Evaluation of extracranial–intracranial bypass using quantitative magnetic resonance angiography

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Object. To date, angiography has been the primary modality for assessing graft patency following extracranial–intracranial bypass. The utility of a noninvasive and quantitative method of assessing bypass function postoperatively was evaluated using quantitative magnetic resonance (MR) angiography.

Methods. One hundred one cases of bypass surgery performed over a 5.5-year period at a single institution were reviewed. In 62 cases, both angiographic and quantitative MR angiographic data were available. Intraoperative flow measurements were available in 13 cases in which quantitative MR angiography was performed during the early postoperative period (within 48 hours after surgery).

There was excellent correlation between quantitative MR angiographic flow and angiographic findings over the mean 10 months of imaging follow up. Occluded bypasses were consistently absent on quantitative MR angiograms (four cases). The flow rates were significantly lower in those bypasses that became stenotic or reduced in diameter as demonstrated by follow-up angiography (nine cases) than in those bypasses that remained fully patent (mean ± standard error of the mean, 37 ± 13 ml/minute compared with 105 ± 7 ml/minute, p = 0.001). Flows were appreciably lower in poorly functioning bypasses for both vein and in situ arterial grafts. All angiographically poor bypasses (nine cases) were recognizable by absolute flows of less than 20 ml/minute or a reduction in flow greater than 30% within 3 months. Good correlation was seen between intraoperative flow measurements and early postoperative quantitative MR angiographic flow measurements (13 cases, Pearson correlation coefficient = 0.70, p = 0.02).

Conclusions. Bypass grafts can be assessed in a noninvasive fashion by using quantitative MR angiography. This imaging modality provides not only information regarding patency as shown by conventional angiography, but also a quantitative assessment of bypass function. In this study, a low or rapidly decreasing flow was indicative of a shrunken or stenotic graft. Quantitative MR angiography may provide an alternative to standard angiography for serial follow up of bypass grafts.

KEY WORDS • cerebral blood flow • extracranial–intracranial bypass • angiography • magnetic resonance angiography

EXTRACRANIAL–INTRACRANIAL bypass surgery is a microsurgical technique used for cerebrovascular revascularization since the 1970s.36,42 Bypasses are currently performed for two types of primary indications: flow augmentation in selected cases of occlusive cerebrovascular disease2,3,24,26 and flow replacement in the setting of planned vessel occlusion for aneurysm obliteration2,17,34 or resection of skull base tumors18,35 involving major vessels. Assessment of EC–IC bypass patency and function has traditionally been performed using angiography.1,42 Less invasive modalities for early assessment and long-term follow up of bypasses are desirable. Noninvasive methods including Doppler ultrasound and simple digital palpation have been used16 but are less accurate and reliable than standard angiography. The imaging modalities of CT angiography and standard MR angiography are currently available for use in follow up,20,23,27,37,38 but—as in catheter angiography—information regarding bypass function and flow must be inferred from static images when these alternatives are used.

Quantitative MR angiography provides the ability to noninvasively assess both the patency and the function of EC–IC bypasses by measuring flow through the bypass conduit. We reviewed our experience with the use of quantitative MR angiography in evaluating EC–IC bypass postoperatively to determine the reliability and usefulness of this noninvasive modality in serial follow up of bypass function.

Clinical Material and Methods

Patient Population and Selection Criteria

We performed a retrospective review of all bypass surgeries performed at the University of Illinois Medical Center at Chicago for the 5.5-year period from August 1998 through December 2003. These operations consisted of by-
passes performed for purposes of blood flow augmentation in the setting of cerebrovascular occlusive disease and for blood flow replacement in the setting of complex aneurysms or skull base tumors requiring parent vessel sacrifice. At our institution, the indication for flow augmentation bypass is as follows: failure of maximal medical therapy, symptoms concordant with radiographic findings, poor cerebrovascular reserve as demonstrated by perfusion imaging, and lack of major medical comorbidity. We also perform STA–MCA bypass in the treatment of symptomatic moyamoya disease in adults. Monitoring of bypass function routinely includes angiography and quantitative MR angiography in the postoperative period prior to discharge, and at 6- to 12-month intervals dependent upon the patient’s clinical status and availability for follow up.

