From October 2000 through April 2001, we prospectively evaluated the flow characteristics of the left internal thoracic artery (LITA) graft in a homogenous group of 44 men with isolated severe proximal left anterior descending coronary artery stenosis who underwent elective coronary artery bypass grafting with cardiopulmonary bypass. We performed transthoracic color Doppler ultrasonography preoperatively and repeated this examination in each patient between the 5th and 7th postoperative days, obtaining cross-sectional area, total flow volume, diastolic velocity, systolic velocity, mean velocity, pulsatility index, and resistance index. These results were compared with those of the intraoperative free-bleeding technique.

Good-quality Doppler images of the LITA were easily obtained with a combined supraclavicular-parasternal approach. After surgery, systolic flow velocity, pulsatility index, and resistance index decreased significantly, but diastolic flow velocity and mean flow velocity increased significantly. The intraoperative flow volume obtained by the free-bleeding technique (32.42 ± 12.33 mL/min) was significantly less than both pre- and postoperative ultrasonographic values (42.22 ± 10.77 mL/min and 45.36 ± 19.52 mL/min, respectively). No significant difference was found when changes in LITA values were compared between patients with (n=19) and without (n=25) normal anterior wall motion.

We conclude that color Doppler ultrasonography is a reliable noninvasive technique for preoperative evaluation of the LITA as a graft and for postoperative long-term follow-up of graft function. However, the intraoperative free-bleeding technique is not reliable for flow-volume measurement due to anesthesia-related hemodynamic changes and vasospasm. Color Doppler can prevent useless LITA harvesting and decrease the need for postoperative LITA angiography. (Tex Heart Inst J 2004;31:376-81)

Surgical results of coronary artery bypass grafting using the left internal thoracic artery (LITA) have stabilized, and the use of the LITA in coronary artery bypass grafting has for some time been associated with long-term graft patency and lower mortality rates. However, some problems with use of the LITA remain. During exercise, flow reserve is limited despite relief of angina, and diffuse or distal narrowing (“the string phenomenon”) may occur when the LITA graft is anastomosed to a left anterior descending coronary artery (LAD) with a low-grade proximal stenosis. In a purely observational study, Villareal and Mathur found support for the hypothesis that competitive flow predisposes all internal mammary grafts to the string phenomenon. Nasu and colleagues reported that the degree of LAD stenosis had an effect on distal LITA flow, which they demonstrated by using an intravascular Doppler flow guidewire. In addition, the size of the LITA graft depends on LITA flow, and the steal phenomenon has been observed in patients who received a LITA graft with a large remnant of lateral costal branch.

Noninvasive color Doppler ultrasonography has been reported to be useful for functional evaluation of the LITA graft. Despite reported discrepancies between angiographic and pulsed Doppler findings regarding the LITA, several recent reports have shown that pulsed Doppler ultrasonography is an effective, sensitive, and reliable method of evaluating LITA graft function.
ficity of a predominantly diastolic Doppler flow pattern for the presence of graft patency were 88% and 100%, respectively, with a positive predictive value of 100% and a negative one of 80%. Our prospective study examined the flow characteristics of the LITA graft pre- and postoperatively and compared the results with intraoperative manual flow measurements in a patient population that had severe single-vessel disease of the LAD with or without apical wall motion abnormalities.

**Patients and Methods**

The study group consisted of 44 men who underwent elective coronary artery bypass grafting surgery with cardiopulmonary bypass (CPB) at Turkiye Yuksek Ihtisas Hospital from October 2000 through April 2001. The mean age of the patients was 51.57 ± 9.44 years (range, 34–75). Twenty-five of these patients had a previous history of myocardial infarction. Other patient characteristics are presented in Table I. All 44 patients had severe (>75%) single-vessel disease at the proximal LAD. Left ventriculography revealed normal motion of the anterior wall in 19 patients (43.2%), hypokinesis in 15 (34.1%), akinesis in 2 (4.5%), dyskinesis in 5 (11.4%), and aneurysm formation in 3 (6.8%).

Only a LITA graft was used for each patient. The LITA was dissected with a pedicle by electrocauterization and protective gauze. Hemoclips were used to clamp the LITA branches. Topical 0.2% papaverine at 37 °C was used to prevent spasm, but we did not inject papaverine into or near the LITA, nor did we perform balloon dilation of the graft. Fifteen minutes after the topical application of papaverine, and immediately before the initiation of CPB, the distal cut end of the LITA was allowed to bleed into a graduated cylinder for 60 seconds under controlled hemodynamic conditions (the mean arterial blood pressure was maintained at 70 mmHg and the heart rate at 60–100 beats/min). In the event that the LITA flowed freely at a rate greater than 20 mL/min after relaxation of its spasm,20 we anastomosed it to the middle portion of the LAD in all patients and used no other graft. Intravenous fentanyl was used as an anesthetic agent for all patients.

