronary stenoses. FFR is calculated as the ratio of distal coronary pressure divided by aortic pressure during maximal hyperemia. In the absence of resistance along an artery, there is no pressure decline, and FFR equals unity. The larger the resistance to blood flow, the larger the decline in pressure and the smaller the FFR. This index is unaffected by conditions known to influence baseline myocardial flow and takes into account the contribution of the collateral blood supply to maximal myocardial perfusion, which is particularly relevant after bypass surgery. FFR is considered specific to epicardial conductance and has been proposed as a clinical tool to identify stenoses susceptible to induce reversible ischemia. Previous studies have shown that a FFR value <0.75 discriminates functionally significant coronary lesions susceptible to justify revascularization. In coronary arteries without focal stenosis at angiography, De Bruyne et al. reported FFR values of 0.97 in patients without atherosclerosis and 0.89 in patients with a focal arteriographic stenoses in another coronary artery.

As a substitute to epicardial vessels, one expects a bypass graft to allow reperfusion of the myocardial coronary territory with a minimal decrease in perfusion pressure and a FFR close to unity. The FFRs measured in the distal branches of the Y-graft in our patients are close to those reported in the distal part of “normal” coronary arteries of patients with a remote coronary lesion and reflect some minimal resistance to blood flow along the graft. All of the values of FFR were superior to 0.75, the cutoff for inducible ischemia.

Summary
Our data confirm previous investigations that suggested that a Y-graft configuration using both ITAs allows an adequate revascularization of the whole left coronary system. Although this configuration opposes some resistance to myocardial blood flow, responsible for a decrease in perfusion pressure during hyperemia, this resistance is modest and similar to that reported in nonstenotic coronary arteries of patients with diffuse coronary atherosclerosis. This resistance is similar in both branches of the graft, which excludes the possibility of a steal from one to the other branch during periods of high-myocardial blood flow demand.

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References
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