Clinical Investigation

Comparison of Intraoperative Transit-Time Flow Measurement with Early Postoperative Magnetic Resonance Flow Mapping

in Off-Pump Coronary Artery Surgery

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The purpose of this prospective study was to evaluate graft patency of off-pump coronary artery surgery intraoperatively by transit-time flow measurement and to compare this technique with postoperative magnetic resonance flow mapping.

Twenty patients (13 men and 7 women; mean age, 67.9 ± 7.6 yr) underwent off-pump coronary artery surgery. Intraoperative transit-time flow measurement of grafts was performed measuring maximum, minimum, and mean flows. For each graft, the pulsatile index was calculated by dividing the difference between the maximum and the minimum flow by the mean flow. In the early postoperative period (1st week), magnetic resonance flow mapping was performed using phase contrast flow quantification. Mean intraoperative flow values and mean magnetic resonance flow mapping values were compared. At the same postoperative session, contrast-enhanced magnetic resonance angiography was performed to evaluate graft patency.

In 20 patients, a total of 49 coronary graft flows were assessed with intraoperative transit-time flow measurement and postoperative magnetic resonance flow mapping. Upon comparison, there was a strong correlation between techniques, with stable and statistically significant differences between the intraoperative and postoperative flow mapping values. One saphenous vein graft was revised intraoperatively, due to graft failure.

Our data suggest that the combined use of intraoperative transit-time flow measurement and postoperative magnetic resonance flow analysis has a potential role in the assessment of graft patency in off-pump coronary artery surgery, although more study is required. ***(Tex Heart Inst J 2003;30:31-7)***

Key words: *Blood flow velocity; graft occlusion, vascular/diagnosis; hemorheology/instrumentation; magnetic resonance angiography; prospective studies; rheology/methods*

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Off-pump coronary artery surgery is a technically more challenging procedure than is conventional on-pump coronary artery surgery. Evaluation of bypass-graft patency during the operation and in the postoperative period becomes more important for the management of patients and for the assessment of anastomosis quality.[1,2] For the intraoperative assessment of bypass grafts, transit-time flow measurement (TTFM) has been used as an effective and reliable technique.[1]

Conventional angiography is considered the gold standard technique for disclosing restenosis and visualizing patent bypass grafts during the postoperative period. Contrast-enhanced magnetic resonance angiography (CE-MRA) has also been used for this purpose, and its results, in general, correlate well with those of conventional angiography.[3,4] However, in cases of moderately severe (50%–75%) stenosis, as determined by both conventional and MR angiography, results do not always correspond with functional status.[5] Therefore, intracoronary Doppler flow measurement has been used in difficult-to-determine cases.[5] However, this procedure is highly invasive, costly, and necessitates hospitalization. Magnetic resonance flow mapping of bypass grafts has been used as a noninvasive alternative technique to assess intraluminal flow.[6]

The purpose of this prospective study was to assess the value of TTFM for the intraoperative management of the patient during off-pump coronary artery surgery, and to compare this technique, in the early postoperative period (1st week), with MR flow mapping of bypass grafts, in conjunction with contrast-enhanced MR angiography.

Patients and Methods

From January 1999 through May 1999, 20 patients underwent off-pump coronary artery surgery through a median sternotomy. Emergency cases and reoperations were excluded. The mean age was 67.9 ± 7.6 years (range, 54 to 81 years). There were 13 men and 7 women. Fifty-three anastomoses were performed with use of off-pump coronary artery surgery. The mean number of anastomoses per patient was 2.7 ± 0.8

Surgical Procedure

All patients were premedicated with midazolam, 0.07 to 0.1 mg/kg. Anesthesia was induced with fentanyl and Diprivan, and vecuronium was used for muscle relaxation. Anesthesia was maintained with perfusion of fentanyl and Diprivan. The operating room temperature was maintained at 24 to 25 °C. Initially, 2 mg/kg heparin was administered, followed by 50 mg every hour intraoperatively.

Intraoperative Flow Measurement

In TTFM, 2 piezoelectric crystals transmit ultrasound through the blood vessel toward a reflector on the other side of the vessel. The volume of flow is calculated by measuring the difference between transit times upstream and downstream in the blood vessel.[7]

In a left coronary graft, blood flows predominantly during diastole, with a short peak during systole, because the smaller intramyocardial vessels are compressed during left ventricular systole. Therefore, flow curves in a patent graft have a large diastolic pattern (Fig. 1A). In the right coronary artery, blood flows predominantly during systole because the pressure differential is more favorable. Flow curves in a patent right coronary graft, then, have a large systolic pattern (Fig. 1B). In a case of stenotic anastomosis, the flow curves become smaller and reveal an irregular pattern (Fig. 1C).