Preoperative transthoracic color Doppler ultrasonography was performed in each patient using computed ultrasonography (Toshiba SSA-270 A; Tokyo, Japan) with a 7.5-MHz linear array transducer or 5-MHz convex transducer. Two-dimensional images and pulsed Doppler signals were obtained with a combined intercostal and supraclavicular approach. The angle of the ultrasound beam was corrected for the velocity measurements. During B-mode imaging, the LITA was measured in cross-section. Then the following parameters were determined: peak systolic flow velocity, peak diastolic flow velocity, mean flow velocity, resistance index, pulsatility index, and total flow volume. Indices were derived by the following formulas:

- **Resistance index** = \( \frac{\text{Peak systolic velocity} - \text{End-diastolic velocity}}{\text{Peak systolic velocity}} \)
- **Pulsatility index** = \( \frac{\text{Peak systolic velocity} - \text{End-diastolic velocity}}{\text{Mean velocity}} \)

In each patient, the color Doppler examination was repeated at some point between the 5th and the 7th postoperative days. All data obtained from Doppler measurements were compared before and after the operation. For total flow volume, we compared separately the pre-, intra-, and postoperative values. Patients in whom the LITA graft was damaged during the operation or in whom the LITA graft was not seen postoperatively were excluded from this study. The other exclusion criteria were severe carotid artery disease, a positive Allen test, subclavian artery disease, poor left ventricular function (echocardiographic left ventricular ejection fraction <0.40), older age (>75 years), and the use of inotropic support.

**Statistical Analysis.** Cumulative data were expressed as the mean ± standard deviation. Statistical analysis was performed using the paired t-test and repeated measures of analysis of variance. The criterion for statistical significance was \( P < 0.05 \).

**Results**

All study patients had an uneventful early postoperative course without any need for surgical revision, follow-up angiography, or percutaneous intervention. No patient had symptoms or electrocardiographic

<table>
<thead>
<tr>
<th>TABLE I. Clinical Characteristics of 44 Patients</th>
</tr>
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<tbody>
<tr>
<td>Characteristic</td>
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<tr>
<td>-----------------------------------------------</td>
</tr>
<tr>
<td>Male</td>
</tr>
<tr>
<td>Mean age (y)</td>
</tr>
<tr>
<td>Risk factors</td>
</tr>
<tr>
<td>Hypertension</td>
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<tr>
<td>Diabetes mellitus</td>
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<tr>
<td>Smoking</td>
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<tr>
<td>Hyperlipidemia</td>
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<tr>
<td>Family history</td>
</tr>
<tr>
<td>Peripheral artery disease</td>
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<tr>
<td>Mean echocardiographic LVEF</td>
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</tbody>
</table>

LVEF = left ventricular ejection fraction
changes that suggested myocardial ischemia. Hence early anastomotic failure was ruled out.

Changes in the LITA variables after coronary artery bypass grafting are shown in Table II. Although both diastolic flow velocity and mean flow velocity increased significantly \((P<0.01)\) after the operation, systolic flow velocity decreased significantly \((P<0.01)\). The total blood flow volume in the LITA did not change, but both pulsatility index and resistance index decreased significantly \((P<0.001 \text{ in each case})\).

Intraoperatively, the total flow volume as measured with the free-bleeding technique was \(32.42 \pm 12.33 \text{ mL/min}\). This was significantly less than both the preoperative values \((42.22 \pm 10.77 \text{ mL/min})\) and the postoperative values \((45.36 \pm 19.52 \text{ mL/min})\) and means that LITA graft flow decreased significantly \((from\ 42.22 \pm 10.77\ \text{ to}\ 32.42 \pm 12.33 \text{ mL/min})\) during the operation and then increased significantly \((from\ 32.42 \pm 12.33 \text{ mL/min} \text{ to}\ 45.36 \pm 19.52 \text{ mL/min})\) after the operation.

