Original Research

Contrast-Enhanced Three-Dimensional Magnetic Resonance Angiography of the Mesenteric Vasculature

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The diagnosis and treatment of mesenteric occlusive disease is important due to the high morbidity and mortality associated with ischemia of the bowel. This article describes the application of magnetic resonance angiography (MRA) as a minimally invasive tool for diagnosing mesenteric and portal vascular disease. The techniques for three-dimensional (3D) contrast-enhanced MRA and flow measurement of the mesenteric circulation are described. Excellent image quality is obtained using sagittal contrast-enhanced 3D MRA of the aorta and proximal mesenteric vessels. Delineation of the small distal mesenteric branch vessels is still limited due to the finite spatial resolution of MRA. The application of MRA techniques to the diagnosis of mesenteric ischemia, revascularization, transplantation, and portal hypertension are demonstrated. Finally, the merits of various acquisition techniques and future contrast agents are discussed. MR angiography using intravenously administered contrast agents provides the clinician with a powerful, minimally invasive method for diagnosing mesenteric vascular disease. J. Magn. Reson. Imaging 1999;10:369–375. © 1999 Wiley-Liss, Inc.

Index terms: mesenteric circulation; magnetic resonance angiography; occlusive disease; gadolinium; phase-contrast; blood flow

ALTHOUGH SYMPTOMATIC MESENTERIC vascular disease is relatively rare compared with coronary, cerebral, and peripheral vascular diseases, its detection is of paramount importance given its high associated morbidity and mortality. Because the incidence of mesenteric ischemia is increasing as the mean age of the the U.S. population increases, new noninvasive techniques are needed to help clinicians diagnose a disease process that has historically required a high index of suspicion. The nonspecific signs and symptoms of the disease can delay diagnosis and subsequently lead to poorer outcomes. The noninvasive nature of magnetic resonance angiography (MRA) could serve to lower the clinician's threshold for ordering angiographic studies and increase the diagnostic rate of mesenteric ischemia.

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Mesenteric ischemia is traditionally divided into the causal groups of acute arterial occlusive disease, nonobstructive mesenteric arterial insufficiency, mesenteric venous occlusion, and chronic mesenteric ischemia (CMI). Patients with acute causes of mesenteric ishemia are rarely evaluated with MRA because of their clinical status and urgent need for diagnosis. Li et al (1) raised the possibility of using in vivo oximetry as a method to evaluate for acute mesenteric ischemia, but conventional angiography and emergency surgery remain the mainstays of evaluation in this setting. Patients with symptoms suggestive of CMI are excellent candidates for MRA, and with the addition of contrast-enhanced 3D techniques, MRA has achieved increased clinical application in evaluating these patients.

Other uses for MRA pertaining to the mesenteric vasculature include evaluation after a revascularization procedure and looking for the extent of tumor encasement of mesenteric arteries and veins. In addition, the noninvasive nature of MRA may encourage surgeons to obtaining a baseline study after a revascularization procedure. The possible benefit of this is yet to be determined.

MR techniques have also been used to evaluate a variety of portal vein abnormalities including portal hypertension, portal thrombosis, and tumor encasement. MRI can evaluate the portal vein for patency and flow direction, anatomy, postoperative transplant vascular complications, and changes of portal hypertension and possible portal vein thrombosis. When combined with spin-echo and dynamic contrast-enhanced imaging of the abdominal organs, the MR methods offer a powerful tool for lesion detection and characterization (2–13).

TECHNIQUE

Mesenteric Artery

Several MR techniques have been advocated for evaluating the mesenteric vasculature. Burkart et al (6) used cine cardiac-gated phase contrast (PC) flow measurements in the portal venous system to document that flow rates in the superior mesenteric and portal veins correlate well with those in the mesenteric arteries that supply them. Burkart et al (7) further studied cine PC techniques in patients suspected of CMI and found that the percentage of flow augmentation in the superior mesenteric vein (SMV) postprandially is significantly lower in patients with CMI than it is in patients without ischemia or in healthy volunteers. Also using cine phase contrast MR imaging, Li et al (14,15) reported that the percent change in the superior mesenteric artery (SMA) blood flow 30 minutes postprandially provided the best distinction among healthy, asymptomatic, and symptomatic subjects. The investigators reported that SMA and SMV blood flow increased postprandially in all subjects; however, the increase was substantially less in patients with atherosclerosis. The study also found that the ratio of the increase in SMV flow to the increase in SMA flow decreased with increasing severity of disease, suggesting that comparison of the ratio of SMV flow to SMA flow may be more useful than assessing SMV or SMA blood flow alone. Additionally, Li et al (16–18) studied oxygenation of the SMV with in vivo MR oximetry and reported preliminary results in humans and dogs demonstrating that a decrease in SMV oxygenation postprandially is an accurate indicator of CMI. The study also suggested using in vivo MR oximetry in the diagnosis of acute mesenteric ischemia.