Flow values and curves were measured by use of the Coronary FloMeter™ System (CFM 100, Transonic Systems Inc.; Ithaca, NY) before the sternum was closed. During this procedure, the mean systemic blood pressure and heart rate were kept at 84.5 ± 9.4 mmHg and 69.3 ± 7.3 beats/min, with a hemoglobin concentration of 8.9 ± 2.6 g/dL. Transit-time flow measurement values, flow curves, and the pulsatile index (PI) were calculated and evaluated. The PI was calculated by dividing the difference between the maximum and the minimum flow by the mean flow. According to D'Ancona and colleagues,[2] a PI value of 1 through 5 indicates satisfactory quality of the anastomosis.

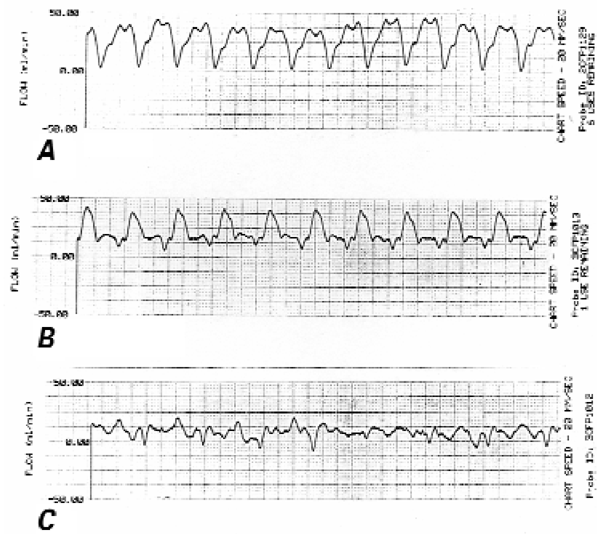

Fig. 1 *Transit-time flow curves: Panel **A** shows normal flow pattern of LIMA–LAD graft; Panel **B** shows normal flow pattern of SVG–RCA; Panel **C** shows flow pattern of a stenotic SVG–RCA anastomosis.*

LAD = left anterior descending artery; LIMA = left internal mammary artery; RCA = right coronary artery; SVG = saphenous vein graft

Several studies have been performed for validation of TTFM using different systems under various conditions (arterial or venous graft material, saline or blood-flow medium), and the results of these revealed that TTFM is a fast and reliable method.[6,8] In our study, the findings of the Coronary FloMeter were also validated by left internal mammary artery (LIMA) flow measurement. After flushing the LIMA with papaverine, we collected the blood in a basin while measuring the flow with TTFM for 60 seconds. The amount of collected blood was compared with TTFM measurement flow values. This procedure was repeated for 16 LIMA grafts.

Magnetic Resonance Angiography and Flow Mapping

All patients underwent MR flow mapping and MR angiography for the assessment of graft patency during the 1st postoperative week. Two experienced radiologists evaluated both the flow measurements and the MR angiography images, and they were blinded to patients' TTFM data obtained by intraoperative measurements. The blood pressure and heart rate of every patient was measured during MR imaging. The mean blood pressure and heart rate were 89.1 ± 5.4 mmHg and 74.6 ± 11.2 beats/min, with hemoglobin concentrations of 11.2 ± 2.3 g/dL.