The changes in LITA variables were compared between patients with \((n=19)\) and without \((n=25)\) normal anterior wall motion, but no significant difference was found. The patients were divided into groups in accordance with the quality of their LAD coronary arteries. The quality of the LAD was decided under direct vision during surgery. The criteria for good quality were a diameter greater than 3 mm and the absence of plaques. According to these criteria, the LAD was good in 33 patients, moderately bad in 8, and bad in 3. These 3 groups were compared by looking at all variables, but no significant differences were found.

### Discussion

Doppler ultrasonography is increasingly used as a non-invasive imaging procedure for the evaluation of the LITA graft and now ranks 2nd to angiography in frequency of use for evaluating such grafts. Indeed its results agree closely with those of invasive intravascular recordings.\(^2\) The intraoperative application of Doppler flow analysis is also possible, provided that specialized microprobes are available.\(^3\) Although intraoperative color Doppler ultrasonography has high sensitivity and specificity, it is of course more invasive.

Preoperative LITA flow has a triphasic pattern similar to that in the peripheral arteries.\(^2\) As an adaptation to the coronary circulation, the postoperative LITA flow pattern becomes biphasic, with an increased peak diastolic velocity and a decreased peak systolic/peak diastolic velocity ratio.\(^24,25\) A LITA Doppler wave with a diastolic/systolic velocity ratio of more than 1.0 has been associated with a good angiographic finding.\(^26\) Coronary flow reserve (the ratio of peak diastolic velocity during hyperemia to that at baseline) of <1.9 has 100% sensitivity, 98% specificity, 87.5% positive predictive value, and 100% negative predictive value for LITA stenosis.\(^27\) Ichikawa and colleagues\(^28\) reported that these graft flow dynamics were unchanged even after 10 years, and this hemodynamic characteristic may be one of the factors related to superior long-term patency.

The high-frequency color Doppler technique enables the detection of a signal from LITA grafts in most patients; patients with nondetectable signals may need the administration of an echo-enhancer agent.\(^29\) Measurements of diastolic variables under continuous infusion of adenosine triphosphate disodium also improve the diagnostic accuracy of this technique.\(^30\)

Nasu and associates,\(^10\) after using an intravascular Doppler flow guidewire (an invasive method), reported that LITA graft flow in the presence of proximal coronary low-grade stenosis is lower than that in the presence of severe coronary stenosis. In the same study, patients with moderate coronary artery stenosis had lower LITA graft flow than did those with severe

### TABLE II. Changes in Color Doppler Variables of Left Internal Thoracic Artery after Surgery

<table>
<thead>
<tr>
<th>Variables</th>
<th>Before Operation</th>
<th>After Operation</th>
<th>(P) Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-sectional area (cm(^2))</td>
<td>0.054 ± 0.017</td>
<td>0.051 ± 0.013</td>
<td>NS</td>
</tr>
<tr>
<td>Systolic flow velocity (cm/s)</td>
<td>88.47 ± 21.12</td>
<td>67.75 ± 31.65</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Diastolic flow velocity (cm/s)</td>
<td>9.26 ± 7.78</td>
<td>16.81 ± 10.32</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Mean flow velocity (cm/s)</td>
<td>26.08 ± 9.62</td>
<td>37.28 ± 15.77</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Pulsatility index</td>
<td>3.56 ± 1.69</td>
<td>1.61 ± 1.05</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Resistance index</td>
<td>0.92 ± 0.06</td>
<td>0.74 ± 0.14</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total flow volume (mL/min)</td>
<td>42.22 ± 10.77</td>
<td>45.36 ± 19.52</td>
<td>NS</td>
</tr>
</tbody>
</table>

NS = \(P\) value not significant
stenosis. The implication of this phenomenon may be that LITA flow competes with native coronary artery flow in patients who have moderate coronary artery stenosis. Our study population was a homogeneous one in which all patients had severe proximal LAD stenosis. Therefore, the competition between LITA graft flow and native coronary artery flow did not occur and did not affect the hemodynamic changes.

In our study, all postoperative LITA graft flow became diastolic dominant, and no abnormal flow pattern was observed in any of the patients. The reasons for which a postoperative LITA graft fails to become diastolic dominant may include competitive flow from the native coronary artery or from a saphenous vein graft that was used for bypass near the LITA graft, stenosis in the LITA graft,31 the presence of a large LITA branch into which much of the LITA blood flows,14 and weakness of contractility in the area affected by myocardial infarction.32 In our study, patients were divided into 2 groups according to presence or absence of anterior wall motion abnormality. Even in patients with apical dyskinesia (n = 5), the diastolic-dominant pattern was observed postoperatively. Despite the presence of noncontractile myocardium, the occurrence of a diastolic-dominant flow pattern may be a sign of improvement in the circulation and of metabolism in the myocardium (the revival of so-called hibernating myocardium);33 but the number of patients with apical dyskinesia was too small to warrant such a conclusion. In order to eliminate other factors, we ligated all side branches of the LITAs and used no saphenous vein grafts.