Using an alternate diagnostic approach, Montalbano et al (19) reported spillage of enterally administered gadopentetate dimeglumine as a discriminator between ischemic and control rats. The method awaits validation in human subjects, however.

Despite these advances, three-dimensional (3D) contrast-enhanced MRA methods offer an important technique for evaluation of the anatomic status of the mesenteric vasculature directly. Because the vessel signal is dependent on the shortened T1 of gadolinium, the problems of signal loss with inplane flow and other artifacts are avoided. Since Prince et al (20) described their 3D contrast-enhanced technique, several studies have looked at its utility for the mesenteric vasculature (21–26). Most recently, Kopka et al (26) demonstrated that the improvements achieved in 3D MRA with fat saturation and a high-caloric meal could help MRA replace conventional digital subtraction angiography for evaluating the hepatic vasculature. Also, the noninvasive techniques of MR are increasingly being used in the transplant population as more research is conducted. Preliminary results from Stafford-Johnson et al (25) suggest that 3D contrast-enhanced MRA and magnetic resonance venography (MRV) may approach the accuracy of conventional angiography in evaluation of vascular complications of liver transplantation.

3D Contrast-Enhanced Mesenteric Technique

At our institution, mesenteric imaging is performed on a 1.5-T system with high-performance gradients utilizing the body coil. For mesenteric arterial evaluation alone, sagittal fast gradient-echo sequences are prescribed from a coronal localizer and performed prior to, during, and after administration of approximately 0.2–0.3 mmol/kg of IV gadolinium. Cine cardiac-gated 2D PC sequences are prescribed orthogonal to the celiac and superior mesenteric arteries to evaluate flow rates. Postprocessing techniques generate maximum intensity projections (MIPs) rotated through 180° and multiplanar volumetric reconstructions (MPVRs) of the three mesenteric vessels (Fig. 1). Postprocessing of the PC sequences calculates cardiac-gated flow waveforms, flow rates, and velocities of both the celiac artery and the SMA.

The fast gradient-echo sequence used for acquiring the source images generally requires a TR $<$ 10 msec, a TE $<$ 2 msec, and a flip angle between 30 and 60°. At our institution, we utilize a TR/TE of 8.6/1.8 msec, flip angle 45°, 512 $\times$ 192–256 matrix, 36 $\times$ 18 cm field of view (FOV), single excitation (NEX), and 24 4.0 mm slices that are zero interpolated to 48 slices at 2 mm intervals. The outer 2 slices of the original 24 are discarded because of slice wrap, making the final result of the acquisition 40 2.0 mm slices. k-space is filled centrically.

The cine 2D PC sequences through the mesenteric vessels can be obtained again postprandially for evaluation of response to a meal (12) (Fig. 2). Fast gradient-echo sequences may be acquired at end expiration in addition to end inspiration to evaluate for median arcuate ligament syndrome (Fig. 3).

Portal Vein

After Zirinsky et al (11) described the usefulness of spin-echo techniques for detecting the presence and extent of portal vein thrombosis, both Silverman et al (2) and Martinoli et al (10) demonstrated the usefulness of adding gradient-echo imaging to decrease the number of false-positive exams due to slow flow in the portal vein. Edelman et al (5) demonstrated the usefulness of MR for measuring portal blood flow, anatomy, and collaterals with 2D flow-compensated gradient-echo images. Applegate et al (8) used 2D PC to evaluate patency and flow direction and velocity of the portal vein. Burkart et al (7) showed that cine PC MR could be used to calculate flow in healthy volunteers as well as patients with portal hypertension.