Magnetic resonance imaging was performed with a 1.5 tesla (40mT/meter gradient strength) cardiac-dedicated MR scanner (Magnetom Sonata, Siemens; Erlangen, Germany), using a phased-array body coil. For the visualization of bypass grafts, an electrocardiography (ECG)-gated, black-blood, half-Fourier, single-shot, fast-spin echo sequence (HASTE) (TR [repetition time] = ∞; TE [echo time] = 60 msec) was performed in axial and coronal planes, with a 4-mm section thickness in a single breath-hold. Magnetic resonance flow-mapping was performed using an ECG-gated, breathing averaged, velocity encoded, phase-contrast, gradient echo sequence (Figs. 2A and 2B). The velocity window was set to 75 cm/sec. A single-slice, phase-contrast, gradient echo sequence was placed in a plane perpendicular to the imaged bypass grafts, and imaging was performed for each graft separately. The following sequence parameters were used: TR = 30 msec, TE = 2 msec, FA (flip angle) = 70°, 2 averages, with an acquisition time of 6 to 8 min according to heart rate. Prospective ECG gating was used to acquire 20 frames covering the entire heart cycle. The acquisition matrix was 300 × 512, yielding a pixel size of 1.7 × 1.9. Contrast-enhanced MR angiography was performed by use of a 3-dimensional (3-D) gradient echo sequence (Flash 3D) with the following imaging parameters: TR = 4.6 msec, TE = 1.2 msec, FA = 25°, a matrix of 180 to 190 × 512, and a coronal slab with a thickness of 60 to 80 mm (60 to 80 partitions yielded slice thicknesses of 1 mm). Gadolinium chelate (Magnevist, Schering; Berlin, Germany) was administered at a dosage of 0.2 mmol/kg with a power injector (Medrad; Pittsburgh, Penn), at a rate of 3 mL/sec; this was followed by a flush of 10 mL of normal saline. For testing purposes, we in every case injected a gadolinium chelate bolus at a rate of 3 mL/sec before the 3-D gradient echo sequence, in order to achieve accurate contrast timing.

Postprocessing of flow measurements was performed with the provided software at the MR scanner. Mean flow (in mL/min) and peak velocity (in cm/sec) were calculated automatically; volumetric reconstruction of MR angiography images was performed at the 3D Virtuoso workstation (Siemens). Maximum-intensity projection images were color mapped, and bypass grafts were viewed at different angles.

Statistical Analysis

All the statistical analyses were performed by use of the SPSS 10.0 (SPSS Inc; Chicago, Ill) statistical package. We tested the parametric assumptions of the variables first and then used Student's *t*-test for paired samples, or the Wilcoxon signed test for assessment of the differences between 2 groups. All data were expressed as mean ± standard deviation. *P* values less than 0.05 were considered statistically significant. In order to find the correlation between 2 variables, we