Postoperative Blood Flow Measurement

The technical success of the bypass was judged by angiographic patency in addition to quantitative measurements of blood flow through the graft using quantitative MR angiography. The technique of blood flow quantification by quantitative MR angiography has been described previously and is now implemented and enhanced in commercially available software called NOVA (Noninvasive Optimal Vessel Analysis, VasSol, Inc.). Axial 2D or 3D time-of-flight MR angiography is performed first. The acquired images are then transmitted to a computer workstation where the NOVA software is used to create a rotating 3D surface rendering of the vasculature, including the circle of Willis, using a marching cube algorithm. From a scan line calculated by a line-fitting algorithm, a double-oblique scan is performed using gated 2D phase-contrast MR imaged perpendicular to the vessel axis. A flow report on each vessel of interest is created using the NOVA software; this report includes the mean volumetric flow rate.

All the images were acquired using either a 1.5- or 3-tesla MR imaging unit (General Electric Medical Systems). Flow measurements performed on 1.5- and 3-tesla units were equivalent.

Angiographic Assessment

Angiographic designation of the bypass was performed a priori, categorizing the bypasses into three categories: occluded, poor, and patent. Bypasses were classified as occluded if angiography failed to demonstrate any visualization of the bypass despite appropriate vessel injection. They were classified as poor if they contained any stenotic segments or if they were reduced in size (shrunken). Those classified as patent were fully patent.

Intraoperative Blood Flow Measurements

Blood flow though the bypass conduit was measured quantitatively in ml/minute using an ultrasonic flow probe (Charbel Micro-Flowprobe, Transonic Systems, Inc.), which is manufactured in a variety of sizes to accommodate intra- or extracranial vessels ranging from 1 to 3 mm in width. The flow probe uses the principle of ultrasonic transit time to sense flow in vessels independent of the flow velocity profile, turbulence, or hematocrit level. The accuracy of the probe has been established in both in vitro and in vivo studies. The final bypass flow at the completion of the anastomosis was recorded when the measurement was available.

Statistical Analysis

An unpaired two-tailed Student t-test was used to assess differences in bypass flow according to the angiographic status of the bypass graft. Flows are presented as means ± standard errors of the mean. The Pearson correlation coefficient was used to assess the correlation between intraoperative flow measurements and postoperative quantitative MR angiographic measurements. All statistical analyses were performed with Stata version 6 (Stata Corp.). Probability values of less than 0.05 were considered significant.

Results

Patient Population

During the study period, a total of 101 bypass procedures were performed in 93 patients. Of these, 62 bypasses in 59 patients were studied with both standard angiography and quantitative MR angiography postoperatively to assess bypass patency and function. The ages of these patients at the time of surgery ranged from 15 to 86 years (mean 54). The majority of the patients (37 [66%] of 59) were men. The mean length of imaging follow up of the bypasses was 10 months.

Operative Procedures

Table 1 summarizes the types of bypass operations performed. Bypass using an in situ donor vessel, namely the STA or the occipital artery, was performed in the majority of the cases. The remainder of the cases involved long vein interposition grafts, including both EC–IC bypass to the anterior or posterior circulation and EC–EC bypass consisting of grafts from the carotid artery to the V, segment of the VA. The majority of bypasses (48 procedures) were performed for ischemic cerebrovascular disease to augment flow. The remaining bypasses were performed for flow replacement for the treatment of aneurysms or skull base tumors when parent vessel occlusion or flow redirection was planned.

Angiographic and Quantitative MR Angiographic Findings

Of the 62 bypasses in this analysis, three were found to be occluded on early (≤ 72 hours) postoperative angiograms, for an overall patency rate of 95% (96% for anterior circulation, 90% for posterior circulation). One additional bypass, initially patent postoperatively, was found to be occluded on an angiogram performed 12 months after surgery.