The string sign and steal phenomenon are 2 anomalous flow characteristics that can affect LITA grafts. It has been reported that the string sign occurred when a LITA graft was anastomosed to an LAD coronary artery with low-grade proximal stenosis.5–8 Kita-mura and colleagues34 showed angiographically that a LITA graft is patent even when the string sign and no flow occur: the so-called no-flow patency. Seki and associates1 reported that the string phenomenon could be regarded as a physiologic change that reflects the LITA graft’s response to lower blood-flow demands. Nasu and colleagues10 showed that LITA flow volume decreased in proportion to the decrease in the grade of the LAD stenosis. The steal phenomenon was observed in patients who received a LITA graft that included a large remnant of the lateral costal branch; however, the role of remnant side branches as a source of the steal phenomenon may be exaggerated. Seki and associates2 reported that remnant side branches do not appear to affect LITA size, and Ivert and colleagues4 concluded that unligated side branches do not interfere with long-term graft patency. However, Singh and coworkers7 reported on 4 patients with remnants of pericardiophrenic artery, the collaterals of which drained into the pulmonary circulation, and this kind of remnant might produce LITA steal. In the present study, all patients had severe proximal LAD stenosis and all side branches of the LITA were trimmed off. Therefore, neither string sign nor steal phenomenon would be expected.

In this study, intraoperative LITA flow volume was measured with the free-bleeding technique. This intraoperative value was significantly smaller than the preoperative and postoperative values, a variation that we believe was the result of hemodynamic changes related to anesthesia and vasospasm during LITA harvesting. Physical manipulation and exposure to cold are the main reasons for vasospasm, which can be relieved by pharmacologic agents.35 In our study, diluted papaverine was administered topically for relief of spasm. There is concern about incomplete relief of intraoperative spasm with topical application of papaverine.36 In our surgical practice, we prefer topical use of papaverine to intraluminal injection, which carries considerable risk of mechanical wall injury—intimal dissection, in particular.37 Re-flow after the establishment of anastomosis contributes to the reversal of LITA spasm, which reversal generally manifests itself as postoperative improvement in flow volume as shown by Doppler. Therefore, transthoracic Doppler ultrasonography is actually more reliable for LITA flow evaluation than is the intraoperative free-bleeding technique, and is a good, simple noninvasive alternative.

Transthoracic color Doppler ultrasonography also completely excludes the possibility of introducing microorganisms into the surgical site. With a combined approach (supraclavicular plus parasternal), the rate of successful visualization is 100% even in postoperative patients in whom the course of the LITA has been changed. Preoperative flow evaluation is important for determining the quality of the LITA as a graft, especially in patients who have a high probability of diffuse atherosclerosis (for example, those with diabetes mellitus). In addition, early postoperative evaluation provides invaluable prognostic information, especially in the rapid detection of flow disturbances due to suboptimal anastomoses. Changes in LITA graft flow pattern from diastolic-dominant to systolic-dominant suggest some occurrence in the LITA graft, the native coronary artery, or both. Decreased diastolic flow, increased resistance, and altered systolic/diastolic velocity ratio are important findings that are observed in dysfunctional grafts both early and late after surgery. Local trauma to the intima from the catheterization procedure may initiate progressive narrowing at the ostium of the LITA; an alternative noninvasive technique would prevent this complication. The intraoperative free-bleeding technique has not produced results comparable with those of Doppler measurement, and the evaluation of LITA flow with this tech-
nique alone may not be adequate—especially for borderline cases. Demonstration of the fact that the LITA can be used successfully for coronary artery bypass grafting even when LITA free flow is very low\(^3\) is more evidence of the inaccuracy of the free-flow technique. Therefore, ultrasonographic Doppler analysis is an excellent alternative for LITA flow evaluation.

Future studies with larger cohorts will be needed to precisely define patient subgroups in which preoperative Doppler analysis of the LITA should be performed. Nevertheless, we recommend routine use of this method for patients who have a high likelihood of diffuse atherosclerosis. Furthermore, it is likely to be useful for the evaluation of patients with chest pain that develops after coronary artery bypass grafting.

References