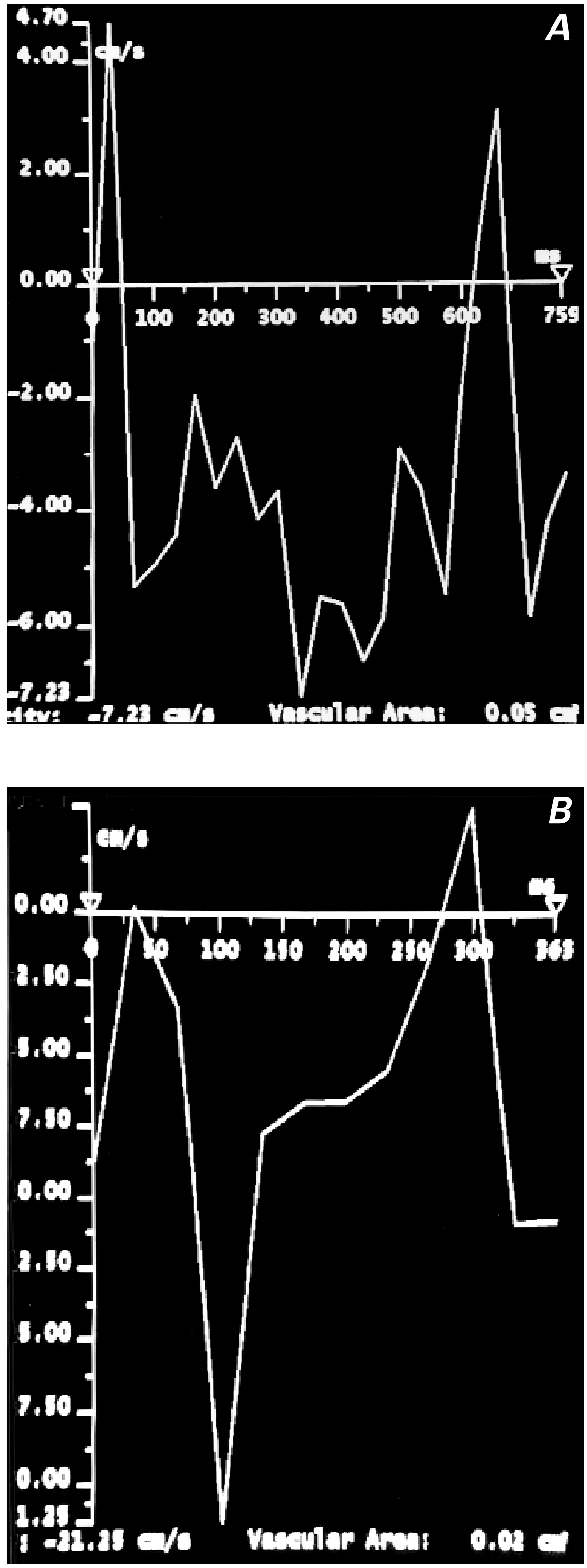

Fig. 2 *Magnetic resonance flow mapping with use of the phase-contrast technique. Flow velocity curves of 2 patent grafts:* ***A****) left internal mammary artery and* ***B****) saphenous vein.*

calculated the Pearson coefficient of correlation. We applied a linear regression module to reveal the relation between TTFM and MR flow-mapping techniques.

Results

Four LIMA grafts could not be evaluated with MR angiography because of problems encountered at the outset of the clinical trial, and these were excluded. A total of 49 coronary graft flows were evaluated in 20 patients. Graft flow parameters measured by intraoperative TTFM and postoperative MR flow mapping are shown in Tables I and II, respectively.

One saphenous vein graft (SVG) was revised intraoperatively due to graft failure. Before revision, the mean flow was found to be 5.2 mL/min, and the PI value was 11.9 with abnormal flow pattern. After revision, the flow pattern improved, and the mean flow was found to be 30.3 mL/min with a PI value of 2.

One graft had decreased flow and another graft had no flow on the MR flow analysis, which was also revealed by MR angiography (Fig. 3). Stenosis and occlusion of the grafts were also confirmed by conventional coronary angiography.

For the validation of findings by the Coronary FloMeter, the volume of the blood collected in a basin in 60 seconds was 72 ± 15.7 mL/min, and the TTFM value was 79.9 ± 19.1 mL/min. The difference between the 2 measurements was not significant (P >0.05), which validated the TTFM performed by the Coronary FloMeter.

Fig. 3 *Magnetic resonance angiogram of a patient with occlusion of a saphenous vein graft to the right coronary artery (arrow).*

TABLE I. Flow Parameters* in 49 Grafts Measured by Intraoperative TTFM

Grafts	No. of Grafts	Mean Flow (mL/min)	Pulsatile Index
LIMA–LAD	16	40.6 ± 21.3	1.8 ± 0.4
SVG	33	21.8 ± 6.8	2.1 ± 0.3

*Values are expressed as mean ± SD.

LAD = left anterior descending coronary artery; LIMA = left internal mammary artery; SD = standard deviation; SVG = saphenous vein graft; TTFM = transit-time flow measurement

TABLE II. Flow Parameters* in 48 Grafts Measured by Postoperative Magnetic Resonance Flow Mapping

Grafts	No. of Grafts	Mean Flow (mL/min)	Mean Velocity (cm/sec)	Peak Velocity (cm/sec)
LIMA–LAD	16	51.4 ± 23.3	7 ± 2.6	14.7 ± 5.1
SVG	32**	27.2 ± 7.4	5 ± 1.5	9 ± 2.8

*Values are expressed as mean ± SD.
**One SVG was excluded because of graft occlusion.

LAD = left anterior descending coronary artery; LIMA = left internal mammary artery; SD = standard deviation; SVG = saphenous vein graft

The mean LIMA–LAD flow value (n=16) was 40.6 ± 21.3 mL/min, and the PI value was found to be 1.8 ± 0.4 with perioperative TTFM and 51.4 ± 23.3 mL/min with postoperative MR flow mapping. There was a significant increase in LIMA–LAD flow values (z=3.517; P <0.01) and good positive correlation between TTFM and MR flow-mapping values (r=0.99; P <0.01) (Fig. 4). On MR flow mapping, the mean vessel area of LIMA–LAD grafts was 12.3 ± 5.7 mm^2, and the average number of pixels in the grafts was 3.8 ± 0.7.

The mean SVG flow value (n=33) was found to be 21.8 ± 6.8 mL/min, and the PI value was found to be 2.1 ± 0.3 with perioperative TTFM and 27.2 ± 7.4 mL/min with postoperative MR flow mapping (n=32). There was also a significant increase in SVG flow values (t=9.090; P <0.01) and good positive correlation between TTFM and MR flow-mapping values (r=0.90; P <0.01) (Fig. 5). On MR flow mapping, the mean vessel area of SVG grafts was 15 ± 6.3 mm^2, and the average number of pixels in the vessel area was 4.1 ± 0.5.