Noncontrast imaging techniques for the portal vein described by Finn et al (4) and Hughes et al (9) used gradient-echo time-of-flight for examining the portal vein. This technique is still widely used in clinical practice today, but studies by Rodgers et al (3) and Stafford-Johnson et al (25) have demonstrated contrast-enhanced techniques that can be performed in conjunction with arterial phase images. Additionally, 3D contrast-enhanced studies of the portal vein have the added benefit of reprojecting the data in any plane.

Mesenteric Arterial and Venous Technique

The portal vein is best evaluated in the coronal plane when using a 3D acquisition. At our institution, we utilize a 256 $\times$ 256 matrix. While arterial MRA is now being obtained with gadolinium doses lower than 0.3 mmol/kg, we recommend the maximum 0.3 mmol/kg dose up to 40 ml when imaging the portal vein because the contrast bolus will become more diluted. Ideally, a coronal multiphase exam is acquired with sufficient

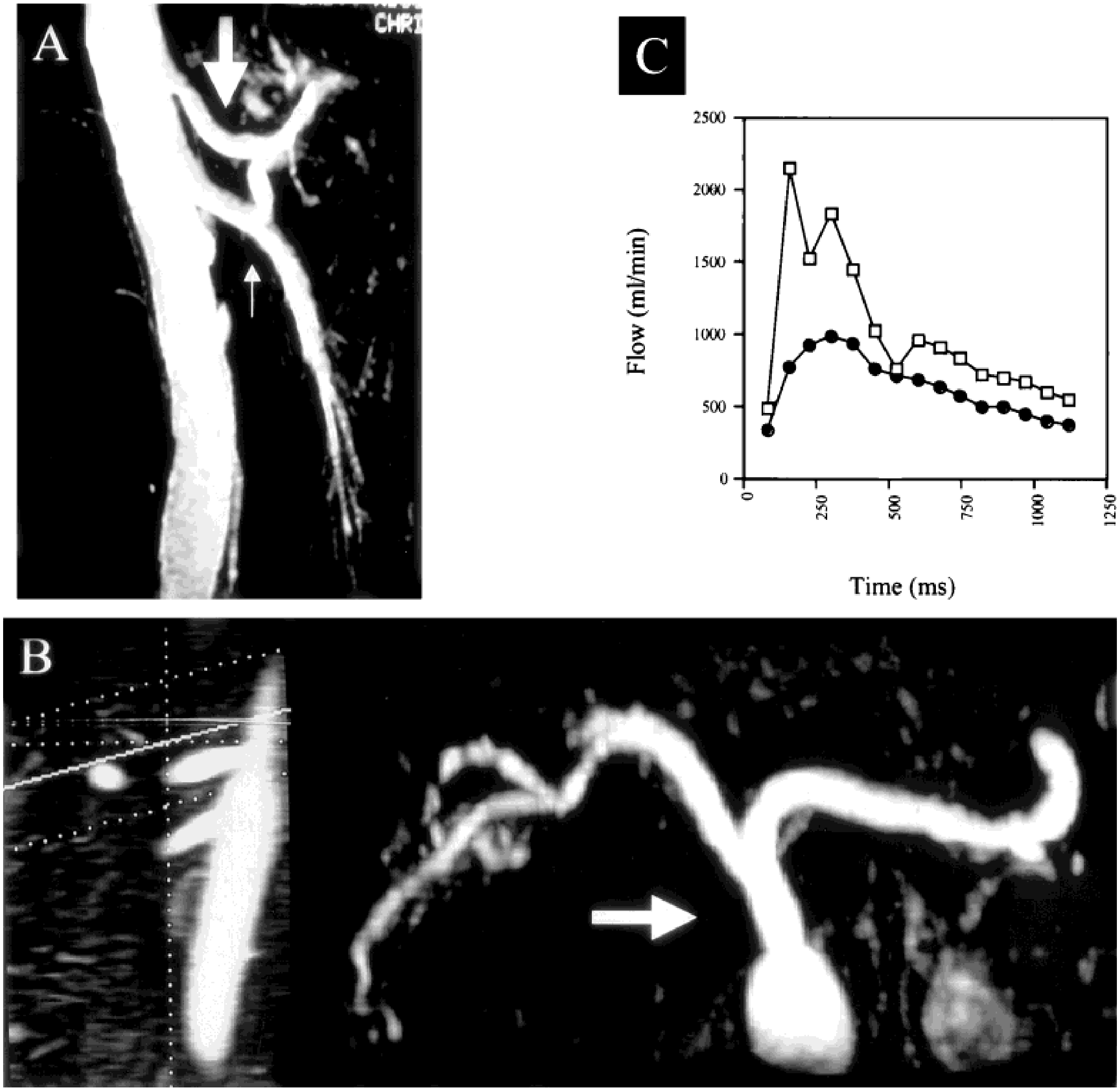

Figure 1. Post-processing. Sagittal maximum intensity projection image (**A**) and axial multiplanar volumetric reformat (**B**) of normal celiac (large arrow) and superior mesenteric artery (small arrow). (Reconstructed from sagittal 3D fast gradient-echo source images: TR/TE 8.8/1.8 