In the 62 cases, quantitative MR angiography was performed at various times after surgery. Overall, 125 quantitative MR angiography studies were performed for documentation or serial monitoring of bypass function. Eighty-one of these studies were performed with contemporaneous angiograms. Analysis of those studies demonstrated that angiographically occluded bypasses were consistently absent on quantitative MR angiograms (four cases). Angiographically evident stenosis or shrinkage of a bypass was present in eight patients; in one patient the same vein graft demonstrated stenosis and then a subsequent restenosis after angioplasty, resulting in nine instances of bypass deficiency. In these cases quantitative MR angiography demonstrated
significantly lower bypass flow, compared with flow measurements obtained in the angiographically fully patent bypasses (37 ± 13 ml/minute compared with 105 ± 7 ml/minute, p = 0.001).

Flows were significantly lower in poorly functioning in situ arterial grafts (17.5 ± 4.1 compared with 86.9 ± 6.9, p < 0.001); a similar trend was also seen in poorly functioning long vein grafts (75.3 ± 27.7 compared with 131.5 ± 13.6, p = 0.19) (Fig. 1). Furthermore, angiographically poor bypasses consistently demonstrated either absolute flows of less than 20 ml/minute, or a reduction in bypass flow of more than 30% within 3 months. No fully patent bypass was measured to have a flow of less than 20 ml/minute; reductions in flow of more than 30% were evident in two cases in which the bypasses appeared patent on angiograms, but in both of these cases the reduction in flow became evident more than 1 year after bypass.

**Correlation With Intraoperative Blood Flow**

In patients who underwent early postoperative quantitative MR angiography (within 48 hours of surgery), good correlation was seen between intraoperative measurements of flow and quantitative MR angiographic measurements of flow (13 cases, Pearson correlation coefficient = 0.70, p = 0.01). The quantitative MR angiographic flow measurements were on average 40% higher than the intraoperative flow measurements (106 ± 9 ml/minute compared with 64 ± 13 ml/minute, respectively) consistent with the expected increase in cerebral metabolic rate (and flow) in the awake state compared with the anesthetized state.

**Illustrative Cases**

**Patient Grafts**

**In Situ Arterial Graft, Case 1.** This 21-year-old man with moyamoya syndrome presented with a history of right hemispheric transient ischemic attacks. Evaluation demonstrated near occlusion of the right M1 segment of the MCA, and left MCA stenosis. Single-photon emission computed tomography demonstrated hemodynamic compromise in the right hemisphere, and the patient underwent a right STA–MCA bypass without complications. He underwent angiography and quantitative MR angiography to assess the bypass 2 days postoperatively (Fig. 2). Flow in the STA was measured at 70 ml/minute. Subsequent follow-up angiography and quantitative MR angiography at 12 months postoperatively demonstrated maturation of the bypass and a flow of 82 ml/minute; follow up at 46 months demonstrated stable patency and flow (87 ml/minute).

**Vein Interposition Graft, Case 2.** This 60-year-old woman with a large symptomatic left cavernous aneurysm underwent a left ECA–MCA vein graft in preparation for ICA sacrifice (on the basis of results of balloon occlusion testing). She tolerated the procedure well, and a postoperative quantitative MR angiogram demonstrated a rate of blood flow through the graft of 180 ml/minute (Fig. 3). The ICA was subsequently occluded via an endovascular procedure, and follow-up quantitative MR angiography demonstrated an increase in graft flow to 244 ml/minute.