Discussion

Measurement of coronary graft blood flow is of great clinical value in determining graft stenosis in off-

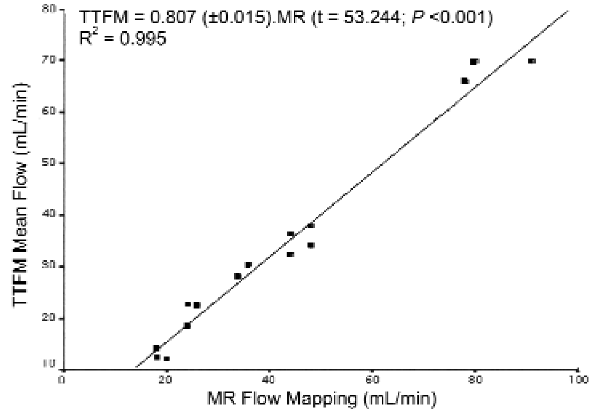

Fig. 4 *Correlation between TTFM and magnetic resonance flow-mapping values in LIMA–LAD flow.*
r=0.99; P <0.01

LAD = left anterior descending artery; LIMA = left internal mammary artery; TTFM = transit-time flow measurement

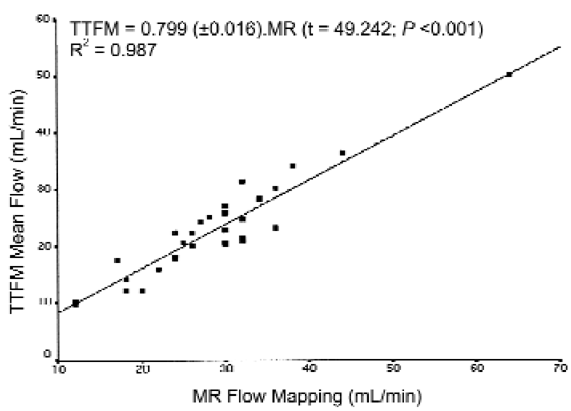

Fig. 5 *Correlation between TTFM and magnetic resonance flow-mapping values in SVG flow.*
r=0.90; P <0.01

MR = magnetic resonance; SVG =saphenous vein graft; TTFM = transit-time flow measurement

pump coronary artery surgery. Intraoperative assessment of bypass graft patency by flow measurement enables early intervention and revision, at the same session, of occluded grafts or failed anastomoses.[5,9,10] Numerous flow measurement techniques are currently in use.[11-13] Recently, TTFM and MR imaging techniques have been used to evaluate intraoperative and postoperative coronary graft blood flow, respectively.

Many authors have demonstrated the superiority of TTFM over Doppler systems in direct real-time detection of flow, regardless of vessel diameter and Doppler angle.[11] Electromagnetic wave flow measurement of bypass grafts depends on the measurement of the deflection of magnetic force created by the movement of the iron atoms in the hemoglobin complex, and such measurement techniques rely on the concentration of serum hemoglobin. Therefore, minor changes in the probe angle affect the accuracy of the measurements.[14] However, measurements obtained by using TTFM are not affected by the concentration of serum hemoglobin and probe angle. Since TTFM directly measures the mean blood-flow value, it does not need a homogeneous distribution of the blood flow within the cross-sectional area of the vessel, whereas the ultrasound Doppler technique requires it.[15] Several studies have demonstrated that the measurement of bypass grafts using TTFM is effective and reliable for intraoperative evaluation of coronary grafts.[2,13,15] Although TTFM appears to be an accurate and reliable technique for intraoperative coronary graft flow measurements, it is not possible to measure coronary graft flow with this technique postoperatively.

In the postoperative period, assessment of bypass grafts is important for the medical and interventional management of the patient. Coronary angiography has been considered the gold standard for the evaluation of bypass grafts; however, it is an invasive procedure and cannot be used as a screening method on every patient. There are some pitfalls of coronary angiography in the evaluation of stenotic segments. Wiklund and colleagues[16] have reported that it is difficult to explain certain findings in early postoperative coronary angiography. They observed, by means of postoperative angiography, a large number of stenoses without clinical symptoms. They also observed that the contrast medium sometimes displayed quick run-off from the graft into the anastomosed vessel, despite the angiographic appearance of significant stenosis, which could lead to overestimation or underestimation of the stenosis.[16] Angiography yields a limited 2-dimensional view of coronary grafts, without supplying specific information about the hemodynamic characteristics of the anastomosis.