msec, flip angle 45°, 512 × 256 matrix, 36 × 18 cm FOV, 1 NEX, 20 4.0 mm thick/0.0 space, zero interpolated to 2.0 mm intervals.) **C:** Normal arterial waveforms of celiac (●) (and superior mesenteric (□) arteries (Calculated from cine cardiac-gated 2D phase contrast source images: TR/TE 18.4/4.9 msec, 256 × 128 matrix, 30 × 15 cm FOV, 1 NEX, 5.0 mm thick/0.0 space, 2 views per segment.)

time between studies to allow for respiration following the breath holds.

APPLICATIONS

Normal Anatomy

Normal anatomy of the mesenteric vasculature is reported to occur in only 50–60% of patients. The classic anatomic branches of the celiac are the splenic, left gastric, and common hepatic. The SMA originates caudal to the celiac and supplies branches to the pancreas, small bowel, and right and mid-colon. The inferior mesenteric artery (IMA) supplies the left colon and portions of the rectum. Collaterals between the celiac artery and SMA include the pancreaticoduodenal arcade and occasionally the arc of Buehler. The marginal artery of Drummond and the arc of Riolan are SMA and IMA collaterals (Fig. 2).

The most common variant of the mesenteric vasculature is a replaced right hepatic artery, usually originating from the SMA but occasionally from the aorta. Other less common variants include an accessory right he-