<table>
<thead>
<tr>
<th>TABLE 1</th>
<th>Operative procedures in 62 cases*</th>
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<tr>
<td>Type of Bypass</td>
<td>No. of Procedures</td>
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<tr>
<td>in situ arterial graft</td>
<td></td>
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<tr>
<td>flow augmentation</td>
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<tr>
<td>STA–MCA</td>
<td>40</td>
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<tr>
<td>STA–PCA</td>
<td>2</td>
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<tr>
<td>OA–PICA</td>
<td>1</td>
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<td>flow replacement</td>
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<td>STA–MCA</td>
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<td>STA–PCA</td>
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<td>vein interposition graft</td>
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<td>flow augmentation</td>
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<tr>
<td>ECA–VA†</td>
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<tr>
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<td>flow replacement</td>
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<tr>
<td>ECA–MCA</td>
<td>6</td>
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<tr>
<td>ECA–PCA†</td>
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* OA = occipital artery; PCA = posterior cerebral artery; PICA = posterior or inferior cerebellar artery.
† Either the external or common carotid artery was utilized as the site of proximal anastomosis.
Poor Grafts

Low Flow (Decrease in In Situ Arterial Graft Flow), Case 3. This 52-year-old woman presented with a right hemispheric stroke and supraclinoid ICA occlusion. An SPECT study confirmed hemodynamic compromise and the patient underwent right STA–MCA bypass following recovery from her stroke. Initial postoperative flow through the graft was established by quantitative MR angiography as 48 ml/minute (Fig. 4). At the 12-month follow up, however, the rate of flow had fallen to 19 ml/minute, and angiography demonstrated a reduction in graft size as well as multiple newly developed areas of dural collateralization, which reduced the demand on the graft.

Low Flow (Decrease in Vein Interposition Graft Flow), Case 5. This 84-year-old woman presented with persistent vertebrobasilar insufficiency, and was found to have long-

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segment proximal stenosis of the dominant VA as well as BA stenosis. A vein graft between the ECA and the V segment of the VA was placed to bypass the VA stenosis and provide a conduit for endovascular treatment of the BA stenosis. The graft initially demonstrated both anterograde and retrograde filling of the VA with a flow of 83 ml/minute (Fig. 6). By 3 months after the procedure, the patient was assessed for endovascular treatment of her more distal disease, and the graft flow was found to have dropped to 33 ml/minute with graft shrinkage presumed due to the downstream BA stenosis. The BA stenosis was found not to be amenable to angioplasty, and quantitative MR angiography at the 12-month follow up demonstrated that the graft flows remained reduced, but stable.

Discussion

The goals of the current study were to assess bypass pa-
tency and function using quantitative MR angiography and address whether this modality may be an adequate replacement for standard catheter angiography in serial follow up of bypass grafts. Comparison of our standard angiographic and quantitative MR angiographic findings demonstrated an excellent correlation. Bypasses that were angiographically stenotic or diminutive demonstrated significantly lower blood flows than their patent counterparts. This was evident both for in situ arterial grafts and for long vein grafts, although the trend did not reach significance for vein grafts due to smaller numbers. Examining the instances of poor bypass revealed that these grafts consistently demonstrated a low absolute blood flow (< 20 ml/minute), or a significant (> 30%) decline in graft flow within a short interval (3 months). None of the fully patent bypasses had flows less than 20 ml/minute.

Methods for assessing bypass patency have ranged from simple clinical methods such as digital palpation of the bypass pulsations to the most accepted method of catheter angiography. The long-term function of bypass grafts is not well characterized, but it is likely to differ based on the type of graft and the reasons necessitating the bypass. In bypasses performed for flow augmentation in the setting of ischemic disease (typically STA–MCA grafts), filling of the cerebral vasculature through the graft may increase over time as the graft matures or it may decrease as collaterals develop. Monitoring graft function over time can improve our understanding of the natural history and expected longevity of such bypasses. Angiographic assessment has demonstrated that in situ pedicle grafts, such as the STA–MCA graft, have very high early patency rates (90–96%).1,9,11,16,31 but that late graft failure occurs in approximately 10% of cases, and up to half of the remaining grafts may not be functioning optimally.22 Schick et al.32 reported bypass failure occurring at an average of 2.7 years postoperatively for STA–MCA grafts, and 1.4 years for vein grafts in patients treated for ICA occlusion.