Coronary MR imaging has been considered a challenging technique because of the small size of the coronary arteries, the abundant signal from surrounding epicardial fat, and the significant motion associated with both respiration and cardiac contractions. However, the relatively motionless position of the coronary bypass graft partly offsets many of the technical obstacles of native-vessel coronary MR imaging.[17,18] Moreover, the bypass graft's relatively straight and predictable course enables the use of MR imaging techniques. Therefore, contrast-enhanced 3-D MR imaging has been used successfully for the evaluation of the bypass grafts[4] and stenotic segments, and the results have correlated well with those of conventional angiography. With the use of cardiac-dedicated scanners, rapid and reproducible MR angiography will be performed routinely in the future. However, there are limitations to MR angiography: occlusion at the anastomotic site cannot be accurately visualized by contrast-enhanced MR angiography alone,[3] nor can the hemodynamics of bypass grafts be accurately evaluated in cases of moderately severe stenoses (50%–75%) that display clinical symptoms.[5]

Because of these limitations, flow measurement of bypass grafts has been performed by the MR flow-mapping technique. This technique relies on the phase shifts of the flowing protons in the vessels. A flow speed needs to be set for the anticipated flow rate in the vessel, which has been chosen as 75 cm/sec in previous reports and also in our study. Our data correlated well with the results of our intraoperative measurements. In previous studies of MR flow measurements, adenosine was used to produce stress-induced flow changes for the purpose of evaluation.[5] In our study, we did not produce stress-induced flow changes, because we wanted to approximate the conditions that existed during intraoperative flow measurements. Our results correlated with those of a previous study[19] that compared intraoperative flow measurement with MR flow mapping, both in terms of comparative intraoperative measurement values and postoperative MR flow quantification methods.

An important limitation of the MR flow-mapping technique is the problem of breathing artifacts, which can impair measurement. We used the breath-hold technique and the navigator-gated 3D-MRA technique to perform controlled, artifact-free visualization of the bypass grafts during MR angiography. For the MR flow measurements, the breath-hold technique can be used despite inadequate spatial resolution (128–256 matrix) and fewer time points (phases).[5,19,20] Our technique of free-breathing, phase-contrast velocity imaging, as applied to MR flow measurements, yields images with better resolution, despite some blurring by the free breathing and by the multiple averages incurred by the technique. The 512 matrix also enabled us to better evaluate internal mammary artery grafts, which have relatively small diameters.

One might ask why the MR measurement of flow for both the LIMA and SVG grafts is so much higher (approximately 30%) than that of the TTFM flow. In all likelihood, this can be accounted for by the intraoperative and postoperative differences in the patient's hemodynamic condition. During surgery, myocardial contractions are depressed because of hibernation and stunning of the heart, and patients take vasopressors to tolerate this. Vasopressors, of course, affect arterial blood flow. In addition, one must consider the metabolic status of the patient in the perioperative period, at which time metabolic acidosis often has a negative effect on myocardial blood flow.

Despite these differences between intraoperative and postoperative conditions during measurements, there was a good correlation between the results of the 2 techniques, with stable and statistically significant differences between the values. Another important limitation of our study is the fact that we derived most of our flow measurements and MR angiographic data from grafts with normal intraoperative flow patterns. In 1 patient, MR angiography revealed an occluded graft that displayed normal intraoperative flow patterns during TTFM. Postoperative occlusion was attributed to kinking of the venous graft due to excessive length. This patient underwent coronary angiography, which also showed an occluded venous bypass graft of the right coronary artery, and was referred to the department of cardiology for further management.

To better evaluate the specificity of MR imaging and TTFM in the assessment of stenotic graft segments, correlative studies should be undertaken in larger series, and conventional angiography should be used postoperatively to confirm stenosis or occlusion.

Conclusion

Our data revealed good correlation between intraoperative TTFM and postoperative MR flow measurement. The combined use of these techniques can evaluate the quality of the operative procedure and improve postoperative screening of patients. Further studies, undertaken on a larger scale and supplemented postoperatively by conventional angiography, should reveal more clearly the value of flow measurements in application to stenotic and occluded grafts.

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