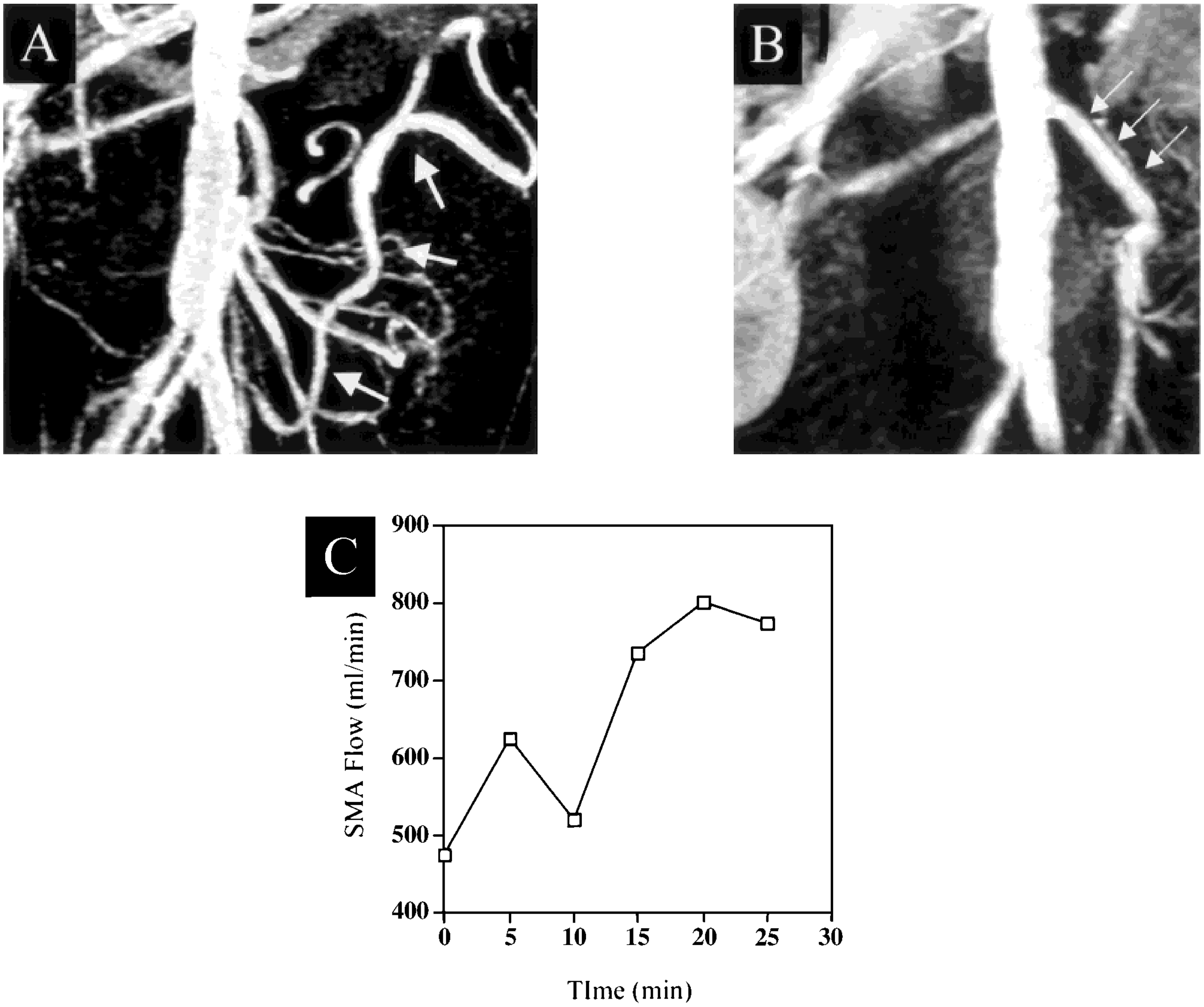

Figure 2. Caloric stimulation. One day post operative MIP (**A**) and MPVR (**B**; reconstructed from coronal 3D fast gradient-echo source images: TR/TE 8.2/1.8 msec, flip angle 45°, 512 × 192 matrix, 36 × 36 cm FOV, 1 NEX, 32 3.0 mm thick/0.0 space, zero interpolated to 1.5 mm intervals) demonstrate a patent aorta-SMA surgical graft (arrows, B). Note the persistent prominence of the arc of Riolan (arrows, A). After caloric stimulation, sequential flow rate (calculated from cine cardiac-gated 2D phase contrast source images: TR/TE 18.4/4.9 msec, 256 × 128 matrix, 30 × 15 cm FOV, 1 NEX, 5.0 mm thick/0.0 space, 2 views per segment) measurements (**C**) indicate a less than normal increase in expected SMA blood flow. The findings suggest more distal small vessel occlusive disease involving the SMA territory.

patic artery, common hepatic origin from the SMA or the aorta, left gastric origin directly from aorta, and, rarely, a common celicomesenteric trunk.

Chronic Mesenteric Ischemia

Patients with CMI typically have a history of postprandial abdominal pain, weight loss, and food avoidance, presenting on a background of widespread atherosclerotic disease. In the past, conventional angiography was used to evaluate the mesenteric vessels for atherosclerotic narrowing. Similar evaluation can now be performed with contrast-enhanced 3D MRA without the expense, invasive technique, and contrast risks of conventional angiography. Currently, conventional angiography remains superior to MRA in spatial and temporal resolution. In the future, increased gradient strengths and time-resolved techniques might nullify this difference.

Angiographic findings of severe stenosis or occlusion of two or three of the mesenteric vessels (Fig. 4) support the diagnosis of CMI and suggest that the patient may benefit from a revascularization procedure. However, due to numerous collateral pathways in the abdominal vasculature, these findings can also be seen in asymptomatic patients; clinical data must be correlated with the imaging findings. Detection of patients with CMI is important because while the operative mortality for elective surgical repair is reported to be between 4 and 12%, the mortality with progression to SMA thrombosis is greater than 90%.