Bypasses placed for flow replacement in the setting of planned vessel sacrifice are more commonly long interposition grafts using saphenous vein or radial artery. For such grafts, there are few long-term studies; early occlusion is associated with a high rate of neurological morbidity, and late failures are less common and less morbid but can still lead to neurological sequelae in 20% of cases.28 Long-term follow up of graft function to detect problems such as graft stenosis can prompt intervention to prevent graft occlusion and embolic or hemodynamic stroke. Consequently, serial follow-up of EC–IC bypass patency and function remains important for detecting impending or actual graft failure, as well as for assessing the short- and long-term success of the cerebral revascularization strategy.

Evaluation of bypass patency has traditionally been performed using catheter angiography.1,42 Grading systems to define the relative success of bypasses have been applied to angiographic images, attempting to classify bypass function based on the extent of the vascular tree filled by the graft.1,21,33 However, such anatomical grading systems have not correlated well with outcome.1,16 Monitoring changes in bypass function over time can be difficult; although the rate of contrast dye filling and washout during the procedure may give some indication of flow changes within a bypass, such observations are difficult to quantify and compare between studies. For routine follow up, a less invasive modality than angiography is desirable, and clinical examination alone has been proposed as an adequate alternative. In a study of 415 STA–MCA bypass procedures performed for
carotid occlusive disease, Sundt and colleagues reported a 98% correlation between the findings on physical examination (digital palpation of the donor vessel pedicle) and angiography in the first 260 cases in which both methods were used. However, the high angiographic patency rate (99%) makes the correlation less meaningful, because there were too few occlusions to allow us to assess the specificity of the clinical test.

Less invasive methods, including CT angiography and MR angiography, have also been used to assess grafts. Comparisons of CT angiography and catheter angiography in small groups of patients following bypass have shown good correlation. However, although changes in the function of the bypass may be inferred from changes in the caliber of the bypass conduit, more specific information regarding bypass function is difficult to obtain from the static images provided by CT angiography. Authors of several articles describing small series of cases have reported successful visualization of bypasses with MR angiography using a variety of sequences including time-of-flight imaging and phase-contrast MR angiography. New techniques based on phase-contrast MR angiography provide the ability to quantify blood flow through cerebral vessels and thereby add a new dimension to the imaging assessment of bypass grafts. The technique of quantitative MR angiography, which we have used in this study, provides the ability to directly measure flow in ml/minute in the vessels of interest. Therefore, blood flow in a bypass can be measured and followed serially, not merely on the basis of structural appearance, but on the basis of hemodynamic assessment. The use of MR angiography in measuring cerebral vessel flow has been reported for a variety of indications including evaluation of occlusive cerebrovascular disease and carotid endarterectomy as well as evaluation of EC–IC bypass grafts. Neff and colleagues reported mean bypass flows of 84 ml/minute in 25 patients undergoing STA–MCA bypass for carotid occlusion. Good correlation with an angiographic grading system characterizing bypass function as extensive, moderate, or poor was also found on early postoperative evaluation. The use of quantitative MR angiography in evaluation of venous bypass for flow replacement has also been reported; Hendrikse and associates reported flow measurements averaging 199 ml/minute in seven patients who had undergone venous bypass surgery for the treatment of giant aneurysms requiring ICA occlusion. Similarly, our results demonstrate that currently available quantitative MR angiography techniques allow quantitation of flow, as well as consistent visualization of patent bypasses. Our results additionally demonstrate the utility of quantitative MR angiography in following bypass grafts serially over time to monitor changes in bypass function.

Conclusions

Bypass grafts can be accurately assessed postoperatively in a noninvasive fashion by using quantitative MR angiography. This imaging modality provides not only information regarding patency as shown by conventional angiogram, but also a quantitative assessment of bypass function. In our patient population, a low, or rapidly decreasing, flow was indicative of a poor graft. We propose that quantitative MR angiography may provide an alternative to angiogram for serial follow up of bypass grafts used for cerebral revascularization.

Disclosure

Dr. Charbel is a consultant for Transonic Systems, Inc., and has a financial interest in VasSol, Inc. Dr. Zhao is employed part time by VasSol, Inc.

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References


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