The mesenteric arterial vasculature can also be affected by conditions other than atherosclerosis, includ-

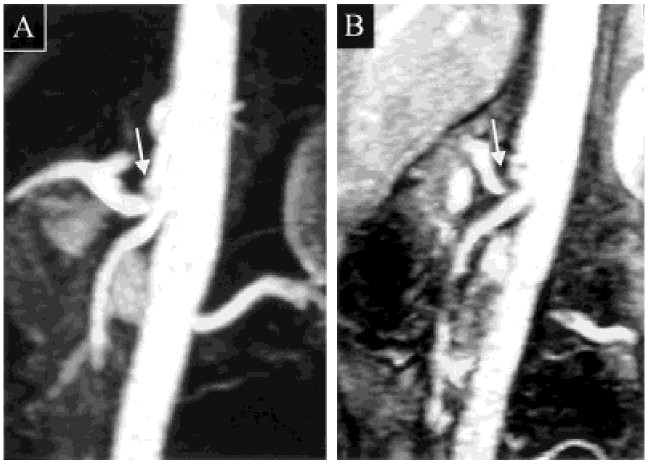

Figure 3. Median arcuate ligament syndrome. Sagittal MPVRs of image sequence obtained during (A) end inspiration (**A**) and end expiration (**B**; reconstructed from coronal 3D fast gradient-echo source images: TR/TE 8.2/1.8 msec, flip angle 45°, 512 × 192 matrix, 36 × 36 cm FOV, 1 NEX, 32 3.0 mm thick/0.0 space, zero interpolated to 1.5 mm intervals). The degree of stenosis and angulation involving the celiac artery (arrow) increases with expiration, compatible with extrinsic compression by the median arcuate ligament of the diaphragm.

ing vasculitides and infectious processes of adjacent organs (Fig. 5). MRA, combined with MRI evaluation of the periarterial soft tissues, allows evaluation of lesions and vascular complications in a single examination.

Postoperative Evaluation

Surgical techniques for revascularizing patients with CMI include endarterectomy and bypass. Transaortic visceral endarterectomy is a technically challenging procedure that requires extensive retroperitoneal dissec-

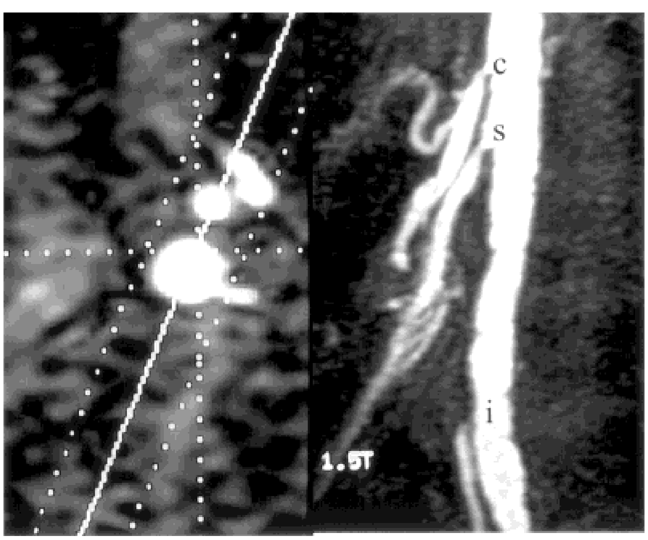

Figure 4. Mesenteric ischemia. Sagittal MPVR (reconstructed from sagittal 3D fast gradient-echo source images: TR/TE 8.8/1.8 msec, flip angle 45°, 512 × 160 matrix, 36 × 18 cm FOV, 1 NEX, 20 4.0 mm thick/0.0 space, zero interpolated to 2.0 mm intervals) demonstrates severe celiac (c), SMA (s), and IMA (i) stenosis suggesting chronic mesenteric ischemia.

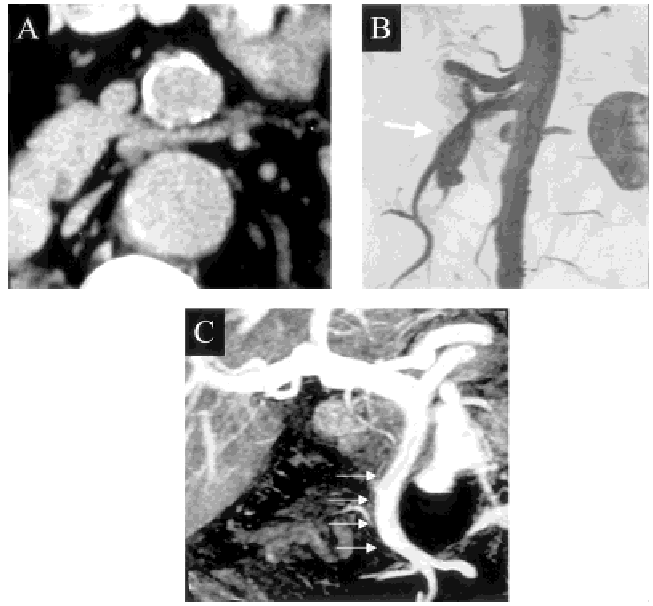

Figure 5. Superior mesenteric artery aneurysm. Computed tomography (**A**) and oblique frontal MIP (**B**) demonstrate a large SMA aneurysm (arrow) in a patient with a history of several episodes of pancreatitis. The portal venous phase MIP (**C**) nicely depicts the displacement of the superior mesenteric vein (arrows) by the aneurysm.

tion. Bypass procedures are the more common choice and can be performed with a graft of either dacron or polytetraflouroethylene (Fig. 6) or with a vein graft. The SMA is more commonly revascularized than the celiac artery or IMA. Mesenteric endarterectomy or bypass is routinely performed on stenotic vessels during an ab-

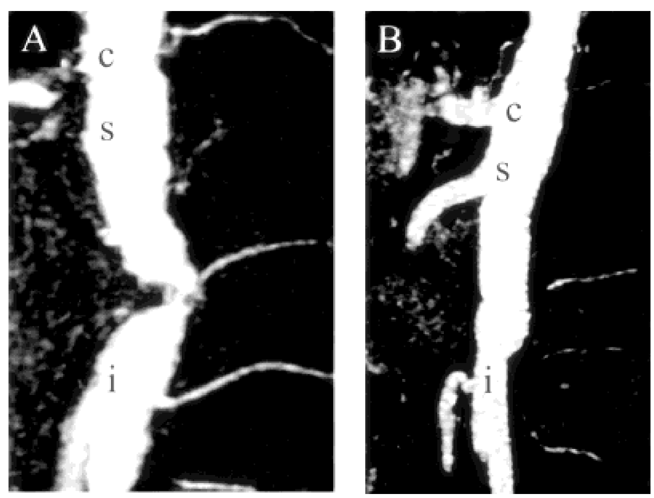

Figure 6. Postoperative evaluation. Sagittal MPVRs (reconstructed from sagittal 3D fast gradient-echo source images: TR/TE 8.8/1.8 msec, flip angle 45°, 512 × 256 matrix, 36 × 18 cm FOV, 1 NEX, 20 4.0 mm thick/0.0 space, zero interpolated to 2.0 mm intervals) prior to (A) and after (B) revascularization for chronic mesenteric ischemia. **A:** Thick slab (22 mm) MPVR shows severe stenosis of the celiac artery, occlusion of the SMA, and patency of the IMA. **B:** Postoperative thick slab (16 mm) MPVR of the same patient shows widely patent celiac and SMA bypass grafts status after abdominal aortic aneurysm repair with reimplantation of the IMA.

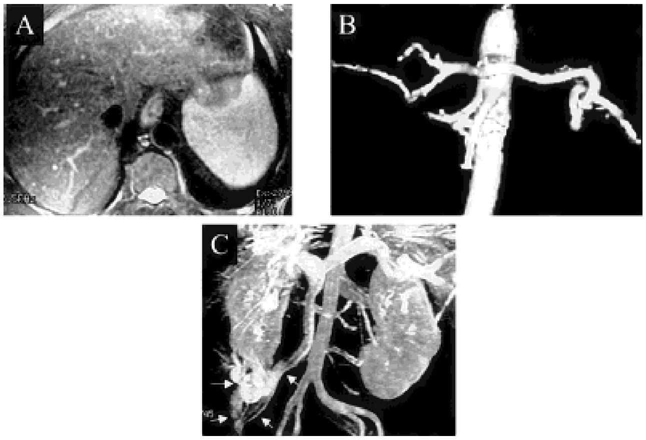

Figure 7. Evaluation for liver transplantation. **A:** Axial fast spin-echo T2-weighted image (TR/TE 5217/72 msec, 256 × 256 matrix, 38 × 28 cm FOV, 2 NEX, 23 7.0 mm thick/3.0 space) from MRI portion of the exam demonstrating normal liver. Additional spin-echo T1-weighted axial, dynamic fast gradient-echo T1-weighted axial (with 0.1 mmol/kg gadolinium) and postcontrast fat-saturated spin echo T1-weighted axial images were also obtained. **B:** 3D volume rendering (reconstructed from coronal 3D fast gradient-echo source images obtained during injection of 0.2 mmol/kg gadolinium: TR/TE 8.8/1.8 msec, flip angle 45°, 512 × 192 matrix, 36 × 36 cm FOV, 1 NEX, 20 4.0 mm thick/0.0 space, zero interpolated to 2.0 mm intervals) of the mesenteric arterial vasculature demonstrates conventional hepatic anatomy. **C:** Oblique frontal MIP (reconstructed from coronal 3D fast gradient-echo source images: TR/TE 8.0/1.7 msec, flip angle 45°, 512 × 128 matrix, 36 × 36 cm FOV, 1 NEX, 32 4.0 mm thick/0.0 space, zero interpolated to 2.0 mm intervals) from the portal phase shows patency of the portal venous system. Note the large varix (arrows) from the superior mesenteric vein to the right renal vein.

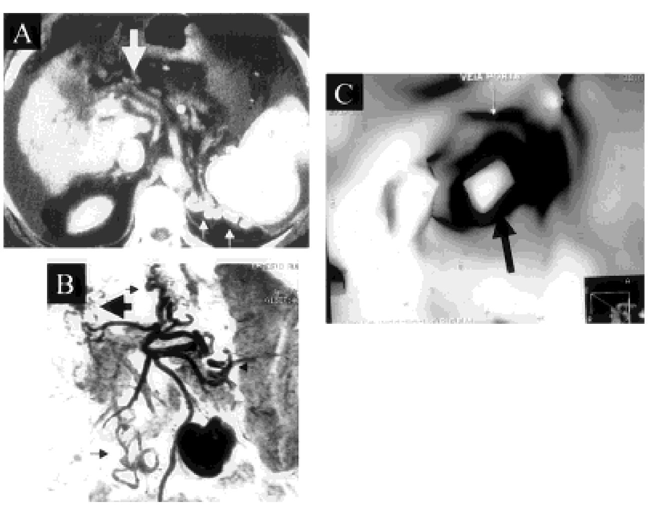

Figure 8. Portal vein thrombosis. Computed tomography (**A**) and frontal oblique MIP (**B**) images demonstrating multiple collateral vessels in the porta hepatis (large arrow) compatible with cavernous transformation. Multiple varices (small arrows) are also present. **C:** The shaded surface endoscopic view (seen as if looking from the confluence to the porta hepatis) shows the thrombus within the portal vein.

dominal aortic aneurysm (AAA) repair. This is done regardless of whether the patient has symptoms of CMI because AAA repair procedures can disrupt the collateral pathways.

Portal Vein

Portal hypertension is a common occurrence in patients with significant liver disease. MR can effectively evaluate the direction of flow in the portal vein and assess for formation of collaterals and varices (Fig. 7) (3–10,12). Portal hypertension can also occur in patients with hepatic congestion or portal vein thrombosis (Fig. 8). While portal hypertension tends to occur in older patients, portal vein thrombosis usually occurs in younger patients and is also well evaluated with MR. (2,11) Portal vein involvement by adjacent tumors such as hepatoma, pancreatic adenocarcinoma, and cholangiocarcinoma has also been reported.

Horizons

Blood pool contrast agents may allow high-resolution imaging of the arterial and venous circulation and may facilitate studies during free breathing. The role of blood pool contrast agents is yet to be determined.

In the future, MRA/MRV techniques of the mesenteric vasculature should achieve even greater utilization. The initial work of Stafford-Johnson et al (25) with MRA/MRV in evaluating liver transplant complications is encouraging. With MR's capabilities of evaluating the liver for mass lesions using dynamic scan MRI and the hepatic vasculature for anatomy using MRA in one exam, MR may quickly become the exam of choice for liver transplantation workup (Fig. 7). As MR begins to be used more frequently for interventional applications, the MRV phase of the mesenteric vasculature is an excellent roadmap for transjugular intrahepatic portosystemic shunt (TIPS) placement.

In conclusion, MR techniques such as 3D contrast-enhanced angiography, 2D PC, and gradient- and spin-echo imaging are proven diagnostic tools for evaluating the mesenteric vasculature, including flow dynamics, atherosclerotic narrowing, extrinsic compression, and hepatic vascular anatomy. These methods will probably play an increasing role in the evaluation of patients with mesenteric vascular disease, due to the safety, physician acceptance, and patient tolerance of the examinations.

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